

FUTURE CHALLENGES FOR NASA:

The Moon, Mars, and More

**By Joseph N. Pelton
with Peter Marshall**

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(Artistic representation courtesy of Nick Goodman).

Full details of this project are in Chapter 11.

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This book provides an analytic review of NASA's astronaut-related activities in terms of current activities and future programs. It urges a new way forward with a more ambitious and better-defined program for deep space astronaut exploration.

It calls for improved technologies, systems and most of all a clear and long-term future vision. This is to be accomplished through an improved strategic planning process that has substance and specifically targeted aims with deadlines. It examines NASA's current progress, especially with regard to the Artemis program. This then proceeds to assessing future potential scientific, technological and systems goals against a thirty-year timeline. It examines critical areas for research and development, possible follow-on deep space exploration missions and the technology and spacecraft that will be needed to support these far-reaching goals. It seeks to review and evaluate NASA's current performance, but it also provides analysis and recommendations as to what might come next. This book also focuses on the need for more targeted and much better goal setting for longer-term deep space activities through better strategic planning. It seeks to look beyond programmatic, scheduling and costing problems encountered with the Artemis Program to future astronaut activities in deep space for Mars and beyond.

This is thus a book about what comes next for NASA.

It identifies possible goals for NASA with regard to developing new technologies, systems, launchers, spacecraft and mission capabilities. It suggests the need for a succession of three back-to-back ten-year plans for true deep space exploration and the future of off-Earth habitats for astronauts and space explorers. It asks NASA to answer what it will accomplish in the next 30 years and how it will do it.

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Joseph Pelton and Peter Marshall - June 2025

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Foreword

The amount of science, technology, and effort that goes into planning to send astronauts into outer space to explore the Moon is a herculean undertaking. The range of knowledge involved spans the disciplines from astrophysics to xenon thrusters. The design of launch vehicle systems that are both safe and powerful enough to escape the pull of gravity and send spacecraft carrying a team of astronauts all the way to the Moon is a truly difficult task, but that is just the start of this undertaking. There is a need to design space suits, robot rovers, habitats for the astronauts, oxygen generation systems, high performance filters to purify recycled water, a host of monitors and sensors, solar power arrays and specialized battery systems, guidance systems, deep space communications and networking systems, treatments to accustom astronauts to living in the special conditions of space, search and rescue systems, and scores of other systems.

It is not easy to design, engineer, build, test, deploy, and operate all of these systems to perform with a very high level of reliability. The Apollo Program involved astronaut missions that lasted hours on the Moon and with landing sites that were the easiest to navigate and access. The Artemis Program involves landing on the difficult terrain of the lunar South Pole area with limitations on solar lighting and involves planning for missions that can extend to months in length.

A program and safety review of the Artemis Program has been undertaken in order to review all of the many complex aspects of this very demanding program. This is a difficult task at the time this book goes to press. This is because Jared Isaacman is in the confirmation process to be the new Administrator of NASA and has signaled, along with fellow billionaire Elon Musk, a greater interest in sending astronauts to Mars than in the Artemis lunar exploration activities to which close to \$100 billion has been committed by NASA and its international partners. As the review in this book indicates, Artemis has had significant problems with delays, budget overruns and technical difficulties involving the Space Launch System, the Orion crew vehicle, and the Human Landing System that is slated to carry astronauts to and back from the lunar surface on the Artemis III mission.

The launch failure of the Space X Starship on May 27, 2025, as the ninth unsuccessful test launch of this vehicle, is especially key. This new launcher is a crucial part of the Human Landing System architecture for the planned astronaut landing with Artemis III. This launcher's continuing failure is thus another crucial setback to the Artemis program. As this book goes to press NASA faces key challenges about its future missions and the Artemis Program, in particular. Critical decisions and astronaut safety issues thus pend for NASA as this book goes to press

Fortunately, the main focus of this book is to seek new ways to improve NASA's longer-term strategic planning, improve its management and goal-setting mechanisms, and make it more innovative, productive, and less bureaucratic. Our prime objective is to create a new, better, and safer way forward for NASA astronauts to not only explore deep space but also forge a new way forward. This book indicates pathways for the future that might well lead to viable space habitats that could be created on both the Moon and Mars.

A thirty-year goal for NASA should be to find a safe, recyclable, and sustainable way for astronauts and space pioneers to master the art of “Living-in-Space.”

If we can master such sustainable biosphere systems for the Moon and for Mars, it might mean unlocking vital new scientific and practical knowledge. It might show us how to not only thrive in deep space, but perhaps more importantly help us sustain a healthy planet right here on Earth. Too often we forget that our very existence as a species depends on the continued viability of “Space Ship Earth.” What we learn from space research and astronaut exploration can unlock new knowledge and perhaps provide access to new resources. Goal number one for space research is to acquire new knowledge that is vital to sustaining a healthy biosphere on our home planet.

One of the aims of this book is to identify ways to improve the odds that astronauts can better meet the challenges of living safely on the Moon, then Mars, and then perhaps even beyond. The effort to identify possible risks, increase resilience, and improve the safety design of this complex venture into outer space has been a difficult, challenging and rewarding activity that has led to a number of suggestions as to possible improvements. The difficulty of such a safety review, however, is nothing when compared to the enormous undertaking of the dedicated scientists and engineers of NASA, as well as the tens of thousands of expert contractors who have been working on the Artemis Program for decades. With a new administrator, new aims, and the prospect of many funding cuts, there are clearly major changes ahead. Will this be retrenchment? Will it involve new goals for Mars? Will it be a new beginning or simply a simplification of the Artemis undertaking? It is still too early to tell.

It is much easier to critique and analyze space programs and make some possible suggestions for improvements than to seek to design and engineer these programs in the first place.

The authors of this study are deeply impressed with the many, many scientists and engineers who have conceived of this lunar exploration program and are now well along in its implementation. The various suggestions as to possible improvements and some critiques of the program are presented in the most positive ways possible without undue criticism. The intent was not to find fault. Rather, the motive was to improve the safety of the Artemis Program and future deep space exploration initiatives as they are planned for over a thirty-year time horizon. We hope that some of the findings in this book can help NASA's technical, management, and planning systems to improve. We are seeking a number of improvements. These reforms or improvements can come in many forms. They can come from technology such as new interplanetary space vehicles fueled by nuclear fusion, or key new developments may come from Artificial General Intelligence (AGI), 'smart robotic' space explorers, bio-regenerative life support systems (BLSS). Alternatively, NASA might well benefit from new ways of setting goals through improved strategic planning, shedding of bureaucratic practices, and reorganizing to be more like "NewSpace" ventures that have produced such impressive innovation in the space industry over the past two decades.

This study has been funded by the Space Shuttle Children's Trust Fund, that has been a champion of safety for astronauts and their families. The SSC Trust Fund, among their many activities, has funded space safety studies to lower the risk of space exploration. The support of the Trust Fund is greatly appreciated. The findings and views

expressed in this book, however, are those of the authors and not of the SSC Trust Fund. Any errors or misstatements contained in this book are the sole responsibility of the authors."

We thus hope NASA will indeed continue to achieve new heights—literally and figuratively. For NASA the sky is no longer the limit!

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Chapter 1

A Future of Safer and More Sustainable Space Systems for Astronauts

Scientific research and development efforts related to outer space are constantly moving forward and at ever greater speed. NASA, other space agencies and a now much enlivened aerospace industry are seeking improved technology to improve the speed, range, propulsive force and cost-effectiveness of space systems.

These efforts are constantly seeking promising new technologies, systems, methods, and processes. In order to make the needed program, this will also increase the need for space agencies, and NASA in particular, to set more challenging goals for the future. This means that there will also need to be some revamping of organizational processes and more goal-oriented strategic planning and the setting of more ambitious goals. Without better goals, more breakthrough innovations achieved with greater efficiency, and an improved organizational structure, and more flexible partnership contracting with aerospace contractor NASA, could well lose its leadership role in deep space exploration. In short, NASA will need to make changes to achieve the types of advances and long-range goals identified and recommended in the analysis that follows. There is now a worldwide effort to advance the performance of launchers, spacecraft, and space-related

systems as well as to lower net costs. The so-called “NewSpace” revolution that has brought to the forefront a new breed of aerospace companies has shown that there can be a new and more dynamic approach to space research, to space science and applications, and especially exciting new capabilities and achievements in space exploration. Yet, for NASA to catch up and lead this progress forward, change and innovation is needed. New technologies will need to be developed. NASA will need to become less decentralized and less bureaucratic and develop a much more goal-oriented set of strategic planning goals and objectives. It must do more than just operate programs funded by Congress. It is not enough to roll out programs such as the Artemis Moon Exploration Program and the lunar Gateway space station, which are consistently over budget and with performance schedules routinely not met. NASA needs to embrace change to lead the many challenges that lie ahead in deep space exploration and research.

This book is thus about identifying and developing the most promising new space-related R&D. This means examining how to make space exploration more innovative, safer, and more risk-free. It views the potential of new technology and systems through the lens of more innovation, better strategic planning, sustainable deep space exploration, and improved space safety. Most advances and research activities begin on the basis of improved performance, lower cost, and greater efficiency. Once such new technology and systems emerge from the labs, safety experts are then typically brought in—after the fact—to see how they might be adapted or improved to also become safer, or at least to reduce their risk. This approach can lead to key flaws in the design and engineering process, weakness in the safety of deep space exploration programs, and can also diminish incentives from aerospace contractors to provide the best and safest results. In short, there are better ways of designing, engineering, contracting

for, developing, and fabricating the space systems for deep space exploration. Fortunately, as will be described in this book, NASA has learned new ways forward that have produced better results through the use of performance specifications for new types of contractor bidding processes that result in “partnership arrangements” with contractors rather than NASA creating its own technical performances and then awarding cost plus fee type contracts that typically end well over budget and consistently over schedule as has been the case with the Space Launch System, the Ares Launch Vehicle, and the Orion crew vehicle. These key elements in the Artemis Program have highlighted the need for reform.

There has been one continuing theme to our studies and related books that we have researched and written for the SSC Trust Fund over the last two decades. This theme is that safety engineering should be a part of the overall development process from the outset. Our mantra continues to be “safety first.” These simple two words are intended to convey the basic concept that space technologies and systems should be researched and developed with safety experts being an integrated part of the design team that develops system specifications for new programs at the beginning of any such process. In short, engineers and scientists with training in safety and system resilience must participate in defining mission requirements for space exploration and, from the get-go, aid in the design, development, and engineering of new systems. Space systems engineering teams who work in isolation by taking a series of quantitative numbers that form the “mission requirements” for going to the Moon or Mars are likely to overlook key qualitative measures and questions that should be considered from the outset. Further, there is an advantage in NASA design teams creating “performance specifications” that define what new astronaut launchers and spacecraft must be able to do, rather than spending years developing technical specifications. It is beneficial to let

innovative aerospace industry designs present competitive ideas as to the best space transportation vehicles. This can also allow astronaut safety design to be a key part of the competitive process.

In other words, space safety needs to be an integral part of the design and definition of new space systems designs. This means that these safety design engineers should also be able to question the mission objectives themselves. Safety design expertise represents an integral part of system design engineering and new mission definition. Inclusion of the latest safety concepts, engineering processes, and standards needs to become a sine qua non for envisioning, conceptualizing, and engineering new space systems. This will save time, reduce costs, avoid costly mistakes, and—oh yes—save astronaut lives.

One only needs to review the history of the Apollo Program, the Shuttle design and development, and the convoluted and erratic development to date of the Artemis Program by NASA to understand the importance of this way to design and develop major new NASA undertakings.

The past process of defining the specification, and for NASA to award contracts to aerospace companies to build new launchers, has proven to be true over and over again to hold many deficiencies. Safety design and engineering are not “add-ons”; they are the sine qua non of the new mission definition and the new systems design. The use of technical specifications based on cost plus fee awards have serious flaws and often create the wrong incentives. NASA has now developed new ways to create constructive partnerships with aerospace contractors through new approaches to specifications, improved competitive design processes that allow contractor innovation, as well as reinforcing contractual partnerships. These are proving to allow new pathways to success.

The roots of the problem of good mission definition and systems design can be traced to NASA personnel and its leadership, its contractors, and overly restrictive, sometimes cumbersome, and slow systems engineering processes. The processes have often added unnecessary delay and inhibited innovation. In many instances, it has also involved political interventions and reversals of programmatic policies and directives that came from the U.S. Congress, the Executive Branch, and lobbying campaigns by outside special interests.

The Artemis Program and the Moon Landing now planned with Artemis III highlight current safety concerns and the use of outmoded procurement processes. The NASA Aerospace Safety Advisory Panel in February 2025 issued a report questioning the safety of this landing as now planned. (See **Fig. 1.1**). Its report notes a string of “Firsts” that the Artemis III now must successfully achieve through its mission. The report notes that the key steps that are now planned lack adequate previous testing, which must go without fault to complete their mission. This safety report cautions against so many steps not being previously tested. The untested status of the Human Landing System and the need to test its end-to-end safe performance prior to the Artemis III landing were highlighted and listed first in their concerns.¹

This recent report and the strained conditions of NASA’s budget to complete its various key objectives within the Artemis Program and its various deep space research programs aimed at going to Mars represent a very key concern. There are many recommended ways forward to develop safer astronaut programs, but the most critical step of all is for NASA

¹ Leonard David, “Risk with Current Artemis 3 Moon Landing Plan May Be Too High” Space.com Feb 11, 2025 <https://msn.com/en-us/news/technology/risks-with-current-artemis-3-moon-landing-plan-may-be-too-high-nasa-safety-group-says/arAA1yMIOj?ocid=msedgntp&pc=DCTS&cvid=5223048d7c054749bf8312f69f55c675&ei=19>

to not over-commit to too many programs without the resources needed to test the technologies and systems needed to complete them safely. Streamlining and prioritizing NASA's top objectives is key. A review of NASA's strategic plans does not provide a useful way to analyze its areas of focus and priorities. Such a review of programs, priorities, scope of activities, budgets, and current research and development is recommended. One recommendation to start this process and give NASA greater focus would be to move aircraft-related research and development from NASA to the U.S. Department of Transportation. This would allow NASA to concentrate on space systems.



Fig. 1.1: NASA Aerospace Safety Advisory Committee List of Concerns about Artemis III Landing (NASA Aerospace Safety Advisory Committee)

This recent report and the strained conditions of NASA's budget to complete its various key objectives within the Artemis Program and its various deep space research

programs aimed at going to Mars represent a very key concern. There are many recommended ways forward to develop safer astronaut programs, but the most critical step of all is for NASA to not over-commit to too many programs without the resources needed to test the technologies and systems needed to complete them safely. Streamlining and prioritizing NASA's top objectives is key. A review of NASA's strategic plans does not provide a useful way to analyze its areas of focus and priorities. Such a review of programs, priorities, scope of activities, budgets, and current research and development is recommended. One recommendation to start this process and give NASA greater focus would be to move aircraft-related research and development from NASA to the U.S. Department of Transportation. This would allow NASA to concentrate on space systems.

This book seeks to review a wide range of new space systems, technologies, standards, industrial methods, organizational concepts, and more. The goal is to define new and far-reaching goals for space safety and risk reduction for astronaut exploration. This will examine current research and capabilities that lead to a range of new technologies and systems that can allow astronauts and “smart” robotic assistants to more safely explore and utilize off-world environments. This will consider technical and scientific innovation, improved systems capabilities, and processes that can lead to a range of better and safer capabilities in a range of areas. These include space transport systems, space crew vehicles and habitats, better health, exercise, medication, and medical capabilities, improved food, water and oxygen supplies, protection from natural and man-made hazards and dangers, life-support systems and bio-regenerative life-support systems (BLSS), key support infrastructure systems for deep space missions, as well as advances in AI, advanced algorithms, and robotic systems to support human space explorers. All of these advances, however, could come to

naught if these technological and process innovations are not supported by improvements in political, technical, business, and economic leadership within NASA, the U.S. Government, and supporting contractors and educational and research institutions, plus international partners.

Clearly, NASA stands at a crossroads as a new Presidential administration is now in place and space exploration goals and objectives are being questioned. Further, serious questions have been noted by the NASA Aerospace Safety Advisory Panel in their Feb 2025 Report. All of these unknowns reflect concerns shared with the authors of this book. These shorter-term concerns must be addressed, and key mission questions and safety issues resolved, before a truly successful longer-term research agenda can be formulated and undertaken. This longer-term program must be more than just the ability to travel safely into deep space; it must also address how to live and work successfully there in the future.

There is a need for safety and risk reduction for all types of space program, but it is particularly true when the longer-term goal is to support human travel and living in deep space in a sustainable and viable way, not just for a few days but for the much longer term.

The longer-term research agenda must not only involve technical innovations and scientific discovery, but also improvements in space agency modes of organization and operation. It should also allow enhanced use of corporate innovation and agilities plus greater use of artificial intelligence and ‘smart’ robots to assist astronauts in their work. This will also likely include the use of new tools such as quantum computing, AI, advanced algorithms, advanced modeling, and other technologies to improve NASA’s abilities and decision-making areas, such as systems design, mission definition, and optimization processes. This will improve

planning processes and decision-making to increase safety, reduce risk, and ultimately achieve better space exploration programs. Although enhanced safety is the prime goal, the dividend is that it will almost always produce cost savings and perhaps better results on a faster schedule as well.

The first step in this analysis is to probe how to develop new space systems to support astronaut missions of the future by undertaking a critical review of historical evidence of past NASA missions. The history of the Apollo Program, the development of the Space Transportation System, and the Constellation/Artemis Program will be reviewed in the context of safety-related shortcomings. Problems associated with the initial planning process and mission definitions are the most common source of difficulties, as the ensuing historical review will reveal.

In many instances, the mission statements and technical design elements for these major crew-based exploratory space programs have been undertaken and decided before key safety review inputs were considered.

This book is primarily about developing new and safer space technology and systems for the future, but it also addresses possible innovations in key processes, standards, and organizational structures in the effective functioning of space agencies and aerospace companies. This involves not only the process by which new mission requirements are defined and specified, but also new approaches in a wide number of areas. These will likely include systems modeling and simulations, improved systems engineering, better risk assessments, safety standards, and risk minimization processes. It might even lead to improved safety-related institutions being conceived and created. This includes consideration of the creation of an international Space Safety Institute.

The next phase of this study will be a transition to key space-related technologies, advanced systems, and longer-term innovations.

The first area addressed relates to the development of advanced systems to sustain astronauts' life support systems, reduce risks, and address major threats to the health and well-being of astronauts in the outer-space environment. This involves new and improved ways to supply both food and water to humans in space through such means as recycling and purification, generation of water, oxygen, food, and agricultural products in space. It also includes more efficient resupply systems, use of suspended animation in long-duration missions, advances in radiation protection and radiation standards, and, of course, improved and more resilient life support systems. As noted earlier, the ultimate goal may be bio-regenerative life support systems (BLSS) that could support astronaut safety and well-being in a diversity of deep space locations.

This initial review of life-improvement support systems will address near-to-medium-term objectives. More advanced concepts will be examined in later chapters. These truly advanced concepts will include such scenarios as the ability to create electromagnetic shielding which might allow the terraforming of Mars into a livable and sustained environment for astronauts and a new Martian ecosystem.

Another area that is explored involves various types of advanced support systems to aid astronaut exploration and survival in space. These areas that are reviewed here include: (a) Improved navigation, telecommunications, tele-location, and search and rescue operations; (b) Advanced capabilities using robotic systems; (c) AI enhanced systems; (d) In-situ energy and power transmission systems; and (e) Universal

safety systems standardization for all spacesuits and equipment linkage and connection systems.

A quite important part of this space safety of the future review will be the path forward for new and improved launch vehicles and other means to lift humans into space. This will address improvements in reusable launch systems involving ‘sustainable’ chemical propulsion, nuclear energy, and other advanced concepts such as mass-driver systems, tethered systems, so-called space elevators, or funicular systems. The discussion will include consideration of design optimization not only to meet mission objectives, but also of risk reduction, safety, and sustainability of operations. This will consider a ferrying system where space travelers will be transported to orbit and then relayed onto an orbital space terminal to travel further on to deep space locations.

This discussion of future launch systems will be followed by a discussion on advanced spacecraft for astronauts to travel to deep space and to return to Earth or to orbital terminals, to then be returned to Earth. This discussion will consider transport propulsion, sustainability of fuels, and safety optimization.

The next discussion and analysis will be of recommended advanced R&D for space habitats in terms of their design, and optimization strategies. This discussion will include consideration of inflatable systems, radiation protection, advanced life support systems, and the differences in design that might apply to Earth orbiting systems, lunar-based and Mars-based habitats, and other deep space locations.

Another space safety discussion will center around the ongoing problem of space debris and its threat to launch systems and spacecraft, orbital satellites, and space stations. This analysis continues on to consider the danger of space debris in the

orbits of the Moon and Mars, plus consideration of other cosmic dangers including solar storms and longer term solar and radiation dangers, and advanced space systems related to potentially hazardous asteroids and comets.

Finally, an analysis is undertaken of advanced space stations and life support systems, advanced spacesuit design, advanced AI-enabled robotic systems, and advanced tele-presence capabilities.

The final chapters will consider new technologies and systems that might support longer-term space capabilities required for “off-Earth systems.” Key areas that will be addressed are the challenges and technologies needed to support remote mining, material reprocessing, and space-based manufacturing in various conditions and environments.

In order to achieve longer-term and more demanding goals, the very last two chapters before the final conclusions and findings focus heavily on the need for sharpened goal definitions and strategic planning practices that try to stretch the reach and imagination of NASA's aims for the longer-term future. Chapter 13 explores far-ranging goals that might include truly sustainable space habitats that could provide astronauts and deep space explorers with such features as artificial gravity, bio-regenerative life support systems (BLSS), sustainable power, and significant levels of self-sufficiency.

It is also proposed that NASA consider developing new space engineering concepts that might lead to a life-sustaining atmosphere on Mars or other off-Earth locations. It also addresses in some depth, new artificial magnetic shielding systems. Such new planetary altering systems could help protect earth from catastrophic solar storms, known as coronal mass ejections (CMEs) that could cripple cities wipe out electrical power grids and pipeline controls, communications.

Networking, navigational systems, plus the Internet. It also explores the need for innovation and supporting international legal, regulatory, and even moral and ethical agreements that might be required to achieve many of these deep space developmental goals.

This leads to discussion in Chapter 14 about achieving greater organizational efficiency and possible restructuring of the NASA organization to become less bureaucratic. This might involve concerted efforts to become less decentralized and more unified and focused on specific strategic planning goals. It is recommended that this might be accomplished through more specific and targeted objectives with specific aims and due dates. This was recommended as A means to become more focused on breakthrough achievements and to achieve some truly amazing new capabilities, rather than simply executive programs that Congress provides yearly funding for to sustain NASA's operations and ongoing programs.

There are many ambitious goals in space exploration and deep space related transportation, scientific exploration, increased use of 'smart' robots, AI capabilities and sophisticated simulation and modeling capabilities that can allow NASA to be more efficient, produce more innovative, effective, and safety-enhancing designs for longer-term space initiatives.

Many of these new designs and capabilities, such as bio-regenerative life support systems, could not only allow the creation of viable space colonies in deep space but also could be reapplied right here on Earth. These breakthrough inventions might prove key to coping with such challenges as climate change, heating of the ocean's waters, and coping with cosmic threats to our largest cities' most vulnerable infrastructure—for which we are currently underprepared.

NASA has already funded the creation of a \$57 million 3-D printer for generating building materials from regolith dust on the Moon as well other systems to be used to support construction produced from materials mined from lunar regolith.² (See **Fig. 1.2**)

In the future, 3-D printers might be used for even more demanding tasks, such as producing food to eat or medications on demand from specialized DNA-specific and patented medications.

This book will also address remote agriculture and genetic organic optimization processes that might be used in low gravitational and gaseous environments, remote medical care, as well as specialized transportation systems that could be used in different types of deep space locations.

Thus, the final area of investigation will be new ways forward in the long term with advanced technologies and concepts. This will seek better ways to consider “outside the box” ideas that will draw on a wide range of ideas through such means as “Concept Competitions” and challenges to create new technologies and processes previously unknown. This may mean that NASA and other space agencies around the world, at least from the Western World, might rely much more heavily on the input of commercial organizations and competitive challenges to create the concepts and technologies of our longer-term space systems. This may also lead to new

²Kristin Houser “NASA invests \$57 million in a 3D laser printer to build moon bases.” Freethink, Dec 3, 2022 <https://www.freethink.com/space/building-on-the-moon#:~:text=NASA%20has%20awarded%20high-tech%20construction%20company%20ICON%20a,designed%20for%20building%20on%20the%20moon%20and%20Mars.>

institutions that evolve in the coming years to cope with the challenges related to truly advanced technologies, regulatory systems, and off-world governance.

Clearly the needs of the longer-term future are difficult to envision and anticipate. These difficulties may be encountered in such areas as new viruses that exist in or originate from outer space conditions. There are health issues that come from living in a low-gravity or other conditions such as high levels of radiation. Such safety concerns and difficulties could develop from risk factors or dangers that are yet to be clearly understood.

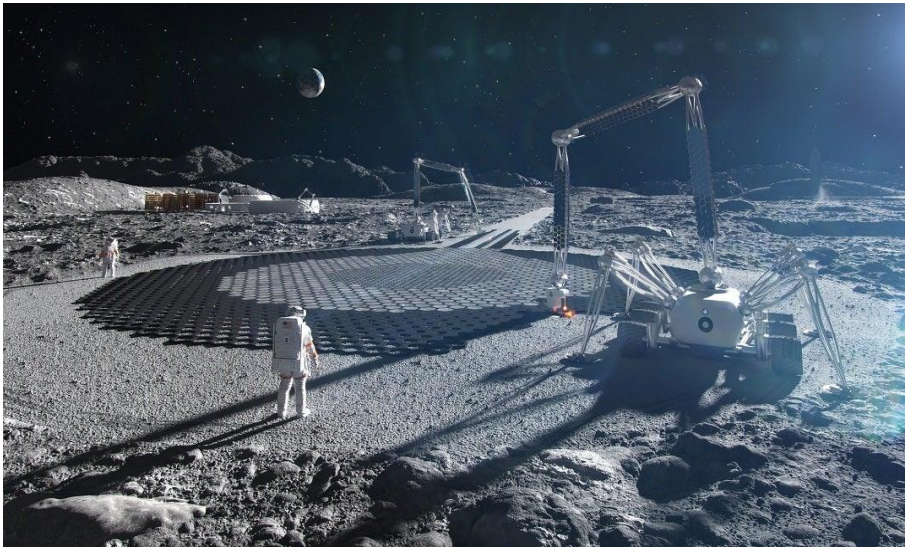


Fig. 1.2: Image of future possible habitat construction on the Moon
(Image courtesy of NASA)

The main thing to understand is that the future means change. It means ever faster rates of innovation, the potential of ever emerging new safety challenges, and much more. There is a need to be able to adapt to an environment dominated by change. This may require new technology and systems, new

regulatory mechanisms and standards, new ways for humans to interact with AI-enabled smart robots—or possibly cybernetic organisms. Certainly, it will require new ways to contend with previously unknown risk factors and the creation of safer systems for astronauts and indeed all humans who travel into space. Protection from aberrant AI systems might well be one of these new dangers.

One way to understand evolving innovation dilemmas and safety trade-offs can be seen in NASA's insistence on flying fully safety-qualified digital processing chips for the ISS despite the very rapid rate of advance of this technology. This created serious onboard processing limitations. In contrast, "NewSpace" companies have moved, instead, to use the latest state-of-the-art, yet still off-the-shelf digital processing chips. These are much less in cost than fully space-qualified equipment. They thus use the lower-cost but higher-performance digital processors and simply back them up with high levels of redundancy. A key challenge of the future is how to anticipate and adapt to rapid orders of change. It is of the essence to be proactive in adapting to rapid transition. We are currently entering a time of transition from conventional digital processing using binary bits to the world of the future, which will soon be forced to seek a rapid transition to the use of quantum computers and work with qu-bits rather than binary bits in their processing software. NASA must plan for the future, and that means planning for rapid change and abandoning the idea of developing space systems with a 30-year usable shelf life.

This book's main focus is to review the most important new technologies, systems architecture, and concepts to support the increased safety of future astronaut missions. This thus includes all associated transportation systems, life support systems, bio-regenerative support systems, health, exercise, medical, and medication requirements, logistical support

systems, and space habitat systems. The list continues with natural and man-made hazards to life, space-based farming and agricultural systems, vital infrastructure in terms of energy, telecommunications, and digital processing systems, navigation, lighting, as well as other advanced technology areas such as robotics, AI, and quantum computers.

The objective is to provide systematic recommendations as to prime areas for R&D and testing of the newest technologies, systems, and concepts to support what might be called “Living in Space” capabilities for the longer-term future. It thus highlights some of the most promising technologies and systems to pursue and notes the need for NASA and space agencies to adapt to a new environment. This is a future where commercial space entities, foundation and university-based research, challenge competitions, and other competitive input processes can help define the best and newest course forward in the fields of space applications, space sciences, and space exploration. This suggests that it is vitally important for NASA not to be insular and close-minded. It must seek to draw on many sources of information from outside its own research competencies. This means working interactively with space agencies, corporate research centers, and such private interactive initiatives as the “Living in Space Initiative.” This is an example of a joint effort where a wide range of space-related organizations, including over a dozen entities, are interested in future technology and systems to support life beyond Earth.

Members of this “Living in Space Initiative” group include: The Alliance for Collaboration in the Exploration of Outer Space (ACES Worldwide) that was founded by the author of this book, Space Renaissance International (SRI), the National Space Society (NSS), the Moon Village Association (MVA), the Space Development Foundation, Inc., Space and Satellite Professionals International, Innova Space, LIFE-To & Beyond Space, MMARS, The Alternative Planetary Futures Institute

(APFI), For All Moonkind, Innova Space, and others that are considering joining this effort. The website for the “Living in Space Initiative” is <http://www.living-in-space.org>, and additional information about astronaut systems for the future and their safety can also be found on this site.³

Many of the most promising new technologies and systems in the field of space may be spawned from efforts to support off-Earth human exploration and eventual settlement. It is, of course, hoped that many of these new breakthroughs and findings can also be reapplied to meet the needs, health, and sustainability goals of people here on planet Earth. The tagline of the “Living in Space Initiative” is “Toward a Robust, Safe and Sustainable Future.”

Of course, such research and development applies to more than just ensuring the increased safety of astronauts traveling out into the vastness of space and efforts to create habitats on the Moon, Mars, and beyond. It is also quite relevant to the future lives of all people on planet Earth as well. We need better ideas and better technology for the future of space, the preservation of life-sustaining vegetation, and the interactive bio-systems and natural environmental processes at work right here on our planet. What NASA learns about designing life-sustaining bio-systems for space habitats can be directly applied to environmental controls and sustenance of life on our home planet. Much of what will be learned can be used in creative ways to help in the achievement of a number of the objectives within the United Nations’ 17 Sustainable Development Goals for 2030—and particularly those goals that apply to ecology, the preservation of the atmosphere, our forests, farmlands, wetlands, and cities, and our oceans and water ways. Such research can also help us to cope with pollution and waste recycling, and constructive ways to use AI

³ *Living in Space Initiative*” <http://www.living-in-space.org> (Last accessed on April 8, 2025)

and ‘smart robots’ to help us create new, more livable and sustainable cities and transport systems. Research for “out there “ can help with a better and safer life right here.

This book thus sets forth a range of new ideas, concepts, and technologies to support future outer space activities for humans in the 21st century, as well as to support sustainability goals here on Earth. There is great potential to be found in new space technologies and systems, new space regulatory rules and policies, as well as great new potential for NASA to be achieved not only through new technical and scientific breakthroughs and longer-term research initiatives, but also through new institutional initiatives and organizational reforms. This can lead to not only key innovations in space safety but also many new pathways forward involving cooperative relationships between humans and advanced capabilities provided by AI-enabled robotic systems, newly enhanced computing systems realized by quantum computing, and advances in life sciences and sustainability-related research right here on Earth.

The final Chapter 15 of this book addresses conclusions and major findings that are presented throughout this book. It seeks to tie together all of the various analyses and recommendations. It presents and emphasizes the major issues and challenges that NASA faces for the future. It suggests important ways to undertake new research and development goals. It proposes smarter ways to undertake space exploration with more assistance and creativity drawn from the aerospace industry, more use of AI, ‘smart robots, computer-assisted modeling and simulations in designing new systems and new missions. It urges NASA to be less bureaucratic, more entrepreneurial, and more targeted in its strategic management, organizational structure, and management. For NASA, failure must continue to be an option that they can never accept where it is with the Apollo 13

mission, a nuclear fusion powered electric ion propulsion system to go Mars, a truly sustainable and almost close deep space habitat for astronauts and space explorers, or a new types of systems to terraform Mars into a living planet, or developing a protective magnetic shield to protect Earth from solar storms or an new directed energy system to protect Earth from killer asteroids or comet strikes.

Chapter 2

Needed Reform of NASA Systems Planning, Financial Management and Procurement

Introduction

This chapter reviews the processes that NASA uses to define and implement space exploration programs. It addresses both the efficiency of the process and how the issues of safety and reliability are handled in the design of new space transportation systems for astronauts. These basic astronaut safety concerns are unfortunately not addressed as a prime mission requirement, but rather a concern to be addressed after space systems engineers have devised plans for a basic new space systems architecture for the mission.

This analysis and review highlights areas of inefficiencies and difficulties that date back to the earliest days of NASA's efforts to undertake the development of launch systems, capsules, and crew systems to support astronauts. Basic concerns related to mission requirement definition and system engineering are highlighted. In short, NASA should integrate space safety systems engineering into new programs from the outset. Mission requirements that are expressed in terms of quantitative specifications should be able to interact with safety improvements and mission risk reductions. Lessons

learned from past NASA missions, as well as innovations introduced by “NewSpace” companies, are particularly relevant here.

This chapter also addresses problems of political interference into these procurement processes. The innovations that come from NASA’s “Next Steps” procurement can often allow NASA to sidestep or avoid such complications by undertaking procurement in a more accelerated manner. The key innovation of using performance specifications rather than the more expensive, time-consuming, and complicated technical specification approach can also lead to safety and risk reduction, but only if safety and risk reduction requirements are integrated into the performance specifications and made an independent and important element of contractor bid analysis. This means making safety analysis and risk assessment one of three major areas for assessment and bid assessment by the selected NASA review team that assesses the quality of contractor proposals.

Finally, there are a host of new opportunities and capabilities that can come from technical and scientific advances. These are related to AI, ‘smart robotics’, and safety engineering and computer simulations and modelling. These advances could add to the safety and reliability of future astronaut exploration programs designed for deep space operations.

This chapter also examines NASA’s historical patterns of the astronaut program, its definition, and the implementation processes that go back to the Apollo Program. It thus addresses key safety issues and concerns associated with the Space Shuttle Program, the International Space Station, the current Artemis Program and Gateway, and future efforts associated with crewed exploration programs intended to go to Mars and other deep space locations. The purpose of this review is to address space safety systems engineering issues of concern,

possible improvements, and how new capabilities and approaches could produce improved results both in a qualitative and quantitative manner.

Historical Review of NASA Systems Planning Processes

NASA was hastily formed on July 29, 1958, when the U.S. Congress passed the 1958 National Aeronautics and Space Act⁴.

This urgent action by the U.S. Congress and the Eisenhower Administration was largely in response to the October 4, 1957, Sputnik launch by the U.S.S.R. This unexpected satellite launch caught the world by surprise and prompted the realization that the Soviet Union was ahead in space technology—for peaceful and, yes, military purposes as well. One of the key elements in the U.S. Presidential campaign of 1960 became the so-called “missile gap.” The launch of Yuri Gagarin on Vostok 1 into space on April 12, 1961, just after President Kennedy took office, underscored just how much the Soviet Union was ahead in space rocketry.⁵

President Kennedy, amid much consternation about this remarkable feat, announced on May 25, 1961, the challenge to NASA to launch a crew to the Moon and safely return them to Earth by the end of the decade.⁶

⁴ “NASA History”, *History.com*, <https://www.history.com/this-day-in-history/nasa-create>, (last accessed January 25, 2025)

⁵ “Yuri Gagarin, Soviet Cosmonaut,” <https://www.britannica.com/biography/Yuri-Gagarin>, last accessed January 25, 2025

⁶ “The Decision to Go to the Moon” <https://www.nasa.gov/history/the-decision-to-go-to-the-moon/> (last accessed Jan. 25, 2025)

Other options to show U.S. technological capability, such as a massive desalination plant, were considered by the Kennedy administration but discarded. There was an urgency to achieve a remarkably swift turnaround in U.S. space capabilities. There was a perceived need to show the world that America would be able to master space technology swiftly and indeed overtake the space systems of its “Cold War” adversary behind the Iron Curtain. This was to be accomplished in the civil space sector domain, but the military implications and concerns were an important subtext understood by the U.S. electorate as well as the world community.

The newly formed NASA was given a mandate to launch a crew safely as soon as possible. They were given a number of new centers, a rapidly expanded workforce, and a massive budget to accomplish this ambitious goal. During the period from the early 1960s to 1973, NASA spent \$28 billion on the Mercury, Gemini, and Apollo Program. When this figure is adjusted for inflation, it represented about \$350 billion in current year dollars.⁷

During the peak year of the Apollo Program, NASA expenditures represented 5% of the U.S. government budget.⁸

At the end of this lunar exploration program, the Nixon Administration sought to control the Apollo Program costs and almost ended the program with Apollo 15. It then ultimately ended the program with Apollo 17, even though several more

⁷Planetary Society, “How Much Did the Apollo Program Cost?” <https://www.planetary.org/space-policy/cost-of-apollo>, (Last Accessed January 25, 2025).

⁸ Richard Hollingham, “Apollo in 50 Numbers”, <https://www.bbc.com/future/article/20190712-apollo-in-50-numbers-the-cost>, July 12, 2019)

Saturn V launches to the Moon were available for possible launch.⁹

This effort evolved at enormous speed and involved the first single astronaut Mercury flights with John Glenn, which were sub-orbital. Then came Mercury astronaut orbital flights, followed by the Gemini Program that orbited two astronauts together. This then transitioned to the Apollo program, which involved a three-person capsule. The NASA systems engineers were urged to define programmatic specifications at great speed, and there was no time to carefully decide what to do with specifications, except to err on the side of caution. This led to what might be called “overkill” specifications to enhance reliability. If something had been specified in the past in terms of strength, precision, tolerance, or other reliability parameters at a 99% standard, it became 99.9% for the Apollo Program, and if it had previously been a 99.9% allowance, then it became a 99.99% specification.

One specific example of the “overkill specification” weakness, as exemplified in the Apollo Program, can be found in the experience associated with the design of the flow monitor and gauge for the water pump for the Lunar Excursion Module (LEM). The function of the flow monitor on the LEM was to measure the volume of water going through the water purification system. This was automatically increased in the design specification process by a factor of ten, as was the case for thousands of other components. In this case, a gasoline pump flow monitor had been specified. Since gasoline has a different viscosity than purified water, this pump never met the demanding specification despite weeks of time spent

⁹ Andrew Liptak, “The Real Story of Apollo 17, <https://gizmodo.com/the-real-story-of-apollo-17-and-why-we-never-went-ba-1670503448> Dec. 12, 2015)

seeking to qualify it. The author knows this since he was the quality control engineer who had been hastily hired right out of college by North American Aviation to fill this position in Tulsa, Oklahoma. The very exacting and rapid development of performance specifications was upgraded by a factor of ten to pursue safety and reliability. This process, plus the rush to hire new NASA and contractor employees, plus the many hierarchical tiers of NASA and corporate employees at many different sites, all served to make communications inefficient. This was likewise true about the judgment as to which of the “overkill safety specifications” were of greatest importance. This automatic increase in component specification made it difficult to differentiate which of the very high safety standards were most critical among the tens of thousands of parts that went into the Saturn 1 and Saturn V launchers, the Command Module, the Lunar Excursion Module (later Lunar Module), and other component parts.

The use of an automatic ten-fold increase in the reliability and performance standards was arbitrarily applied, and, in many ways, this was a “non-logical” way to produce increased reliability and safety. Nevertheless, this approach produced results because there was an ever-increasing flow of money to cover the cost of these inefficiencies that flowed from the arbitrary increase in reliability standards. This same sort of process was also often used within the U.S. Department of Defense in developing new armament systems, aircraft, and other new capabilities. Aerospace contractors, who had come to depend on cost reimbursement plus incentive-type contractors working for DOD, had since World War II developed a reliance on this type of contract that was based on cost-plus-fee payments.

In the case of the water flow monitor, a two-fold increase in standards rather than a ten-fold increase might have been sufficient. Yet, in terms of a fuel pump for one of the rocket

engines for the Saturn vehicle, a ten-fold increase might have been insufficient. And this was not the only reliability-enhancing process that came with the Apollo development program. The standards for significantly increased test firings, design engineering inspections, and other quality assurance processes were also implemented. The Qualitative Reliability Program for the Apollo Program was very demanding indeed. When one compares the Apollo program testing with the Artemis Program, the significant lack of testing with the current lunar missions is alarmingly sparse. This has been recently noted with great concern by the NASA Aerospace Safety Advisory Committee, as reported later in this book.¹⁰

But what is clear from reviewing the history, is the fact that NASA, from the very start, accepted a practice of systems engineers being given a set of mission requirements to design a new launcher, astronaut capsule, or new capability and then giving it to system design engineers who created the specifications of a new system. Then, after the initial design had been developed, the personnel associated with quality control, safety, and mission assurance were given the task of making it safer and more reliable once the basic design had been formulated by the systems design team. Such a concept for new space systems design is ultimately flawed. Safety optimization should be ‘designed in’ from the outset. It is not an ‘add-on feature’ that is ‘designed in’ later. Such measures as raising the specification margins by a factor of ten, or through enhanced quality assurance measures, or a higher number of qualification tests, are certainly possible but expensive and a sub-optimal strategy. A thorough discussion of this concern, and the need to have safety design engineers involved in the

¹⁰Yasushi Sato, “Reliability in the Apollo Program” NASA (https://extapps.ksc.nasa.gov/Reliability/Documents/122001_Reliability_in_the_Apollo_Program.pdf)

initial systems design and to be able to question the “mission specifications”, are key aspects of systems design that are vital to astronaut safety, system resiliency, and higher reliability.

This concern is that NASA's practice has traditionally been to create a team of space system design engineers to develop technical space system specifications after the White House and NASA management have agreed to launch a new major space program. Sometimes, this is coordinated with Congress and congressional hearings, and sometimes, it is announced. Then, designs are developed and presented to Congress for review and appropriations. This is always agreed upon with NASA officials, the White House, and associated budget officials before the complete design process is finished and signed off by the president or his designated senior advisors. The problem with space safety engineering that was common to the design and approval of big space programs such as Apollo, the Space Shuttle, the ISS, the Ares and Orion vehicles that transitioned into the Space Launch System and Orion capsule for the Artemis Program all were designed by space system design teams without space safety reviews and initial designs were approved to for these initiatives. Subsequently, extensive safety design reviews and possible modifications and improvements were considered, but the mission design and basic architecture for the programs were then largely fixed in place.¹¹

In the case of the Apollo Program, as well as the Mercury and Gemini Programs, safety engineers could have used risk assessment methodologies to increase safety of the design for the Saturn vehicles, the Lunar Module, and the Command Module and to enhance the testing and design processes.

¹¹ Joseph N. Pelton and Peter Marshall, *Safety First: A Review of NASA Spacecraft for Astronaut Missions*, 2nd edition, (2024) Washington, D.C. PM Associates. Chapter 2

Political interference in the design of the Space Shuttle to add solid fuel booster rockets to the design might have proven more difficult to implement if this design process had been used. The design of the power systems for the Lunar Modules and Command Modules, and particularly the design of the fuel cells and their supporting oxygen and hydrogen fuel tanks, might well have been re-envisioned to be much safer in their conception. Certainly, the overall design and conceptualization of the International Space Station could have been simplified in many ways to be safer, less massive in scope, and easier to design, build, and maintain.

The most powerful tool of a space safety design engineer would be the leveraged power to ask the ‘why’ and ‘why not’ questions in the initial design of a new space system. In the case of the design of any new system, Probabilistic Risk Assessment techniques should be applied to the initial mission requirements before a technical design is created, even in a completely conceptual way. A classic example of this would have been a safety design review of the initial mission statement that called for the Orion Capsule to be designed for eight astronauts, when a four-astronaut design would have proven to have been a superior specification. The smaller capacity capsule would have been much less costly, required a much less demanding heat shield design, been easier and safer to operate, and required a much less demanding emergency escape system. The idea that this system would be able to support future missions to Mars was an illusion and indeed was a false premise from the outset. In many ways, it was used as a ploy to win Congressional approval of such a large investment. The accelerating rate of technological innovation rules out thinking that a viable and safe capsule design for a Mars exploration program could have been initiated in a viable way some 20 years ago. Indeed, there are serious questions about whether the Orion spacecraft capsule and its thermal

protection system are truly viable and safe for the Artemis Program.

Today, the problematic heat shield for the Artemis Program, as found on the Orion capsule, represents a key safety issue for the Artemis 3 Moon landing. The difficulties with the giant heat shield and its thermal coating materials represent one of the key pacing items for the Artemis lunar landing. This would likely have been a non-issue if a four-passenger capsule design had been accepted as a smarter, wiser, more achievable, safer, and more reliable mission requirement when it was first accepted as a mission requirement some two decades ago.¹²

Optimization of Design for the Lunar Gateway Space Station versus the ISS

NASA has learned a great deal from the operation, safety enhancements, and improvements in the International Space Station over its lifetime since it first began operation with the deployment of the first module in 1998. It has been able to develop and demonstrate the Sabatier Reactor to capture waste carbon dioxide from astronauts' breathing to produce oxygen and exhaust methane rather than carbon dioxide. It has certainly gained significant and valuable experience with the Environmental Control and Life Support System for the ISS, which will largely be reprised in the Lunar Gateway Space Station.¹³

¹² Joseph Pelton and Peter Marshall, *Safety on the Moon: NASA Artemis Lunar Exploration Program*, (2003) PM Associates, Washington, D.C., Chapter 7.

¹³D. Barta, C. Stanley, K. Lange, K. Lange. "Improving the Recovery of Oxygen from Carbon Dioxide", FO.1.0007-21
<https://ntrs.nasa.gov/api/citations/20205011724/downloads/Barta%20C>

It has also improved electrolysis systems to produce hydrogen and oxygen through the breakdown of water. It has also developed better monitors and processes to detect leaks. As was noted above, the most important development was the proven reliability of a fully integrated Environmental Control and Life Support System (ECLSS), which has achieved a high degree of reliability and efficiency. Its waste management system continues to improve, but there are new challenges in designing processes to develop much more efficient waste-recycling systems for going to Mars.¹⁴

Dozens of innovations and improvements that range from smart on-board robotic assistants to on-board toilets and improved docking systems and standards have also evolved over time. These are all key improvements that have increased astronaut safety and survivability, both for on the Gateway Space Station and lunar surface habitats.

But there is another perspective that suggests there were significant oversights and miscalculations with the design, construction and operation of the ISS, that should be noted and avoided in future plans to create deep space astronaut quarters for the future. These can be summarized in the following concepts.

OSPAR%20Fo.1-0007-21%20Full%20Presenation%20V10.pdf.) (Last accessed Jan 25, 2025)

¹⁴ *Environmental Control and Life Support System (ECLSS)*
https://www.nasa.gov/wp-content/uploads/2020/10/g-281237_eclss_o.pdf)

Simplicity, the Importance of Ockham's Razor, and Problems of Developing Overly Complex and Multi-Use Systems

The original NASA concepts were for a truly giant system that would form an extensive square structure at a much lower altitude. The decision to partner with the Soviet Union and other international partners resulted in a different design that would be at an elevated latitude to accommodate the partners and a different structural design. Although the design was less massive than the original NASA design, this huge, planned space station envisioned the largest solar power array ever deployed in space. Due to problems with the recovery from the Challenger and the Columbia Space Shuttle accidents, on the order of five years of delays were incurred with the ISS construction.

In the planning by NASA and its ISS partners, there was a false confidence in the Space Shuttle as being a reliable “space truck” that could provide rapid, reliable, and cost-effective transport to orbit that could allow the rapid construction of the ISS and support its cost-effective operation. The complexity of the Space Shuttle’s ceramic heat shield and its thousands of ceramic pieces required an army of technicians to retrofit was the fatal flaw in the design that prevented it from becoming truly successful as a reliable and cost-effective space truck. Ockham’s Razor, named after the English mathematician, simply said: “If there are two solutions, pick the simplest one.” NASA was conceived as a research organization, and it has typically seen its role as carrying out R&D and creating new science and technology. It is not well-staffed, organized, or geared to be a development, production, and operational organization.

The Space Station and the Space Shuttle were both overly complex, and their conception could have benefited from a smaller scale and simpler design. A space scientist and frequent critic of NASA has stated that the Space Shuttle was oversized for astronaut transportation. He has likened the Space Shuttle's design to perhaps creating an aircraft carrier for waterskiing. (See **Fig. 2.1**)

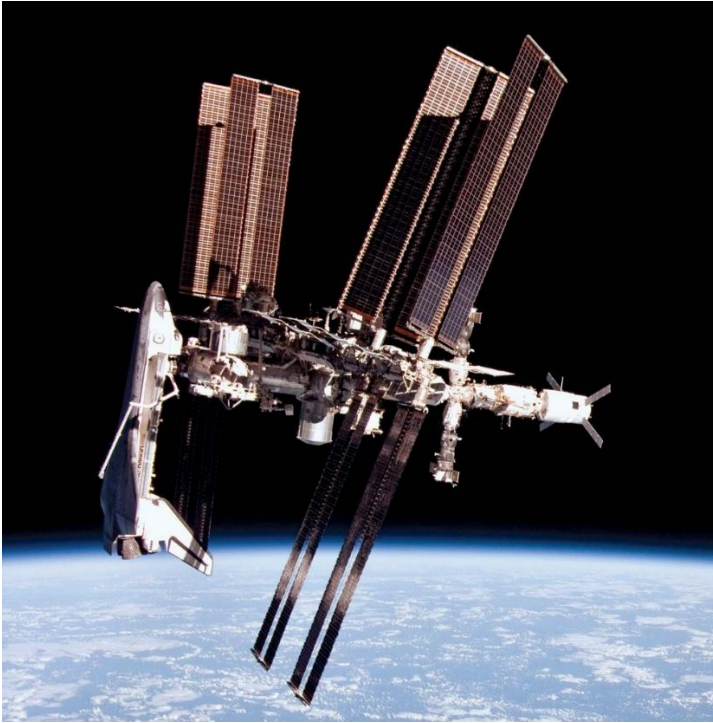


Fig. 2.1: The Overly Large International Space Station—Can NASA Learn from Past Mistakes in Terms of Size and Complexity?
(Courtesy of NASA)

NASA has learned some lessons with regard to the design of the Gateway Lunar space station. In contrast to the ISS, the Gateway, with its various modules, is now planned to be

about seven times smaller in scale than the ISS. Yet with the international habitat module and the HALO units, it can support up to eight astronauts. A possible additional habitation for the Gateway would support the presence of yet another four astronauts, and with the Orion capsule and the Human Landing System, it could support several more. The most astronauts simultaneously aboard the seven times larger ISS was thirteen, and that was only briefly in July 2009. In short, the ISS was needlessly oversized in terms of its dimensions and the size needed to accommodate the astronauts it would ever need to accommodate.¹⁵

The ISS, as a facility for life support for astronauts and cosmonauts, could clearly have been much smaller in scale. It could have been, perhaps, five to ten times smaller. Today, with current levels of robotics, computer systems, and AI capabilities, much experimental equipment can be deployed without astronaut assistance and without giant space stations equipped for sustaining dozens of astronauts. Indeed, the Gateway can be operated remotely, and thus astronauts do not necessarily need to be aboard. This new facility is about one-seventh the size of the ISS. It is currently planned to be deployed in a special lunar orbit that provides visual coverage, so it avoids a three-satellite coverage to provide electronic and visual coverage of both the Moon's polar areas and the lunar surface that faces toward Earth. This Gateway lunar orbiting space station has been designed to operate both with astronauts providing on-board support and also in a completely automated mode in tandem with ground control monitoring and commands.

¹⁵ International Space Station Records, July 2009, <http://www.nasa.gov/international-space-station/space-station-astronaut-record-holders>) (See **Fig. 2.1**)

This allows astronauts to be aboard for only short stays and thus be exposed to radiation dangers for long periods of time, since they do not need to be onboard all the time. This also simplifies and minimizes operations, resupply missions, and logistical support. The Habitat and Logistical Outpost (HALO) and Power and Propulsion Element (PPE) units are now combined to be launched on a single SpaceX launcher to be inserted into its special lunar orbit. This means that these two Gateway elements will remain together rather than being configured as shown in the graphic below. This allows a much more cost-effective and efficient deployment by NASA than the many launches by the Space Shuttle used to support the ISS construction. (*See Fig. 2.2*)

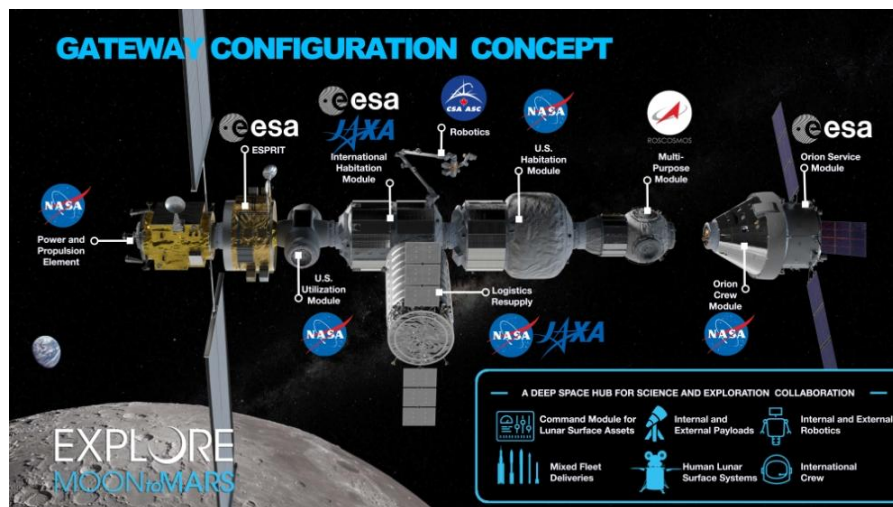


Fig. 2.2: The Planned Lunar Gateway at One-Seventh the Scale of the ISS Will Be Much More Efficient to Construct, Launch, and Operate (Graphic Courtesy of NASA)

As NASA goes forward, it can clearly find advantages in doing more with less by way of smaller and more efficient technological designs, plus more cost-effective launch

operations for construction and resupply. The lessons from both the ISS and Space Station have shown the advantages of scaling down the size of space missions and using separate facilities and launch systems for astronauts from those used as cargo systems--where and when possible. The SpaceX Heavy launch for cargo is on the order of 11 times more cost-effective than the Space Launch System (SLS) launch operations. Also, NASA engineers have learned that making astronaut capsules overly large and complex can lead to safety issues, such as in heat shield designs. Efforts to create an 8-passenger-sized capsule led design engineers to undertake intensive mass reduction efforts. Such efforts created a more compact and less massive design, but they led to problems such as ease of access to wiring and other conduits, and also increased the difficulty of failed component replacement.

The Orion capsule provides multiple examples of these types of risk-related problems. Ironically, the current plans for the Artemis missions envision launching only four astronauts at a time. And the Orion capsule, for perhaps a dozen reasons, will be technically obsolete for missions to Mars. The Orion capsule, as first conceived during the administration of President George W. Bush in the early 2000s by Lockheed Martin some two decades ago, would represent 30-year-old technology if it were to be somehow used in the future for any possible crewed Mars Mission.¹⁶

¹⁶ Jacob Williams et al, *"History of Orion Mission Design, Copernicus Software Development , and the Artemis Trajectory"* Document 23-241, 2023
<https://ntrs.nasa.gov/api/citations/20230010149/downloads/Artemis1-History%20Rev%201.pdf>

Paying Heed to the Speed of Technological Innovation and Obsolescence

NASA's main astronaut transportation systems for the Artemis Program are the Space Launch System and the Orion capsule. These systems are 15 to 20 years old in their conception. In many ways they are technologically obsolete and excessively costly when first designed. The SLS uses four RS-25 rocket engines that were originally developed for the Space Shuttle and for multiple re-use and not completely disposable one-time use.

The Orion capsule began development in 2004 as part of the Constellation Program. In contrast, the SpaceX Corporation is now producing reusable Raptor rocket engines of a simplified design on an assembly line basis that achieve remarkably reliable thrust at significantly lower cost than the outmoded and quite expensive RS-25 motors. The concept that one could continuously rely on the same types of rocket motors, launchers, and space capsules to be used over many decades for missions to the International Space Station, to the Moon, and then on to Mars was a faulty premise. It was based on costs of production but did not recognize the increasing speed of technological advances, and ultimately, such issues as the obsolescence of component parts due to improved materials and manufacturing processes, as well as improved computers and other components. Perhaps most importantly, it did not allow for such innovations as new types of smart machinery to manufacture state-of-the-art launch systems that would be fully reusable.

The Space Shuttle and its capabilities and performance in terms of reliability, cost, and turnaround launch functionality were oversold and perhaps misrepresented to the U.S. Congress in the 1980s and early 1990s. The

capabilities of the Space Launch System and the Orion Capsule were likewise oversold to the U.S. Congress based on their ultimate performance, cost, inherent reliability, and future ability to support missions to the Moon and then ultimately to Mars. Most recently, the functionality of the Gateway Lunar Space Station to support not only the Artemis Program for exploration of the Moon, but also to support missions to Mars, was oversold in terms of heightened expectations. These were representations of oversold performance, costs, and expected schedules. The biggest error, however, was a strategic planning agenda that greatly miscalculated and did not anticipate technological innovation that would produce new capabilities and efficiencies, and did not understand how NASA procurement processes had served to limit innovation in the past. Within another decade, these innovations would produce new capabilities that far exceeded the decades-old design, engineering, and manufacturing systems for launch systems, spacecraft capsules, and space station technology.

The age of “NewSpace” innovation has produced a leap in space technology innovation. This revolution occurred when the innovative processes and practices born of “Silicon Valley” met the complacent Aerospace Industry. This has shown how incremental advances could be replaced with breakthrough advances and innovation. The past decades have seen rapid advances in reusable launch systems that are not only reliable but much, much lower in cost. This is a time of not only rapid technological advances, but also significant advances in manufacturing efficiency and new ways of developing launch engines and launchers. This has included such practices as vertical integration of production, enhanced management processes, and new ways to achieve reliability and safety.

The contract with SpaceX, for a Falcon Heavy at \$178 million to replace an SLS launch that is reported by the NASA Inspector General to be \$4 billion per launch, is just one example of the extent of this technological innovation. These technological advances in space launchers and systems are occurring not only with a more than twenty-fold cost reduction but also with advances in reliability, safety, reusability, and even resources consumed. These innovations have produced reductions in costs related to labor, shipping, subcontracting, and manufacturing efficiencies.¹⁷

One of the biggest challenge NASA faces with the Artemis Program at this stage is that the huge cost associated with each Space Launch System has forced the deployment schedule for the Artemis 3 to Artemis 7 Astronaut Moon landings to be strung out over 8 years, and problems with the development of the space suits, the Human Landing Systems, and issues associated with technical performance of the Orion have led to schedule issues for the Artemis 3 astronaut landing. This slow-motion rollout of the Artemis Program is problematic in many ways, but it could also offer opportunities.

There could conceivably be a transition to an entirely different mission architecture that might deploy the SpaceX Human Landing Systems from low Earth Orbit directly to the Moon and back. Such an overall mission architecture

¹⁷ Jeff Foust “Falcon Heavy Launches NASA’s Europa Clipper Mission” Space News, October 24, 2024 <https://spacenews.com/falcon-heavy-launches-nasas-europa-clipper-mission/#:~:text=NASA%2C%20though%2C%20warned%20in%202020%20that%20%E2%80%9Cpotential%20hardware,of%20the%20estimated%20cost%20of%20a%20single%20SLS%20>)

could leverage this new technological innovation to make the Artemis lunar investigation much more productive and efficient in its scientific discovery operations, while also reducing costs. The bottom line is that the rate of technical innovation continues to accelerate, and NASA must consider how to transition away from obsolete systems such as the SLS and the Orion capsule as quickly as possible.

The Increasing Importance of Smart Robotic Capabilities in Space Exploration

The key to NASA's historical success is seldom based on efforts that provide new space-related scientific information or assist with space applications. Important missions, such as the Hubble and Webb Space Telescope, have achieved some widespread recognition, as do major planetary probes such as the Europa Clipper mission. Nevertheless, the most significant aspect of NASA's public support comes from astronauts and space exploits. It is the heroic aspect of these "space adventures" that provides a personal and human connection. The success of the Artemis Program and its competitive accomplishments vis-à-vis China and Russia are, for better or worse, the keys to NASA's future support.

Despite this public focus on Artemis and its achievements, there are also concerns about the huge expenses this \$100 billion activity entails. Thus, the use of 'smart robots' and other capabilities to leverage the success and achievement of astronauts on the Moon will also be key. Robotic systems can undertake dangerous tasks such as extracting ice from depressions at the Moon's South Pole areas. They can also work very long hours without risk and do not require food, water, rest, entertainment nor life-support systems. NASA has invested in significant robotic technology to develop systems that can do a multitude of tasks.

This includes robotic systems that can allow refueling of tasks in space such as the Dexterous Mobility Laboratory (DML). There are also various versions of the Robonaut systems - including the Robonaut 2 on the ISS.¹⁸

But the most critical robotic assistance capability long extolled by NASA management for the Artemis Program was to be the key VIPER (Volatiles Investigating Polar Exploration Rover) robot vehicle. This critical capability, however, has come up short. NASA was forced to cancel the VIPER rover due to major cost overruns.¹⁹ Even if this key capability is restored by Congressional action, it remains a black mark on its management prowess. Under the new Trump Administration, such difficulties and cost overruns are not viewed favorably.

This VIPER system was designed to carry out a number of tasks to identify possible frozen volatile ice in the southern areas of the Moon and also undertake the evaluation of the materials it extracted. The key features of this wheeled device were that it was equipped to both extract and analyze materials it discovers, such as frozen water and other volatiles.²⁰

¹⁸ NASA online release, "Mission to the International Space Station" Feb 24, 2011, <https://www.nasa.gov/robonaut2/mission-to-the-international-space-station/>

¹⁹ NASA release, "NASA ends VIPER project, continues moon exploration" July 17, 2024 <https://www.nasa.gov/news-release/nasa-ends-viper-project-continues-moon-exploration/>

²⁰ "VIPER", NASA Science <https://search.yahoo.com/search?fr=mcafee&type=E210US565Go&p=NAS+A+wheeled+robot+VIPER+for+mining+on+the+Moon> (Last accessed Jan 28, 2025)

There has been extensive testing of the mobile **Synchronous Position, Hold, Engage, Reorient, Experimental System (SPHERES)** mobile robotic systems that are now being replaced by Astrobee's mobile units on the ISS. There is also the very large Valkyrie robot system that is being tested in mining operations in Perth, Australia, at this time, and which is pictured in Chapter 8 . Exactly how and if these capabilities will be deployed for the Artemis Program is not currently clear.

NASA has now awarded contracts for so-called Moon Buggies (known in NASA-speak as Lunar Terrain Vehicles). It has also been considered a much larger lunar surface vehicle, the size of an RV. This mobile system would include a controlled and pressurized atmosphere and would be able to accommodate up to three astronauts. It would also include various degrees of automation, robotic systems, and augmented AI capabilities. Again, some of these developments have been shown to be disconnected from needed launch capabilities for soft landings on the moon. Part of the VIPER cancellation discussions, when it was phased out in July/ August 2024, were about whether there was a suitable lander capability to support this mission requirement. A once vital tool that could have aided astronaut safety in lunar surface mining on the Moon was abruptly cancelled, and NASA management competence was rather publicly called into question.

Mobile robotic systems such as VIPER, as well as human-like systems such as the Valkyrie large robot, could substitute for astronauts to undertake a number of tasks. In operations such as mining, mapping, seeing in the dark, and a range of activities involving strength and endurance robotic systems they can likely outperform astronauts. For future NASA missions to the Moon and Mars, robotic systems can replace astronauts. This can reduce risk, reduce

costs for the supply of food and water, and allow a 24-hour operation. Mobile units can extend the range of operations, and unlike humans, they can be left behind to support future missions.

The VIPER lunar vehicle was close to being tested for autonomous mobile operations and mining and sample testing in the southern polar regions of the Moon when cancelled.

This once-thought critical exploratory and mining vehicle was nearing completion and testing for launch in late 2025, but in August 2024, NASA officials cancelled its launch. This action was taken by NASA officials without warning, despite huge expenditures of some 450 billion dollars to design and build this system. Estimated cost overruns of some 200 million dollars over the initial budget. This did not include the additional costs of the launch and the landing system, which had not yet been clearly identified and successfully tested. If Congress and NASA reverse course and decide to proceed, there is still an estimated cost for final testing and integration that would add \$84 million more in costs. NASA development problems and cost overruns with Artemis have been revealed in a number of ways. These include the Space Landing System, the Orion space capsule, and, most recently, the VIPER vehicle. This shows a pattern of management miscalculation and missteps that are not easily overlooked. (See **Fig. 2.3**)²¹

²¹Hannah Means, “NASA Cancels Flight-Ready Lunar Rover” *Physics Today*, Dec 13, 2024
<https://pubs.aip.org/physicstoday/online/43851/NASA-cancels-flight-ready-lunar-roverHannah>)

The problem was not only cost overruns, but also the lack of a proven and safe lunar lander that could deliver the VIPER robotic system safely to the lunar polar region. Astrobotics, Inc., the Pittsburgh, Pennsylvania, company that has become a developer of lunar landers, had been selected by NASA to deliver the VIPER robotic vehicle, plus a very small, shoe-box-sized “Cube Rover” to the Moon via a SpaceX Falcon Heavy Rocket.

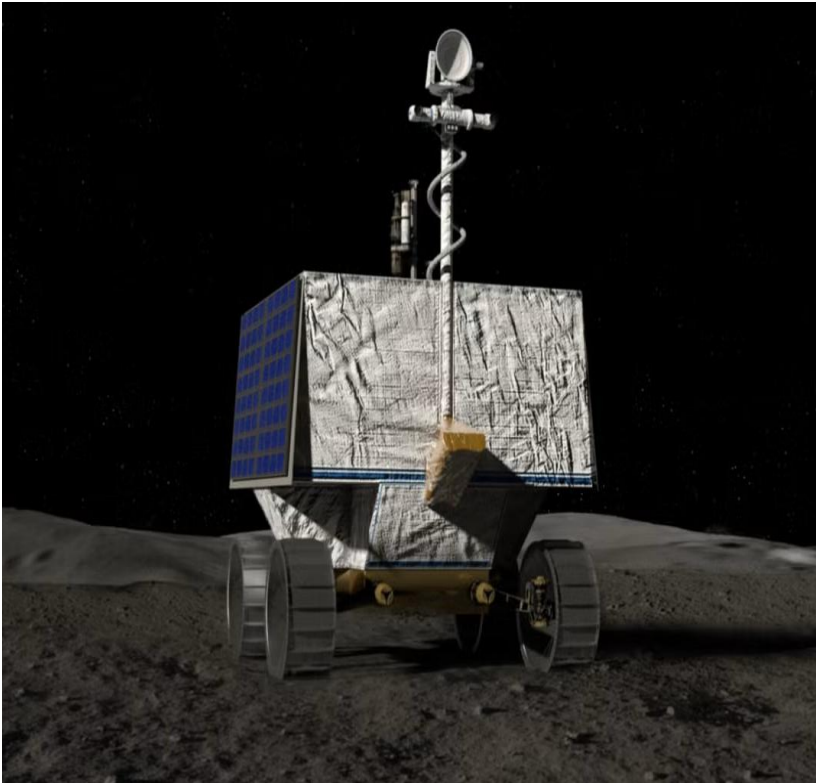


Fig. 2.3: The Canceled VIPER Robotic Vehicle Designed for Lunar Mining and Analysis
(Photo courtesy of NASA)

That was the news as of April 2024. The delivery system was to be the Astrobotics’ Griffin lunar lander. This Griffin

lander, that was designed to carry the VIPER and specially designed to carry this intermediate-sized load to the lunar surface, had not been tested as of the time of the cancellation. Also, the unsuccessful previous lunar landers that tried the difficult task of landing in the Moon's polar region remains a key part of NASA's concern. This highly specialized device, after testing, would have represented over half a billion dollars in investment, and the Falcon Heavy rocket launch and Griffin lunar landing would be well north of \$300 million. The possibility of this expensive device and the untested Griffin lunar lander crashing into the Moon with a total investment of nearly a billion dollars was clearly part of the concern that led to NASA's decision not to launch the VIPER.²²

The question is, how could the story change so dramatically in two and a half months? Was the VIPER unnecessarily built to be more massive and complex than needed? Why wasn't the lunar lander for the VIPER developed, tested, and proven on the necessary timetable? Could testing equipment for identifying the contents of ice samples have been designed to be launched separately, so that VIPER could have been smaller and more compact? Could the wheels on VIPER, for instance, have been made of inflatable rubber or plastic to reduce their mass, and so on? In short, was there an overall systems design engineering process that considered every aspect of the mission goals and found a well-planned and integrated design? Why was this robot transport, mining, and analysis system not clearly planned and designed to be launched to the Moon on well-proven and appropriately sized lander systems? This question

²²Mike Wall, "A(Mike Wall, "Astrobotic to launch mini-rover along with NASA's ice-hunting VIPER on next moon mission", *Space.com*, April 9, 2024, <https://www.space.com/astrobotic-griffin-1-moon-mission-viper-cuberover>

remains with no clear explanation of how this major series of problems and miscues came to happen.²³

The situation, at the time of this book's release, may still be in flux, and Congress might find the resources to deploy VIPER after all. Maybe the Griffin lander will prove safe and reliable in time. The instruments to identify ice volatiles extracted from the polar area may be removed from the VIPER and used effectively for their designed purpose to save some of the invested monies. This particular project, despite these outcomes, still indicates a weakness in critical design review, holistic planning, and systems engineering assessment. If the VIPER is not deployed to carry out its planned functions, will this ultimately expose astronauts to greater risk? Will it make the Artemis explorations more inefficient and indicate that the NASA planning and procurement processes were ultimately at fault, starting with the specifications part of the development? At the start of the process in 2017 and 2018, there should have been a competitive design process involving a number of "new space" companies. They should have been asked to explore design alternatives, understand transport options and alternatives to advance safety and contain costs, and explore a rich set of alternatives for the optimum design.

AI Capabilities, Intensive Computer Modeling, and Probabilistic Risk Assessment in Space Systems Design

There are clearly areas of future technological development that can benefit NASA exploration missions in a number of ways. Three of the more promising areas for future

²³ "Astrobotic to launch mini-rover along with NASA's ice-hunting VIPER on next moon mission", *Space.com*, April 9, 2024, <https://www.space.com/astrobotic-griffin-1-moon-mission-viper-cuberover>

development are enhanced use of AI capabilities in an expanding range of areas, enhanced computer modeling in mission and systems design, and more intensive probability risk assessment. AI capabilities that can operate at greater speeds on quantum computers and through the use of qubits can allow the consideration of millions of design options to optimize new systems, but also to lower risk. The use of these tools and software can enable consideration of a thousand times more designs for launch vehicles, capsules, and space stations. This can allow systems design, mission requirements, and safety optimization to be an integrated process.

This expanded capability can potentially consider billions of factors before even deciding what the mission design objectives should ultimately be. Such capabilities could allow a re-thinking of how space mission planning is undertaken. This extends to launch systems design and propulsion alternatives, optimized life-support systems, possible failure modes, logistical requirements and efficiencies, medical and health related options such as suspended animation, artificial gravity, and dietary needs.

A space mission, such as “astronauts going to Mars as soon as possible,” could examine the billions of options in these areas. These could take into consideration safety, astronaut health and radiation protection, cost, timing, robotic assistance, transportation systems, logistics, habitation, exploration objectives, international participation, risk profiles, experience from other space exploration programs, and much more. This more complex and holistic systems design process, using the latest analytic and assessment tools, could produce a systems design that is superior to major space programs of the past, starting with Mercury and extending to the Artemis Program and beyond, such as missions to Mars.

The Complications and Potential Downsides of International Cooperative Programs

The earliest space exploration programs for the U.S. were essentially executed as national undertakings. The Mercury, Gemini, Apollo, and Space Shuttle Programs had elements that required international program support, such as Tracking, Telemetry, and Control (TT&C). However, these programs were essentially national in their conception, design, fabrication, launch, and operation. In the case of the International Space Station, the Artemis Program, with its Artemis Accords, and the Gateway Lunar Space Station, these programs are significantly international in both planning and execution. This can lead to cost savings with other entities providing key elements of the hardware, but it can also lead to significant delays or even serious problems and accidents. If an international partner fails to deliver a key element of a program or decides to opt out of a joint program, as Russia has done with the ISS and now the Gateway Lunar Space Station, this can lead to serious problems. Also, international partnership arrangements leave the U.S. with limited opportunity to cancel or redirect a program if it is committed to a project under what amounts to an international treaty commitment.

There is thus a key question to be addressed up front. This is whether international partnerships do indeed represent a significant opportunity for cost sharing and strengthened relationships or not? If not well defined and clearly limited in the design process, this might create open-ended commitments that expose the U.S. Government to open-ended financial, operational, and technical programs in such a way that it has limited control of a program that might well become a liability. This is not to say that international participation should not be explored and implemented, but the risks and constraints should be

carefully considered up front, and thoughtful precautions should be taken.

Leveraging Commercial Innovation and Flexibilities

It has become clear in the age of “NewSpace” innovation that new NASA Space Act Agreements allow joint development opportunities through Next Steps commercial partnership agreements. These new types of contractual arrangements can provide NASA with new opportunities to leverage its partnerships with industry to its significant advantage. These would allow the use of “performance specifications” for new programs rather than NASA’s past practice of insisting on and then developing “technical specifications.” This performance specification approach allows NASA to pick from a range of technical designs and a number of prospective contractor design proposals. It also allows for the consideration of a much broader range of technical designs, proceeds with the much more rapid process of developing performance specifications, and the awarding of fixed cost contracts that can lead to significant cost savings.

The power of this approach was demonstrated in the development of commercial transportation systems to provide needed connectivity missions for the ISS--first for cargo and then for astronauts. It has now been used to create partnerships for commercial space stations, for the development of new space suits for the astronauts, and for the development of the Human Landing System for the Artemis Program. This approach, in terms of cost, time of development, and innovative design, has seemingly proven far superior to past developmental programs such as NASA’s development of the Space Launch System and the Orion capsule, which used cost-plus fee types of

development processes and NASA's creation of detailed technical specifications.

In addition to new business models and new contracting procedures, these "lessons learned" also suggest that NASA's highly distributed network of research and testing facilities and decentralized supplier processes have serious drawbacks. Past practices often ended up with many layers of contractors and subcontractors. Such practices can lead to elevated costs, increased risks of various types, and delays in achieving successful results in their various programs. The same might also be said of its widely distributed Centers that are located at many different sites, which can lead to duplication of effort and other inefficiencies.

Conclusions

The above descriptions of new ways that NASA might proceed in the development of future astronaut transportation systems, new capsules and space stations, and, indeed, a wide range of other new systems and capabilities, suggest the need for new ways forward. The various lessons learned and other innovations that have emerged over the past few decades should be implemented with improvements that could be applied to the Artemis Program, future missions to Mars, and ultimately safer astronaut exploration programs in the decades ahead. There is a need for new and improved NASA systems planning, design engineering, financial management, and procurement processes for major space exploration programs. There are lessons to be learned from the "NewSpace" industry and the NASA "Next Steps" procurement process that uses NASA Space Act Agreements. Such agreements can include fixed price contracts, commercial partnership arrangements, and contractor investments.

These new ways forward are in large part based on learning from past programmatic program activities that produced the now much criticized and ultra-expensive Space Launch System rocket launchers and the Orion Capsule. It also involves more current issues with the VIPER rover. The ways forward, new technical and operational capabilities, and innovative practices developed by both NASA and its “NewSpace” contractors include the following:

- a. Focused, well-defined, and suitably simplified systems that do not seek to do too many things, avoid being overly complex, or serve too many purposes.
- b. Seek to avoid developing systems and technical innovations that operate over many decades of service, since rapid technological innovation will render them obsolete in many cases.
- c. Recognition that robotic innovation can increasingly supplement the capabilities of astronauts and substitute for human capability. Robots can provide safety, risk reduction, need much fewer expendables or resupply, and can work longer hours. In short, robots should be used as supplements to astronauts wherever possible.
- d. More intensive use of other technologies that can be leveraged to improve the planning and successful implementation of future space programs includes artificial intelligence, computer modeling, and probabilistic risk assessment.
- e. International participation in major space programs can provide significant opportunities, shared costs, and improved international alliances, but there are also risks. These risks and potential downsides should be assessed candidly and thoughtfully at the very

beginning, and cooperative agreements should be carefully designed with optional “off ramps” if need be.

- f. “NewSpace” industry innovation and flexible commercial partnerships should be embraced as much as possible. These new space development resources can lead to leveraged contractual agreements that should be utilized where possible along with competitions based on performance specifications. This provides opportunity to maximize the potential for innovative design and win-win agreements as opposed to NASA developed technical specifications and the negative aspects of cost-plus fee contracts.

In the remainder of this book, new technologies and research innovations of many types will be explored, but these six areas of innovation and improved processes will be returned to on a number of occasions.

Chapter 3

A Space Safety Institute: A Possible Key to Lower Space Systems Risk

Introduction

The future of human space exploration and how to make it more risk-free might be most often foreseen to hinge on a range of new technologies or improvements to software that control space operations. Indeed, that is what a great deal of this is about. Yet it is not only new space technology and software that provides operational controls for space missions that must guide the future. Space safety standards must also be improved. Likewise, there is a need for new ways forward to control the creation and disposal of space debris. Indeed, beyond the space debris problem, there is a closely related need for global agreement and coordinated processes to achieve space traffic management, just as there are global agreements today for airline safety around the world. There is also a need to improve Probabilistic Risk Assessment (PRA) systems and more intensive and AI-driven computer modeling and safety assessment systems, both at the planning and implementation stages. This chapter thus investigates the current conditions in these areas and how they are rapidly changing. It then also sets forth a number of areas where improved safety systems, standards and practices, and

improved capabilities, are needed and must therefore be pursued and developed.

This is not only a matter of recognizing the potential of new technologies, software, and standards that might be developed, but also recognizing the whole context of why these new capabilities are needed and are rapidly changing as well. The need for safety and health standards related to space exploration and development that NASA and other space agencies have faced in the past is now changing. The issue is not only space safety for official astronauts, but also thousands, and indeed, relatively soon, even tens of thousands, of people may venture into space. Health and safety standards for NASA astronauts represent one type of challenge. A new world where there are thousands of “private astronauts” that travel to visit commercial space stations is quite another. These are entirely new challenges, and they represent a need for totally new approaches, not only involving NASA, ESA, and other space agencies, but also other federal agencies. These include the Occupational Safety and Health Administration (OSHA), the National Transportation Safety Board, the Department of Transportation, and the Federal Aviation Administration (FAA), and perhaps others such as the Health and Human Services (HHS).

A Space Safety Institute and Its Potential Contributions to Risk Minimization

NASA has a problem that has not often been emphasized. This is that largely it is a unique organization in that it sets its own safety standards. The Nuclear Regulatory Commission oversees the nuclear power industry. The Department of Transportation and the FAA oversee the development and safety qualification of new airline jet aircraft, and so on. NASA has overseen the safety of its development of the Space Shuttle, the International Space Station, various launch systems such

as the Space Launch System, as well as commercial launch systems and capsules for astronaut transport. Presidential Commissions have been formed to review the safety of the Space Shuttle as a consequence of the Challenger and Columbia failures, but this has not resulted in the creation of an independent safety and reliability review capability to oversee NASA's development and launching of astronauts into orbit or deep space. The world of space travel, however, is changing, and safety certification of private space stations, private launchers, and capsules going to private space stations and coming back to Earth is a safety regulatory issue that deserves more serious consideration. This is not a task that NASA should be asked to take on. It is not clear if this is something that the FAA, to authorize such activity on an ongoing "experimental authorization" process, is well equipped to undertake. The FAA-ASD unit is in an awkward situation in that part of its mission is to encourage the development of new commercial space transportation and travel industry on one hand, and yet also authorize commercial launches by SpaceX and Blue Origin on an "experimental basis," which could and should continue into the future. The advent of private space stations that NASA is promoting as an "anchor client" further questions how the safety certification and oversight of these systems are to be addressed.

The International Association for the Advancement of Space Safety (IAASS) has recommended that such an independent Space Safety Institute be created. The purpose of such an institute would be to create consensus on international space safety standards. Its most important task would be to certify commercial space transport stations, commercial space suits, commercial space capsules, and commercial space stations. There could be a series of national space safety institutes or, ideally, a single, globally accepted international space safety institute. The IAASS indeed undertook the study of the possible structure of such an institute, the various functions it

might perform, and how it might be structured. The funding for a further in-depth study was never ultimately provided. (See **Fig. 3.1**)



Fig. 3.1: The IAASS Study for an International Space Safety Institute
(Graphic Courtesy of the IAASS)

A book commissioned by the SSC Trust Fund in 2023 investigated this subject and subsequently outlined the key elements of a Space Safety Institute. This book contended that such an institute could address a wide range of space safety concerns. It set forth a number of areas for the institute to undertake, such as the development of space safety standards and certification procedures, and that it should actively respond to many types of space safety concerns. It also suggested that such a Space Safety Institute could perform a number of functions, such as creating safety certification standards for private space stations, private space suits, private launch sites, private launch systems to launch citizens to orbit, and many other key activities to increase global space safety. These functions would include seeking to create common international standards in all relevant areas involving asteroid exploration, plus an active program to harmonize global safety and health standards for launchers, capsules, space stations, astronaut suits, and thousands of other space-related technical and performance standards.

The book also suggested that this international space safety institute could provide useful standards and processes to address such space hazards and dangers as asteroid strikes, solar storms, launch site facilities, space debris concerns, and debris removal/deorbit, launch operations, etc.

Such a global institute would be most effective if it were structured so it could work in tandem with the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), the U.N. Office of Outer Space Affairs (OOSA), the International Asteroid Warning Network (IAWN), and the Space Mission Planning Advisory Group (SMPAG). It would also address issues of space agency concerns, as well as space safety standards that could and would apply to private or commercial space industries.

Its mandate would be to harmonize and improve global space safety standards, practices, and safety certification processes in all of these various areas. It could help to assume a number of safety-related tasks and certification processes that are now undertaken by NASA, the FAA, and perhaps even other U.S. agencies such as the Occupational Safety and Health Administration (OSHA). This might be particularly the case if the Space Safety Institute were to be authorized to undertake the safety testing and certification of launchers, capsules, and even space stations that are carrying human passengers and crew and which are being developed, manufactured, and/or operated by private space companies.

Indeed, the regulatory and standards approval and safety certification role with regard to commercial space systems involving human crews, if safety certification were to be continued to be performed by NASA or the FAA-AST, might ultimately lead to potential major liabilities on the part of the U.S. government. This could be a particular problem in the event of accidents or fatalities on private space flights or visits to private space stations that had been certified by the U.S. Government to be safe.

Preliminary Models of a Space Safety Institute

The types of activities that might be carried out by a national space safety institute have been preliminarily demonstrated, at least to some degree, by the Aerospace Corporation's Space Safety Institute. The official status of this body is that of being a Federally Funded Research and Development Center (FFRDC). Its principal funding sponsor is the U.S. Air Force, plus some other U.S. governmental agencies working in high-tech areas. This institute was newly created in 2021, and it carries out a number of activities. These include the assessment of dangers associated with space debris in the context of both possible orbital collisions involving deorbiting

debris that might cause damage to aircraft and/or create serious accidents on the ground. It also has ongoing activities and research efforts that include: (a) Best Practices for Generating Space Environment Specifications with Modern Tools; (b) Space Traffic Management Terminology; (c) Policy Compliance for Small Satellites; and (d) In Space Rescue Capability Gap.²⁴

The proposed new, more broadly defined, Space Safety Institute's prime role would be to undertake the safety certification of rocket launchers, private space stations, or space suits to be utilized by citizen astronauts. There could also be a number of other roles that could and should grow over time as space related industries expand to ever larger areas.²⁵

The Department of Transportation and the FAA-AST Role in Space Safety Licensing and Certification

The FAA currently has the responsibility for certifying the safety of aircraft, but it no longer has responsibility for promoting the development of the airline industry. The U.S. Congress altered the FAA's charter to take away promotional duties with respect to the airline and aircraft industries. This was a consequence of the Air Florida Boeing 737-222 accident that occurred on January 13, 1982. The wings of this aircraft were improperly de-iced before takeoff, and as a result, this flight crashed into the Potomac River in Washington, D.C., and killed all 78 people who were aboard. The part of the Federal Aviation Agency that is responsible for overseeing the private or commercial space flight industry (namely the FAA-AST) is responsible for the licensing of commercial space launches, including

²⁴ *The Aerospace Corporation Space Safety Institute*, <https://aerospace.org/fact-sheet/space-safety-institute-ssi-fact-sheet> (Last accessed Jan. 31, 2025)

²⁵ *The Space Safety Institute: A New way to Safety Certification in the "New Space" Age* (2022) PM Associates, Washington, D.C.

experimental launches and overseeing their safety, but a different part of this same office is responsible for promoting this new industry's commercial success and development. In the case of NASA and the FAA, there are liability concerns about their future role in the certification of the safety of private space launch systems. There is logic in having an independent institute separate from NASA or the FAA that is able to review the safety, reliability, and resilience of private industry-designed and manufactured launch vehicles, capsules, or private space stations.

There is a growing number of space-related safety issues that are becoming increasingly apparent. These are the issues related to space debris and the need for a systematic approach to space traffic management to avoid orbital collision, as well as the safety of space launches and operations that involve governmental or defense-related operations on one hand and private space activities on the other. As private space launch systems, private capsules and private space systems become more numerous it would seem prudent to have an independent and highly qualified staff of independent experts within a Space Safety Institute. They would provide the regulatory oversight and certification of these private businesses rather than have NASA or FAA employees providing such certification and also potentially becoming subject to liability claims. If NASA serves as an anchor tenant in a private space station enterprise and provides for the "safety certification" for this facility, such actions could also lead to NASA becoming potentially liable. This would be the case if the operator of the private space station had an accident that resulted in fatalities related to its strictly private and commercial operations. NASA, or the FAA-AST, if it certifies private space stations as safe, will be taking on a role with many possible liabilities that would only expand over time.

Breadth of Duties and Responsibilities for a Space Safety Institute

Beyond these issues, standards, and safety certification concerns, there is the further issue and concern as to whether such a space safety institute would be narrowly focused on specific issues or address a broad range of space safety matters. Another key question concerning the nature of such a Space Safety Institute is whether it would be addressing space safety concerns from a U.S. perspective or in concert with a number of other space programs around the world. There is merit to having a broad range of expertise in many technologies, scientific knowledge, and the ability to coordinate space safety standards and certification processes internationally. It might be that the institute is established with a U.S.-perspective mandate, yet be defined in such a way that it might be expanded to become an international entity that would and could undertake activities for other countries and help create internationally agreed-upon safety standards. In light of current U.S. administration policies, such an initiative would likely only address U.S. space safety-related issues.

NASA has a number of international partners with whom it works frequently in terms of joint space projects. This is especially so with regard to the European Space Agency (ESA), the Canadian Space Agency (CSA), and the Japanese Aerospace Exploration Agency (JAXA). There could be economic, technical and programmatic efficiencies if such a space safety institute might be envisioned as an international organization that could include current international partners with NASA and perhaps also the U.S. Federal Aviation Administration and the Office of Commercial Space (FAA-AST). The institute should be ideally created in such a way that it could provide services, standards, and certification uniformity for U.S. governmental agencies, private space

companies and entities, universities and institutes, and perhaps others.

First Steps Toward Creating a Space Safety Institute

The most logical way to start this process would be if the U.S. Congress were to take the lead in creating a National Authorization Act that calls for the creation of a Space Safety Institute. This would contain an initial charter of operation and likely enumerate a number of possible functions. The charter for this Institute could assign the task of certification processes and seek harmonization of various safety standards that are currently used. This could apply to NASA, the U.S. Department of Defense, private aerospace companies involved in the design, manufacturing, launch, deployment, and operation of launcher systems, satellites, spacecraft, commercial astronaut and supply capsules, space stations, space suits, and other commercial space products. This charter would be designed to be flexibly expanded to take on a widening range of functions over time. It could also be designed so that this U.S.-chartered institute might ultimately partner with other institutes created by other governments to perform parallel functions as well as commercial space industries in other countries. The first step would be to standardize key processes leading to space safety certification and approvals, as well as to confirm and approve space safety standards involving private space systems beyond NASA programs.

This could also include the admission of other countries into the framework, as the Space Safety Institute became the International Space Safety Institute. At this stage, it seems unlikely that the Chinese National Space Agency or the Roscosmos Russian Space Agency would agree to become an integral part of such an International Space Safety Institute, but the main thing would be to allow for flexibility for other

countries to be active partners under some type of cooperative agreement.

Other Space Safety Institute Activities of Importance

It could also be chartered to address other issues where space-related activities might threaten public health and endanger people's lives. This would not need to be structured as a governmental agency, but rather be launched as a separate institute funded by an initial federal grant. It would be authorized to develop a revenue stream through the undertaking of certification processes and other activities. There is precedent for such types of an approach from the shipping industry where certification of ships safety was needed to obtain insurance for vessels of various types.

This institute could be assigned various tasks related to launcher and space travel safety, and also undertake research to improve public safety for space travel, in all of its aspects, such as launch operations and safety, emergency abort operations, medical, health, radiation standards, etc. To the extent that it could expand to be international in scope and have certification standards that are broadly accepted, this would be a true advantage. This would be of particular value with regard to space-suit standards and interface connections, search and rescue systems, telecommunications and streaming standards, energy and electrical power distribution systems, etc.

Even beyond astronaut-related safety standards and exploration systems for astronauts, there would also be significant value in the institute, which would also become a source for international standards and agreements related to other important space safety issues.

These additional mission goals for a Space Safety Institute would logically include such space safety hazards and concerns as:

- (i) **Protecting Launch Site Safety:** These activities would address public safety associated with the operation of launch sites that give rise to a number of dangers;
- (ii) **Addressing Space Debris and Creating Space Traffic Management Systems:** These are critical efforts to cope with the mounting problem of space debris and developing a process to achieve global agreement on space traffic management processes and systems.
- (iii) **Adapting and Updating Space Safety Standards and Certification to the Latest Space Systems Innovations and Development:** This book addresses the many technology innovations and new space exploration capabilities in development. This comprehensive review includes everything from new launch systems to capabilities to terraforming Mars, from new ways to use artificial intelligence and computer modeling to developing new space systems capabilities such as “system aware” robots. The institute’s role will be to identify the need for new or updated space safety standards, certification processes, and adaptation methods that exploit these new capabilities to ensure that these systems are developed as rapidly as possible to reduce risk and maximize space safety.
- (iv) **Facilitate Innovations and Safety Standards and Systems Needed to Cope with Cosmic Hazards that Threaten Humanity:** These efforts would seek ways forward to global agreements to address significant threats to humanity from such sources as asteroid strikes, solar storms that threaten

the world's electrical power systems, telecommunications and computer networks, and other potential cosmic dangers.

The important reasons for moving forward with space safety innovations in all of these areas are set forth below.

Public Safety and Launch Site Certifications

This Space Safety Institute would be of great value if it were able to strengthen safety standards for launch sites and the safe operation for astronauts, commercial space travelers, and all those who work there or live in proximity. The key areas of space safety involved here are government launch sites, plus the growing number of launches from commercial launch sites and space ports for the U.S., plus also working with other governments, including their space agencies' launch ranges, plus a growing number of commercial launch sites around the world.

Of particular value would be the ability to provide widely accepted global safety standards and certification processes for launch operations around the world, as well as the safety of deorbiting operations and active debris removal practices. This might most usefully be undertaken with regard to private launch operations, including those that involve private astronauts and crew as well as space adventurers flying into space on a commercial basis.

Again, the precedent of insurance companies providing guidance in terms of safety practices and standards, such as in the case of Lloyds of London, can assist in establishing safety standards and certification requirements for 21st century privately developed operators. They are well positioned to carry out these tasks on an ongoing basis as the commercial

operations expand in scope and geographical impact to more and more sites.

Further, it is clear that if a particular U.S governmental agency is to undertake such a role and certify the safety and reliability of various types of commercial space services and their operations, this could lead to substantial future liability concerns. Currently, there is a rapid evolution of private space companies undertaking the development of private space stations, private space adventure flights, private space suit design and manufacture, and more. This evolution of new types of businesses and services will very likely lead to an expanding range of other future space business activities that would require some form of safety certification, inspection, and quality verification. Exactly what U.S. governmental entity is to be tasked with the certification of such space products and services, including launch site operations, needs to be planned now and in a systematic way. This would be a particular U.S. governmental entity, such as the Department of Transportation, FAA Office of Commercial Space Transportation (FAA-AST). The Office of the FAA is now the governmental entity that inspects the safety of commercial flights. If all of these duties were to be assigned to a governmental unit, this might be a clear option to consider.²⁶

The most logical option, from a technical competency, safety standards, and operational efficiency perspective, could well be the Space Safety Institute approach. The key point is currently this is neither NASA nor the FAA-AST is well equipped or staffed to take on this role.

Further, there are a number of key issues that now need to be addressed with some urgency. These are issues related to

²⁶ *About the Office of Commercial Space Transportation*
https://www.faa.gov/about/office_org/headquarters_offices/ast (last
Accessed on April 15, 2025)

safety standards, technical competency, legal liability, the costing of the expense of inspections, licensing, and certifications that need to be addressed that immediately arise after there is a determination of what entity or governmental agency is to assume this role.

Space Safety Institute and Space Debris Concerns and Need for Global Agreement on Space Traffic Management

There could be an important role here for a Space Safety Institute with respect to space debris removal standards, support to space traffic management operations, and also standards that provide quality of design, manufacture, safe and clean launch, and operation of space vehicles and systems. There are many ways to ensure that these standards are met. Space insurance and re-insurance companies might play a key role in the enforcement of the safety standards and recertification processes related to dangers arising from launch operations, safe operation of satellite constellation, and more. The expanded role for space insurance and re-insurance companies in this process may strengthen this process and also provide for protection of U.S. governmental agencies against future liability claims.

The institute's engineers and scientists could collaborate with space regulatory officials around the world to better define the safety standards and certification processes. Once agreed, insurance companies might also play a key role in the enforcement of the operational safety standards in this area as well. The main point to emphasize is that active study and resolution of these issues is required and at present there has been no systematic review of these types of safety issues. Currently, the number one area of concern appears to lie with the management of large-scale constellations (often called "mega-constellations"). There are concerns here with regard

to many factors. These include insertion of satellites into constellation orbits, space satellites in sub-orbit available for insertion as a replacement to a failed satellite, safe de-orbit operations, overloading satellite constellations at particular altitudes, deorbiting of satellites, collision avoidance capabilities and their reliability, as well as other types of concerns such as amendment of the Liability Convention to create financial incentive for removal of defunct satellites. One of the other key issues is to create a coordinated effort to actively remove the largest defunct satellites and upper stages of launch vehicles from orbit. There is currently a listing of the fifty largest space debris objects in orbit that create the largest cross-section for orbital collisions that need to be removed. The Space Safety Institute's role needs not only to undertake research into these topics to explore solutions, but also to coordinate with relevant governmental agencies, trade organizations, insurance companies, organizations that are deploying satellites to orbit.

Another important area is to coordinate with aerospace companies that are engaged in on-orbit services and active debris removal services. Likewise, a Space Safety Institute needs to interface and coordinate with the United Nations and its relevant organizations, such as COPUOS, the ITU, the UN Office of Outer Space Affairs, and the International Civil Aviation Organization, among others, in its efforts. The mission of the institute would be to help achieve a broader understanding of the problems in this area and the technical, operational, regulatory, and financial solutions to this increasing space debris problem. It would also provide information and support to an international agreement on a practical way to implement a space traffic management system that would allow safe active de-orbit or re-utilization of space debris and create a process whereby space debris is gradually reduced rather than continues to increase in magnitude. These

objectives should become a part of the Space Traffic Management program of activities and strategic objectives.

This proposed Space Safety Institute might be responsible for setting space safety standards and even defining space safety certification procedures for U.S. aerospace companies, but this might also be undertaken in tandem with space insurance companies. These issues are not unique to the U.S., but it is U.S. private space companies that are leading the way to creating mega-constellations. These companies include Amazon's Kuiper System LLC, SpaceX's Starlink, Planet's Flock constellation, and a number of others that are deploying very large constellations that pose serious concerns related to the future expansion of space debris.

There will, however, be an expanding number of space businesses in other countries beyond the U.S., such as China, the U.K., and Canada, that are or will soon be planning to deploy large constellations as well. This active safety regulatory role would obviously require working closely with space insurance companies to expand the range of coverages available, not only for private space flight, but perhaps also to address other forms of potential dangers and liability claims.

The Space Safety Dangers and Cosmic Dangers

The Space Safety Institute should be empowered to address not only human-created dangers, launchers and space systems, but also other cosmic dangers with the potential to create significant dangers and hazards to human life. Thus, when it comes to space safety, the largest-scale dangers from space to humanity as a whole comes from solar storms and asteroid and comet strikes that could threaten all of humanity.

The Institute might start efforts of this type by developing a series of ways that might be undertaken to provide for

systematic risk reduction on a planetary scale to protect transformers and electrical power grids from dangerous ions incoming to Earth from coronal mass ejections (CMEs) that originate from magnetic storms in the Sun's corona.

The Institute would not be able to fund such protective space-based systems, but it might be able to assist in developing detection and observation systems that could identify vulnerabilities and assist in research with regard to possible infrastructural protections such as “blocking capacitors” and heavy-duty circuit breakers for the worldwide electrical power system. A truly violent solar storm, such as the so-called Harrington Event CME, in September 1859, that set paper on fire in telegraph offices, would potentially leave billions of people without electricity. This might require years for recovery and is perhaps the largest cosmic threat to the world's infrastructure in terms of likelihood of occurrence. Such storms may occur once every 150 years. This is not only a matter of shielding electrical power systems but also planning for system recovery and restoration of electrical power transformers.

The other big cosmic danger, of course, is from asteroid or comet strikes that might hit Earth with devastating impact. We know today that about 67 million years ago, a massive asteroid smashed into the coast near Chicxulub, Mexico, with such force that it created a massive crater. The mud debris went into Earth orbit, blocked out the sun, and led to the demise of not only the dinosaurs but also began the fifth so-called mass extinction event that killed off 70% to 75% of the world's species. This K-T Mass Extinction Event is the only one of the five that was not due to major thermal temperature changes, but rather the result of a six-mile (or 10 kilometers) across asteroid strike. However, there are more frequent asteroid strikes of smaller but still deadly force. In 1908, there was a strike by an asteroid that was about 40 meters across in

Siberia. It was in a remote area of the country known as Tunguska, but if it had hit the San Francisco Bay /Silicon Valley area, this city-killer stone from the sky would have potentially wiped out millions of people. Space safety has many dimensions, and we need to look at many space sciences and engineering tools to protect astronauts. Similarly, we also need to protect people at launch sites and people flying in aircraft. We also need to protect our towns and cities against CMEs that can destroy modern infrastructures, and also rocks from the sky that are city killers or even instruments of mass destruction. A space safety institute could be designed to help protect everyone from astronauts to the major cities of the world if not human civilization.

The dinosaurs did not have a space program nor a Space Safety Institute. If we are at least a bit smarter we can create modern institutions that can save our world and our astronauts too. The need to address these types of cosmic dangers and possible protective actions that might be taken are addressed in further detail in Chapter 14 on long-term possible breakthrough goals for NASA.

Currently there is no U.S. governmental agency that is actively seeking to prevent catastrophic cosmic dangers that could endanger most of modern civilization. It seems to be an oversight that deserves some attention. We avoid being alarmist, but this is truly a very serious and in our view urgent concern.

The key question is whether government regulatory agencies, space agencies, defense forces, or homeland security agencies are the first line of defense? Or should it be some sort of space safety institute or insurance/re-insurance conglomerate, or is some other type of mechanism needed to address these safety and liability issues?

The Space Safety Institute and Key Training and Education for the Future

Yet another area where an institute might play an important role is with regard to the education and training of engineers and scientists who specialize in the field of space safety, which will require well-trained professionals in the coming years. There is a growing need for professionals to be trained in the field of space safety engineering, standards, and regulatory policy. The institute could play a role in defining the curricula for Master's degrees in the field. This definition of a model curriculum would be just one of the ways a space safety institute might support universities in developing and reviewing the quality and content of their curricula. It might also serve as a source for defining key new topics of research for master's theses as well as inspiration for the design of laboratories and test sites to support these educational and training programs.

Run Down on Prime Functions for a Space Safety Institute

To recap the areas that a Space Safety Institute should address in supporting future space industry needs, here is a useful rundown of the various areas of activity.

Space Safety Standards and Key Certification Processes

The prime role for a Space Safety Institute, as noted above, will be to define and harmonize space safety standards and for these to be certified in a professional and reliable way across the world's various national government space exploration programs and private space programs. This is particularly important in terms of achieving standardized interconnection of spacecraft capsules, docking systems for space stations,

oxygen and power supplies, and other key systems that might be key to rescue operations in space. If such an effort should fail, then search and rescue operations could most likely fail since aid from one national rescue team would not be able to help another because of incompatible breathing apparatus, oxygen supply units, etc.

Thus, a range of national, commercial, and international agreements to ensure compatibility is critical. This effort should emphasize the importance of standards for technical and reliability certification standards for all crewed systems at a minimum. This would include launchers, especially those with human crews, for capsules, for space suits, and particularly space systems for crewed missions. These space safety standards and certification procedures would support the safety and interconnectivity of commercial space systems in Earth orbit and deep space, but also would seek compatibility with governmental space agencies such as NASA, the FAA-AST, and the U.S. Space Force. The next, more difficult step would be to achieve this for all spacefaring nations as well as for all commercial space enterprises engaged in space services involving crew and commercial astronaut exploration and habitat units in space.

Institute's R&D and Space Safety Technology Awareness Campaign

The Institute should carry out an ongoing research and development campaign. This would monitor progress in the safety and reliability performance of all areas related to commercial and governmental space systems safety. This effort to create comprehensive space safety standards should include all types of launch systems in terms of safe design, manufacture, operation, deactivation, and disposal. This would include the safe and reliable operation of liquid and solid launch systems, nuclear-powered systems, electro-

magnetically powered lift systems, tethered-lift systems, gravitational enhanced-lift systems, magnetically accelerated systems, enhanced understanding of environmental pollution concerns, plus life-support systems and space suits, astronaut health and medical systems, search and rescue and telecommunications systems, electrical power supply systems, etc. Since the main focus of the Institute is space safety standards and certification standards, the research and development activity will focus on monitoring the R&D activities carried out around the world. This would include awareness of progress in space sciences, space medicine and health and life support systems, space propulsion, space habitations, safety and reliability of space telecommunications and energy, and progress in the aerospace development field. The top focus is thus on safety and reliability innovations.

Space Safety Process Research, Development, and Improvement Effort

Space safety innovation frequently comes from new technology such as reusable launcher systems, mass produced rocket motors of simplified and high reliability production methods, improved thermal protection materials, or integrated design life support systems. Yet another part of space safety advances come through improved processes and integration of space safety techniques with new space system engineering processes. This is an area of advancement on which the Institute should focus its efforts.

These efforts within the Institute should stress the following elements:²⁷

(i) Safety and Resilience by Design

²⁷ Joseph Pelton with Peter Marshall, *The Space Safety Institute: A New way to Safety Certification in the "New Space" Age* (2022) PM Associates, Washington, D.C.) (Chapter 6)

- (ii) Effective Use of Fault Avoidance and Acceptable Fault Tolerance, and Risk Identification
- (iii) Safety Innovation and Advanced Concepts and Related Research Goals
- (iv) Hazard Analysis, Computer Modeling of Risk Analysis, and AI Assessment of Risk Modes
- (v) Safety Requirements, Technical Standards, and Certification
- (vi) Safety Analyses (Preliminary Safety and Risk Review Analysis at Mission Definition Stage, At All Design Reviews, Final Testing and Analysis)
- (vii) Independent Surveillance (Independent Verification and Validation Testing)
- (viii) Systematic Safety Review Processes and Concepts
- (ix) Manufacturing Review Processes and Manufacturing Management Systems
- (x) Human Factors and Space Safety
- (xi) Human Habitation and Life Support Systems
- (xii) Inclusion of Safety and Risk Analysis in Readiness Reviews
- (xiii) Systematic Safety Verification Program (Tests, Analyses, Inspections, Demonstration) and
- (xiv) Knowledge of Key Space Safety Policy, Regulations, and Legal Provisions

Space Debris Mitigation Standards and Need for Space Traffic Management Agreements

The new technical capabilities to address debris mitigation, active debris removal, and new capabilities to implement space traffic management will be addressed later in this book in more detail. There are, however, key standards and international agreements that are also needed to address space debris and collision avoidance concerns. Both of these standards and institutional agreement reforms are critical to astronaut safety going forward.

Space Debris Mitigation

The first step involves agreement on what the requirements are to achieve cleaner launches that do not create debris at the start of a mission through due diligence before launch, not leaving upper stages in orbit at launch, operational controls and collision avoidance capabilities to prevent collisions, and to remove debris at the end of life. The U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), with assistance from the Inter-Agency Space Debris Committee (IADC), finally reached agreement on the Space Debris Mitigation Guidelines after many years of negotiation. This process took over 12 years from start to finish. Discussion of the issue began in 1994, and guidelines were finally adopted by the Committee and then endorsed by the U.N. General Assembly in 2007. The negotiation of these mitigation guidelines was very difficult, and the adopted guidelines were only recommended and thus not mandatory and had no enforcement powers behind them, even if they seemed to propose a required procedure.²⁸

The weak nature of these Guidelines is seen in Section 3 of Applications that states:

“Member States and international organizations should voluntarily take measures, through national mechanisms or through their own applicable mechanisms, to ensure that these guidelines are implemented, to the greatest extent feasible, through space debris mitigation practices and procedures.”²⁹

²⁸ UN COPUOS, “Space debris Mitigation guidelines of the Committee on the Peaceful Uses of Outer Space” Adopted in 2007 (<https://www.un-ilibrary.org/content/books/9789213630921s007-co01>) (Last accessed Feb 18, 2025)

²⁹ UN COPUOS, “Space debris Mitigation guidelines of the Committee on the Peaceful Uses of Outer Space” Section 3 (Adopted in 2007)

Since that time, very little progress has been made despite increasing levels of space debris that have continued to accumulate. The member states of Canada, Germany, and the Czech Republic have put together a “Compendium” of Space Debris Mitigation Standards Adopted by States and International Organizations. This has appeared as a UN COPUOS document, but this compendium, which was started in 2014 and has been updated through 2024, does not have particular legal standing. It does show that many nations have taken action to limit space debris, and in some cases, such as in the French Space Operations Act, they have even created penalties for noncompliance with its provisions.³⁰

Space Traffic Management

In parallel with the U.N. COPUOS discussions and actions related to space debris, a Working Group on the Long-Term Sustainability of Outer Space has been formed. This Group has considered a wide range of space safety issues and concerns including the problems of space debris and the possible need for nations to cooperate in the creation of some form of Space Traffic Management that is somehow akin to the international air traffic system that is coordinated through the International Civil Aviation Organization (ICAO). Although a number of resolutions agreed within the Working Group on actions that might be taken to make the exploration and utilization of space more sustainable, several nations, and perhaps most notably Russia, have maintained that such an international space traffic management system is not a proposition to which they

<https://www.un-ilibrary.org/content/books/9789213630921s007-c001>
(Last accessed Feb 18, 2025)

³⁰ “Compendium” of Space Debris Mitigation Standards Adopted by States and International Organizations”
<https://www.unoosa.org/oosa/en/ourwork/topics/space-debris/compendium.html>

feel action is ready to be agreed. Thus, no specific international agreements in the area have yet to be formulated with unanimous consent, even though draft agreements have been considered within this Working Group on an ongoing basis for at least the last seven years, but with some key nations strongly withholding their agreement. Dr. Simonetta di Pippo, then Director of the U.N. Office of Outer Space that serves as the secretariat to the U.N. COPUOS, publicly stated on September 7, 2021: “Although COPUOS still has a long way to go to bring in all 193 UN member states, it can serve as a forum for discussions of space traffic management.”³¹

Since that time, some four years ago, no breakthrough agreements have been achieved. It is to be hoped that a Space Safety Institute that has support from most of the space-faring nations of the world could work with the Compendium of space safety documents, backed by true concerns about runaway space debris. This action might be able to help break the log jam and serve to create a rudimentary system to which more and more nations might choose to join in support. This might be one of the truly important safety challenges for which the Space Safety Institute could provide significant support. (See **Fig. 3.2**)

Certification Standards for Launch Site Facilities

There are other areas where a Space Safety Institute might provide key new input to support both astronaut flights and public safety. This would be to develop clear safety standards and certification procedures with regard to launch sites. Although the FAA-AST has created standards for the safety of

³¹ Debra Werner, “UN Space Office Seeks Consensus on Space Traffic Management” *Space News*, Sept. 7, 2021 <https://spacenews.com/un-space-office-seeks-consensus-on-space-traffic-management/>

launch sites and an inspection schedule for recertification, these safety standards and certification processes are not always clearly defined in other countries.

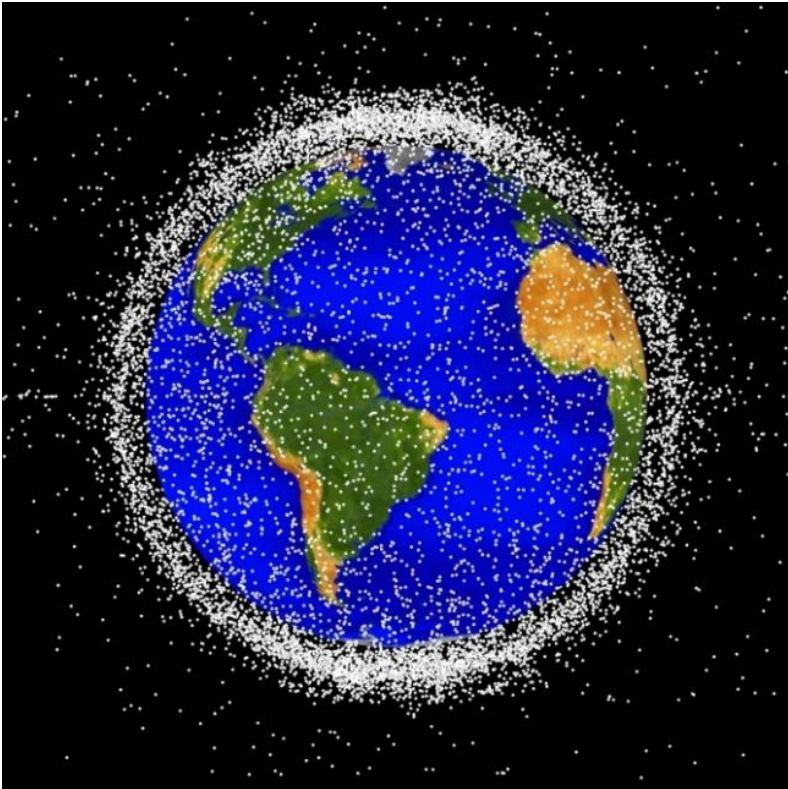


Fig. 3.2: Space debris in Earth orbit, continues to increase, but no agreement on Space Traffic Management has been reached
(Image courtesy of NASA)

Further safety standards, certification processes and accident review processes with regard to accidents at launch sites are a shared responsibility with the FAA-AST and the Office of Safety and Hazards Assessment (OSHA) and the National Traffic Safety Board (NTSB) and a key element in deciding

governmental regulatory oversight authority depends in part as to where and how accidents might occur.

As of the end of 2024, there have been 15 astronauts and four cosmonauts killed in outer space accidents in a half dozen events. Incredibly large efforts have been taken to ensure the safety of launch systems and space capsules designed to carry crew and passengers into space.³²

However, there have also been a number of accidents around the world within launch sites or in close proximity to the launch site, in cases where rockets have quickly crashed back to Earth, and proper precautions were not taken. On Feb 14, 1996, a Chinese 3B rocket rather immediately went off course and crashed down at a nearby hotel, and four workers were killed. Ironically, these workers were installing safety equipment in the hotel that was located much too close to an active launch site.³³

In 2007, there was an accident at the Mojave Airport test facility of Scaled Composites, where three workers were killed 2007 when an improperly protected fuel system exploded in a hangar facility where improper safety standards were being observed.³⁴

Workers at launch sites, or people who live or work in proximity to launch sites who are injured due to insufficient safety precautions, receive much less news coverage in

³² “*List of spaceflight-related accidents and incidents*”
https://en.wikipedia.org/wiki/List_of_spaceflight-related_accidents_and_incidents (Last accessed Feb 27, 2025)

³³ “Chinese Rocket Crashes”, UPI Archives, Feb 15, 1996,
<https://www.upi.com/Archives/1996/02/15/Chinese-rocket-crashes/6146824360400/>

³⁴ “Three Scaled Composite Workers Killed at Test Site” LAT Times, July 27, 2007
<https://www.latimes.com/archives/la-xpm-2007-jul-27-me-explode27-story.html>

comparison to astronauts who die on a space mission during a simulated live test, such as occurred in the Apollo 1 fire that killed three astronauts on the launch pad test. Many fatalities or serious accidents occur when satellites launch to orbit without astronauts, cosmonauts, or taikonauts aboard. Nevertheless, there are many dozens of such events, and investigations about how these accidents have occurred have identified many safety deficiencies. For example, there are fuel tanks or explosive materials that are improperly stowed and are not sufficiently isolated from workers. Also, there are not sufficient methods to destroy a malfunctioning rocket before it can harm nearby homes or buildings.

The Space Safety Institute can play a key role in creating standards to spell out the safety perimeter to isolate launch site facilities from populated areas. Likewise, there are standards for launch site officials who can trigger an explosive destruct or abort command to ensure that nearby towns or populated areas are not harmed. There are many dozens of protective measures that help to define the safety perimeters for launch sites, the safe storage facilities of explosive materials, and the types of gear workers are to wear when handling dangerous materials. Also, security precautions and perimeter barriers are required to prevent intrusions into dangerous launch facility areas, and dozens of protective measures, as well as inspection processes and frequency of independent inspections, exist to see that all needed safety provisions are being observed and enforced.

The FAA-IST and OSHA officials have generally high standards in this regard, but some countries do not have strict protective measures and inspection requirements fully in place. The Space Safety Institute can seek to establish clear and stringent standards to be observed. Further, there are not only launch sites that require this level of safety protection, but also facilities for test firing of rocket motors and other facilities for

storage of rocket fuels. There is clearly a need for safety standards, enforcement, and inspection processes that are periodically carried out with suitable fines and penalty measures for unsafe actions and failure to meet safety standards for launch sites, rocket fuel storage sites, and rocket motor test facilities. This is not only a problem in countries with less stringent safety standards, but for the U.S. rocket launcher suppliers as well.

Most recently, there have been investigative reports by Reuters News about increases in accidents and failed safety measures occurring at SpaceX test site facilities near Brownsville, Texas. There has been increasing pressure to complete, test, and qualify the giant Star Ship launcher, which is key to the Artemis Program for lunar exploration. A modified version of this Starship is based on the earlier Star Ship vehicle. The report found that accidents at the Brownsville facility were significantly elevated, and indeed, the review found safety concerns at all three of the SpaceX facilities. The November 10 report by Reuters indicated: “at least 600 previously unreported workplace injuries since 2014 at SpaceX, including crushed limbs, amputations, head injuries, and one death. The Reuters report found that injury rates at three major SpaceX industrial facilities in Texas and California far exceeded the average for the space industry.”³⁵

The risks of human spaceflight are well known. There is clearly a need for strict safety standards and exacting certification processes for rocket launchers, capsules, space stations, and space suits. It is also true that launch facilities and their staffing and operation also require clearly defined safety

³⁵ Marisa Taylor and Joey Roulette, “U.S. Lawmakers Urge Scrutiny of SpaceX worker injuries After Reuters Report, Reuters, Nov 18, 2023 <https://www.reuters.com/sustainability/us-lawmakers-urge-scrutiny-spacex-worker-injuries-after-reuters-report-2023-11-18/>

standards and independent certification processes repeated with some regularity. These are to ensure the health and safety of these facilities and the much larger number of people that work there, beyond the astronauts that fly into space. There are many tens of thousands of employees who work at sites that fabricate launch vehicles and capsules for astronauts, plus the launch sites and the test facilities that fire rocket motors. The presence of explosive and flammable materials, complex gantry towers, cryogenic gases and liquids, and the launch of rockets that can explode are all reasons why safety precautions are required. Currently, NASA and the U.S. Department of Defense oversee their own safety and arrange for such aspects as range safety officers. Similar safety procedures, standards, certification, and independent verification and validation arrangements are observed by other space agencies and defense agencies around the world. There is an increasing number of space businesses that are now designing launchers, capsules, private spaceships, private space stations, and space suits, as well as operating their own launch facilities. Private space industry activity and its overall economic size now greatly exceed the level of expenditure of governmental space agencies. These trends strongly suggest the need for strong safety measures and certification processes for these quickly expanding commercial space enterprises. An independent Space Safety Institute that can provide global standards and uniform certification practices and processes can help to ensure a uniformity of practice, and especially help to prevent unsafe practices. This will prevent the development of commercial sites for launch and test facilities that carry high levels of risk and avoid dangerous operations involving launch facilities, vehicles, spacecraft, space stations, or space suits.

The cited example of SpaceX should not be considered a unique situation. There is pressure on for-profit companies to perform. Safety precautions and the costs associated with launch facilities or storage facilities associated with rocket

fuels, cryogenics, etc., are quite expensive. Some smaller companies developing lower-capacity rocket systems have sought to launch from mobile facilities, launch from balloons, or be released from a high-altitude aircraft.

One of the important roles that a Space Safety Institute can perform is to provide clear safety standards and certification guidelines for all types of launch facilities including mobile or elevated altitude launch augmentation aircraft or balloons.

Clearly, there is a major focus on developing safety standards and certification processes to make all types of launch systems as reliable and risk-free as possible. This effort related to astronaut safety in orbit has received wide attention from the press and the general public. This is especially true for launches involving human crew and passengers. Yet launch range facilities, rocket firing test sites, fuel, hypergolic gases, and other noxious material storage areas, as well as other dangerous areas associated with rocket launches, plus perimeter security for such sites, actually serve to protect a much larger population of people. Thus, public and employee safety for launch facilities, testing sites, and dangerous storage areas represents a very important area for a Space Safety Institute—or Institutes—to be actively engaged. This involves safety for these areas, perimeter security, sufficient isolation from the general public, and arrangements for good coordination among all of the entities and agencies that are involved.

Governmental space agencies and defense agencies develop their own safety standards and certification processes. The private or commercial space industry has had to rely on evolving guidelines for performance testing and Independent Verification and Validation (IV&V) procedures as they develop new launcher systems, design capsules for cargo and astronauts, and now engage in commercial development of

space stations and space suits. For the U.S., there is also the Occupational Safety and Hazards Association (OSHA), the National Transportation Safety Board (NTSB), labor union negotiated safety standards, and various national laws affecting safety standards to consider. The Space Safety Institute could serve as an important service in untangling the very complicated network of actors, safety standards, and certification processes. The area of greatest concern might well be with regard to private aerospace companies entering new space-related activities with contractual schedules to be met, a desire to make a profit, and yet being faced with stringent safety-related costs and expenses. Although the SpaceX-related accident-incident reports noted above have recently received the most attention, there are concerns across the board about how to maintain safety for the ever-expanding scope and scale of aerospace activities.

Finally, it must be noted that the Space Safety Institute must be attuned to constantly emerging new space technologies to support space transportation and how to maintain public safety. These concerns include minimization of adverse environmental impacts, such as launching systems' polluting effects and ejections of particulates into the atmosphere, and how to minimize these effects.

Solar Storms, Coronal Mass Ejections, and Asteroid and Comet Strike Concerns

To many people, space safety relates to keeping astronauts and launch facilities safe, and perhaps also relates to space debris concerns. However, there is a very important aspect of space safety that involves a much wider sector of the global population. There are significant dangers to the entire population of planet Earth. Most people do not realize that we exist on a spaceship Earth that travels over six hundred million miles (or about a billion kilometers) through deep space in its

journey around the sun each year. Humanity is protected from cosmic hazards by a thin atmosphere equivalent to the skin of an apple and an electromagnetic shielding system that varies in its protective strength. There is serious potential danger from asteroid or comet strikes, where even a 35-meter-wide asteroid could be a “city killer.” Likewise, our world faces great dangers to vital global infrastructure from powerful solar storm events called coronal mass ejections (CMEs). Such giant solar flares carrying ions at millions of miles an hour could wipe out our electric power grid, disable control systems for vital pipelines, and trigger what we call an electromagnetic pulse (EMP). Solar radiation that reaches Earth through weak ozone layers can cause skin cancer and dangerous genetic mutations.

This is not often discussed as an aspect of cosmic dangers, which could result in devastation to cities with over 20 million people in population or destruction of vital infrastructure on which billions of people depend. This aspect of space safety is also an area where a Space Safety Institute could add great value. The UN COPUOS Working Group on Long-Term Sustainability is concerned with not only space debris and space traffic management, but these cosmic hazards as well. This is an area of research and protective planetary defense system capability that NASA and the other space agencies should consider to be a higher priority mission.

Space exploration, space sciences, and space applications are all important missions for NASA, but saving humanity from massive, destructive cosmic dangers should be job one.

Conclusions

It is believed that a well-conceived and cross-disciplinary Space Safety Institute could be all of these things. The Artemis Program to explore the Moon will cost well over \$100 billion.

A much less investment involving millions of dollars a year for protecting astronauts, making launch centers safe, strengthening NASA's Office of Safety and Mission Assurance, and protecting the citizens of Earth is an excellent investment. It is possible for NASA and other space agencies to be modestly reorganized and to create a Space Safety Institute as outlined in this chapter and spelled out in some detail in the book *The Space Safety Institute*, with modest changes to space agency budgets. The same applies to departments for Homeland Security.

A Space Safety Institute designed to address all the elements described in this chapter would be a wise investment that could support a wide range of capabilities. This effort could create new safety standards, certify government and commercial space systems as safe, provide for safer launch sites, and even serve to protect humanity against significant cosmic dangers, and help promote the growth of commercial space industries. It could serve to save the lives of astronauts, workers at launch sites, create new life support systems, create global space safety standards, promote education and training to support these efforts in the future, and protect Earth from space debris, help implement space traffic management, and give new meaning to planetary defense.³⁶

³⁶ See: *The Space Safety Institute: A New Way to Safety Certification in the "New Space" Age*, (2022) PM Associates, Washington, D.C.

Chapter 4

Reform of NASA's Systems Engineering, Specification Development, and Systems Risk Assessment

Introduction

The largest and most significant NASA projects, such as the Apollo Program, the Space Shuttle Program, and the Artemis Program, either started at the White House level or emerged jointly from the U.S. Congress and the White House. The mission statement and even the performance schedule for the Apollo Program came from President Kennedy's address, calling for astronauts to be sent to the moon. The Nixon White House saw the need to launch the Space Shuttle program development as a way to shut down the hugely expensive Apollo Program and as justification for ending lunar exploration with Apollo 17. The initiation and requirements for the Artemis Program are more complicated. This is because, in some ways, it began with President George W. Bush's launching of the Constellation Program, which morphed over time into the Artemis Program, which has had varying levels of support from Congress.

The point is that top-down defined major space programs, which typically end up costing more than 100 billion dollars (US), tend to become political in nature, can balloon into a

form of “jobs program”, and can be altered and expanded as a result of lobbying campaigns. In particular, congressional legislative and appropriations support, or even directions from the White House, can frequently be impacted by lobbying efforts to create contract awards and jobs in various congressional jurisdictions. Legislative bills can define mission requirements and even which types of launchers or spacecraft are to be used, as well as specification elements that favor a particular contractor or lock in a specific technical element of this undertaking.

This approach to space program definition can serve to drive up costs, slow the program’s developmental progress, and have an adverse impact on the safety elements of the program. The mandate to accomplish the Moon landing before the end of the decade, the political interventions to include the addition of solid fuel boosters to the Space Transportation System (STS), and the legislative mandate to include the Orion capsule in the Artemis Program are just some of the examples of imposed design elements that may have adversely affected the safety of these astronaut-based space exploration programs as well as cost, schedule, and effective design and performance.

Even if space program definition elements and specification do not come from the White House or Congress, the official process used by NASA to undertake the definition of new programs and the systems engineering definition process used within NASA—and other space agencies around the world—have a “top-down” process. This is where mission requirements are provided to systems engineers to design a program. It is only after these requirements and the initial systems design are developed that space safety engineering reviewers are given a chance to help “perfect” the design to improve its safety and lower risk and potential hazard factors. As has been said many times by many people: “Safety must be designed in and not added in later.”

This chapter explores an improved process whereby space safety engineering capabilities for major astronaut exploration programs can be improved in at least three key ways. One way, already noted in Chapter 2, is for NASA to define “performance requirements”. This is where bidding contractors are challenged to provide innovative designs that seek to accomplish the “performance-defined tasks” in the best, most efficient, safest, and cost-efficient way. This approach, as defined in the “Next Steps” program, also opens the door to a partnership opportunity with the aerospace industry. This is where the contractor “partner” might be able to offer future commercial services to NASA and “invest” in the undertaking as a precursor to future commercial partnerships with NASA or other future “customers.”

When NASA defines the technical design specifications, it is reviewed by Congress and sometimes impacted and even “set in stone” during Congressional review in terms of the appropriation provisions. This process can serve to benefit particular contractors, add to costs, and lead to schedule delays. Under the performance requirements approach that is undertaken under “Next Steps” procurement processes and NASA Space Act Agreements, the selected contractor defines the best and most effective and efficient technical design, and not NASA, Congressional oversight staff, or officials. This process offers the possible opportunity for contractors to become investors in the new technology and ultimate “product” under a cost-sharing agreement that allows that investment to be recouped in subsequent commercial use. This has several advantages. It creates an incentive to produce a better product more quickly and with greater efficiency, as well as a heightened eye for safety, reliability, and resiliency. Cost plus fee contracts awarded against NASA technical specifications and with no fixed price tend not only to lack these incentives but also to work in the reverse direction. There may be advantages in extending the process, which

would add to cost and complexity. There can be an ‘advantage’ for finding reasons to change the technical design, not for needed safety or for reliability purposes, but simply to add to costs and the resulting contractor fee.

Secondly, NASA’s current review process to examine contractors’ proposed designs does not essentially review the proposed design and contractor workplan, management and projected cost to accomplish the proposed work. This results in a NASA technical performance review team making an assessment of the management and work team and the associated bid and the proposed cost to complete the work.

This review and assessment process also needs to be revised. There should be three teams and not two. These review teams would be tasked to assess technical performance, cost, management and staffing arrangements, and a third team to assess safety and risk as an added element with a co-equal assessment value. At NASA and most other space agencies, the technical design and engineering concept and its safety and risk aspects are currently co-mingled, with safety being one of a number of elements to be considered.

This current review process and rating serves to depreciate the value of safety and risk minimization. There is no particular reason for bidding contractors to stress or seek important new safety design innovations.

The third way is for NASA, or other safety agencies, to alter the way it defines safety and risk minimization in its performance requirements as an independent and key project goal. The corollary would, of course, be to include safety design engineers in the process from the outset of a project. Their role would be upgraded from the process. They would be a part of the design engineering team as the performance specifications were developed, especially with regard to risk minimization

and safety. And, of course, they would also head the third team that would assess the contractor's bid. This inclusion of safety goals, risk reduction, and performance-related enhancements should be a prime rather than a subsidiary element to be considered as one of many technical goals. Implementation of these changes would make safety and risk minimization a top-level element from the very start of a new astronaut-related program. Safety, in short, becomes an essential and highly rated performance requirement, rather than something to be added afterwards.

The importance of Emphasizing Space Engineering, Safety Specifications, and Assessment of Contractor Proposals

One of the key objectives of the International Association for the Advancement of Space Safety (IAASS) over the last two decades has been to create within leading universities with aerospace engineering departments a Master's degree specialization that focuses on the area of space safety engineering. Most employees at space agencies and aerospace contracting firms are involved in space safety concerns today. These range from independent verification and validation (IV&V) to computer systems analysis for design safety and key areas of safety. These areas include such topics as explosive fuels or fire hazards, propulsion systems, environmental controls, and life support systems. This is to name only a few areas of the dozens of concerns important to space safety engineering.

Today, most space safety engineers and processes experts are those who have learned their craft from on-the-job training. Yet, space systems engineering has become more sophisticated, software engineering and analysis more critical, and the elements involved with safety engineering, risk analysis, fault detection, and failure profiling have all become

more technically intricate and sophisticated. There is a growing need for academic training and specialization that is much greater today than ever before.

As a result of these efforts, more and more courses are being developed at universities at the master's level that could be key to the expert training of space and aeronautics safety engineers. For instance, at the University of Southern California within their Aeronautical Engineering program they have the following courses that could be of key importance for the training of space safety engineers: Orbital Mechanics, Space Navigation, Theory and Practice, Solar System Navigation, Spacecraft Attitude Dynamics, Spacecraft Attitude Control, Liquid Rocket Propulsion, Solid Rocket Propulsion, Advanced Spacecraft Propulsion, Physical Gas Dynamics, Space Launch Vehicle Design Spacecraft Structural Dynamics, Spacecraft Structural Strength & Materials, Spacecraft Thermal Control, Spacecraft Power Systems, Space Spacecraft Sensors, Space Studio Architecting, Entry and Landing Systems for Planetary Exploration, Human Spaceflight, Human Factors in Spacecraft Operations, Spacecraft Life Support System, Safety of Space Systems and Space Missions, Reliability of Space Systems, and Safety of Space Operations.

At the Massachusetts Institute of Technology there is focus on software development for risk analysis. This involves better developing ways to identify possible failure modes in subroutines, but also as a completely integrated system that is not fully integrated and checked out on an end-to-end basis. It also examines risk analysis and evaluation of probabilities of a wide variety of risks to mission performance based on both historical data and complex systems interoperation.

The entire scope of emerging knowledge about how to design safer spacecraft and systems, as well as an expanding number of academic courses and training systems, would allow for the

increased development of sophisticated capabilities to educate highly capable space safety design engineers. These new educational capabilities would enable space safety system capabilities which are far more sophisticated than in the past. In addition, computer modeling, system simulations, and fault detection programs are increasingly allowing the development of software that can aid new safety engineers in their work.

All of this new capability—both safety engineers and new space systems software—could, and indeed should, be employed to design safer and more capable space transportation capabilities, new space capsule systems, new life support systems, new logistical supply systems, and new types of space stations. This new capability should be deployed to the maximum extent possible in the definition of new space systems, in the definition of performance specifications, and space safety assessment of contractor proposals. The creation of a Space Safety Institute, particularly if it were an international body, with strong links to universities teaching these courses and granting Masters' degrees in these areas could greatly strengthen the global resources available. The graduates would be well and perhaps better trained to support these space safety offices in the worldwide aerospace industries and the space agencies around the world.

This means that when bids come back from contractors, the technology assessment, cost and delivery schedules, and safety design and systems engineering should all be given at least equal weight. When new missions are being envisioned and requirements defined, space safety engineers should be at the table with equal capability to make input and apply critical thought to all such efforts from the very outset. There is wisdom in the statement noted earlier that space safety is not something to be added after the design has been created, it must be a part of the design process itself.

After the Space Shuttle Challenger accident occurred, it was recommended that NASA should create a NASA Engineering and Safety Center (NESC). The problem that NASA had was that its extensive operations were spread out over nearly twenty different Centers, offices and facilities all across the U.S. and even had offices overseas to interface with other space agencies that were contributing parts of the International Space Station. The solution was to create certain areas of expertise in various centers and also create a wide range of experts on call from universities and research institutes. On paper, the NASA Engineering and Safety Center (NESC) looks very impressive. Hundreds of experts from NASA Centers, universities and research institutions are listed. If there is a problem, then NASA can activate resources from the NESC and expertise can be assembled and fly in to address the problem. The result is that the NESC is a “reactive” program that can be activated to respond to problems and support efforts to fix the problem and re-engineer things to make them safer and more resilient. The problem is that such an assemblage of capability is not able to be proactive. It is not geared to design the safety into rockets, space stations, astronaut capsules, and new space systems at the outset.³⁷

There is also a NASA Safety Center located in Cleveland, Ohio, with a staff of about 50 people. This unit helps to develop courses on various topics related to Safety and Mission Assurance that employees across the organization can take. This helps the many thousands of NASA employees to be more competent in the areas of space safety, but this is essentially a training program and not a space safety design engineering capability.³⁸

³⁷ NASA Engineering and Safety Center, <https://www.nasa.gov/nesc/> (Last accessed Mar 5, 2025)

³⁸ NASA Safety Center, <https://www.nasa.gov/nasa-safety-center/> (Last Accessed Mar 5, 2025)

The spreading of NASA capabilities in space safety engineering across so many different locations hampers the ability to proactively address improved safety design and risk reduction. This also largely restricts the NASA Engineering and Safety Center to being an “on-call” resource to respond to safety problems and remedial action. This is a problem that is not unique to NASA’s effort to address safety and risk reduction. In fact, it applies to the entire scope of NASA’s various activities. SpaceX, Blue Origin, and other so-called “NewSpace” organizations have found that vertical integration enhances efficiency and aids development, design, manufacturing, testing, and safety in a variety of ways.

NASA’s Office of Safety and Mission Assurance is not so much an office as a collection of parts. Each of the major NASA Centers has its own Safety and Mission Assurance (SMA) operations. Thus, the Ames Research Center, Armstrong Flight Research Center, the Glenn Research Center, the Goddard Space Flight Center, the Jet Propulsion Laboratory, the Johnson Space Center, the Kennedy Space Center, the Langley Research Center, the Marshall Space Flight Center, and the Stennis Space Center all have their own collection of space safety staff and officials. Then, there is an Agency Risk Management Office and a Resource Management Office at NASA Headquarters.

Also, there are five functional divisions that address different areas. These are: (i) Mission and Program Assessment Division; (ii) Institutional Safety Management Division; (iii) Mission Assurance Standards and Capabilities Division; (iv) NASA Safety Center; and (v) NASA Independent Verification and Validation Program.³⁹

³⁹ (NASA Office of Safety and Mission Assurance, <https://www.nasa.gov/safety-and-mission-assurance/> (Last accessed Mar 6, 2025))

This collection of human, testing, and analytic resources is spread across the nation, not only at NASA facilities, but also at a very large number of aerospace contractors and subcontractor sites. At these widely separated facilities, tens of thousands of contractor staff are working to fabricate various products or software for NASA-funded projects. In addition, this diverse collection of space safety resources and facilities must interface with the NASA Safety and Engineering Center on demand, particularly when accidents or critical problems and key safety issues arise.

As will be discussed later, most of this oversight of safety, risk reduction, and problem solving has historically been geared to fabrication of space systems and equipment, but in the twenty-first century, it is frequently software and software issues that can be the source of accidents and failures. The problem of oversight and delivery of safe and risk-free software by NASA staff, and particularly with contractor oversight, has been a continuing problem. This has been a particular concern with the development and safe operation of the Boeing CST-100 Starliner capsule for many years, beginning with the first test flight and most recently with regard to the safe undocking and safe return of the astronauts who flew on the latest test mission in 2024. Currently, these astronauts, as of March 2025, are still living aboard the ISS with the Boeing CST-100 still docked at the ISS, some six months into their unsuccessful test flight. But this is just one of many examples of software issues.⁴⁰

In addition to NASA OSM internal staff activities, thousands of NASA employees outside the Office of Safety and Mission Assurance can take courses offered remotely through the NASA Safety Center located in Cleveland, Ohio, to improve their knowledge of space safety concepts and best practices.

⁴⁰ “Boeing Starliner Undocking Software Issue Complicates NASA Astronaut Return”, August 6, 2024, <https://simpleflying.com/boeing-starliner-undocking-software-issue-nasa-astronaut-return/>

The geographic, functional, and mission diversity of this widespread operation, with its potential for overlapping activities and opportunity for confusion associated with such a complex operation, is of concern.

An outside assessment of this office would likely find that there would be major and systemic overlap and confusion that comes from each of the major NASA Centers having their own space safety operations. Further, this wide collection of people and operational facilities is somehow augmented by the very large collection of experts represented by the National Engineering and Safety Center (NESC). The complex and perhaps redundant collection of space safety personnel at the Office of Safety and Mission Assurance is an accumulation of ‘safety related competence that is designed to “to find and respond to problems” and not to proactively design future space systems that are to be safer, lower in risk, and more resilient.

In theory, NASA could spend less money and have fewer staff involved in space safety while focusing on improved space systems design and engineering in more effective ways. The issue for NASA efficiency, productivity, and improvements in safety all involve centralization of effort and vertical integration, as opposed to operating as a massively decentralized operation. This was one of the central conclusions of the 2004 Report of the Presidential Commission on the Implementation of the U.S. Space Exploration Policy, which was entitled: “A Journey to Inspire, Innovate and Discover”. This report called on NASA to be “reorganized for success. To accomplish this, the Commission proposes a new model for the NASA Centers. We feel that NASA should reorganize for success, provide a wider role to industry, and focus on R&D central to its core mission. One of the ways to accomplish this would be to undertake a transition in the organizational status of its Centers. This

would be achieved through an open, competitive process to become Federally Funded Research and Development Centers. (FFRDCs). This is not a new idea. It was one of the top recommendations of the so-called Aldridge Commission over 20 years ago.⁴¹

The Aldridge Report in 2004 proposed that NASA be restructured and that several of the NASA Centers be “auctioned off” to universities. Pete Aldridge was the chair of this Presidential Commission, which included notables such as Neil deGrasse Tyson and Carly Fiorina, then Chairman and CEO of Hewlett-Packard. The ideas in this report about NASA being restructured and right-sized without so many large and distributed Centers were “rediscovered” during the first Trump administration in 2018. An OMB Order was written to re-examine the idea of changing NASA Centers to Federally Financed Research and Development Centers.⁴²

The OMB Report stated: “The new National Space Strategy and National Space Policy Directive 1 make examining the potential advantages of an FFRDC model at NASA particularly timely.....FFRDCs may offer a powerful approach to enable NASA to better align its workforce skillsets with Agency priorities, while simultaneously engendering an entrepreneurial spirit that better allows NASA to infuse talent from industry and commercial partners.” These ideas from the past are now seemingly

⁴¹ “A Journey to Inspire, Innovate and Discover” P. 25, July 2004, P. 25

https://www.nasa.gov/wp-content/uploads/2015/01/60736main_M2M_report_small.pdf

⁴² S. Kuthunur “What a 2nd Trump Administration could mean for NASA Space Exploration” Space.com, Nov. 11, 2024,

<https://www.space.com/space-exploration/what-a-2nd-trump-term-could-mean-for-nasa-and-space-exploration>

being reconsidered in ways to cut NASA costs and improve cost-effectiveness.⁴³

The new Trump Administration, in its most recent actions in early May, 2025, is clearly focused on the slow progress and very high costs of the Artemis Program. The proposed budget for NASA for 2026 would cut costs by 24%.

The Trump White House clearly wants to reduce the costs of the Artemis Program and shut down elements of the lunar exploration program by astronauts after the planned Artemis III landing. However, this budget clearly targets space science research as well. There are major concerns with the high costs of the Space Launch System and the Orion capsule. The newly released NASA budget for the next fiscal year from the U.S. Management and Budget Office, if adopted, would essentially serve to ground the Artemis Program in its current form after the planned Artemis III Moon landing in 2026. This would also involve stopping the production of the super expensive \$4 billion Space Launch System and transferring from the SLS rocket to the use of commercial vehicles such as the SpaceX Starship. As this book goes to press, no final budget has been approved by Congress, and the future direction of NASA research and the Artemis Program, in particular, is in serious doubt. This lack of direction also extends to the deployment of the lunar Gateway space station, which was designed as a key element of the Artemis Program and the so-called “Moon-Mars” space exploration program.⁴⁴

⁴³ Jeff Foust, “NASA to Study Converting Centers to FFRDCs”, *SpaceNews*, June 21, 2018, <https://spacenews.com/nasa-to-study-converting-centers-into-ffrdcs/>)

⁴⁴ Mike Wall, “Reshaping our return to Moon; Trump’s 2026 budget gives Artemis a major facelift”, *Space.com*, <https://www.space.com/space-exploration/reshaping-our-return-to-the-moon-trumps-2026-budget-gives-artemis-a-major-facelift>

It also seems likely that there may be further directives to NASA for organizational change. These may well be with regard to possible modifications to the NASA organizational structure. This could include significant changes to the status of its various Centers as suggested in the 2004 Presidential Commission Report and the 2018 OMB Directive. This could mean moving these Centers to a more independent FFRDC status, narrowing the scope of work conducted in-house, and moving more effort now conducted by NASA personnel to the corporate world.⁴⁵

At this time, hearings on the confirmation of a new NASA administrator, Jared Isaacman, have been held. During these hearing Isaacman backed NASA's efforts to send astronauts back to the Moon with the Artemis Mission Program that is now under way. The current proposed budget supported by the Trump Administration includes deep cuts to NASA's space science missions. It is still early to determine exactly the future course that NASA will take and the priorities that will be set for the U.S. space agency going forward.⁴⁶

Currently, the proposed budget to Congress for fiscal year 2025-2026 makes significant cuts in scientific, environmental, and health and medical related fields while bolstering funding for Homeland Security. Unless Congress fiscal allocations shift these priorities there seems little opportunity for major new

⁴⁵S. Kuthunur "What a 2nd Trump Administration could mean for NASA Space Exploration" *Space.com*, Nov. 11, 2024,

<https://www.space.com/space-exploration/what-a-2nd-trump-term-could-mean-for-nasa-and-space-exploration>

⁴⁶ Brooke Edwards, Jared Isaacman backs return to the Moon in Senate confirmation hearings for NASA Administrator, *Florida Today*, April 9, 2025,

<https://www.bing.com/search?q=new+nasa+administrator&qs=SC&pq=new+nasa+administrator&sc=3-21&cvid=40B3E5617D754EA5A306200B72A7A9B1&FORM=QBRE&sp=1&lq=o>

space exploration initiatives by NASA in the nearer term future.⁴⁷

NASA Is Uniquely Its Own Safety Regulator

The oversight of safety, reliability, and risk-reduction of NASA's various missions is largely left to NASA alone. The development of rockets, capsules, space stations, launch sites, mission support operations, radiation standards for astronauts, and more is currently left to NASA's internal oversight and decision-making. This is unique to NASA. Today, the Nuclear Regulatory Commission is charged with protecting public health and safety with regard to nuclear energy. The Federal Aviation Authority provides for the safety of aircraft operations and for certification of aircraft. The Occupational Safety and Health Administration (OSHA) oversees safety and sets standards for workers in factories and workplaces across the U.S. This lack of formal outside review and oversight as well as the lack of competitive process in deciding on the design of space missions and development of space transportation systems has led to several adverse conditions.

First, NASA tends to see its primary role as the development of new systems to support exploration and scientific discovery about outer space. It is not, in examining its four stated goals in its strategic plan, **to create or invent systems with the highest degree of safety**. Its strategic planning process actually does not clearly define its top priorities. Indeed, its strategic plan seems to be a sort of vague statement of goals in a generalized manner that is so broad and sweeping as to cover almost any possible activities it might wish to pursue. It does not, for instance, identify as a key priority space research and implementation projects that are central to saving the human

⁴⁷ Jeff Stein and Jacob Bogage, "Trump takes ax to 2026 budget," *The Washington Post*, May 3, 2025 pp. A-1 and A-6.

race from catastrophic dangers. This would seem worthy of stating in its strategic plan.⁴⁸

The word safety or risk minimization does not appear anywhere in the NASA strategic plan, although Goal 2.3 does use the word “safeguard.” It also almost overlooks its mission in aviation and aerospace R&D, although the word “aviation” makes a single appearance in goal 3.2. There is no mention of education, although goal 4.3 might be presumed to suggest this role.

It might be helpful if those in Congress who provide oversight to NASA ask the organization to define its mission more clearly, and also to ask for a rank ordering of its top fifteen or twenty goals and objectives, and to line these up with their proposed budget for 2025. It is possible that the new Administration might insist on more clarity as to strategic goals and more alignment of such goals to its mission. (See **Fig. 4.1** NASA’S Vision, Mission Statements, and Strategic Goals)

NASA does have a series of expert panels that review its various programs, but these are all appointed by NASA, and they are all advisory in nature, with no real oversight authority. Further, most of these panels include academics or researchers who are dependent on NASA for research contracts or grants. Such a dependent arrangement serves to restrain NASA-appointed review panelists from voicing any strong criticism of NASA programs or safety procedures. As a result, few expressions of serious missteps come from such program reviews. Rather, there are opinions and suggestions about how programs might be improved or strengthened, but not true alterations in program architectures or suggested

⁴⁸ “NASA’s Vision, Mission, and Strategic Goals”, (Accessed Mar 8, 2025) <https://www.nasa.gov/wp-content/uploads/2024/02/strategic-goals-discover-explore-innovate-advance02-24.png>)

cancellations of a design. The lack of any truly technically qualified outside space safety review and annual review of safety by something like the Space Safety Institute is a weakness in oversight largely unique to NASA and other space agencies.

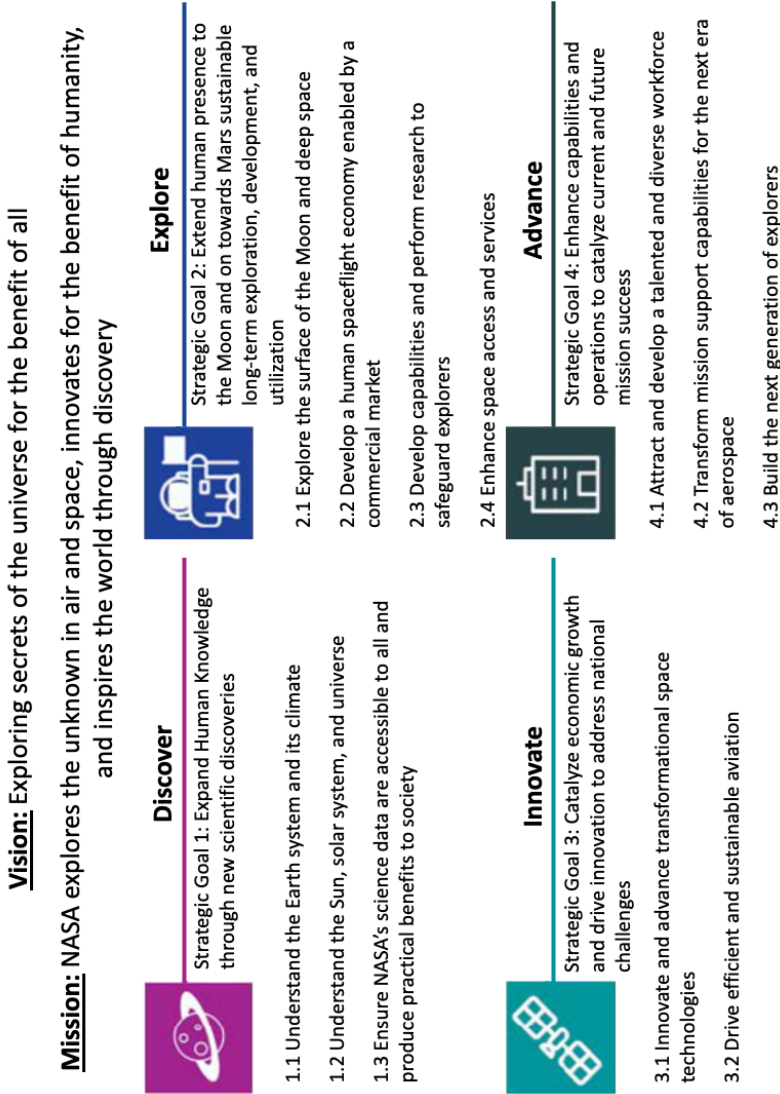


Fig. 4.1: NASA’s Four Strategic Goals
(Source: NASA)

NASA's prime mission is often seen by the general public as being to create new space exploration and scientific discovery systems. Yet, a cynical assessment of NASA's budget would perhaps be seen as maintaining the network formed by its Headquarters, numerous centers, and research facilities staffing, as well as operating the International Space Station and undertaking the Artemis Program. The massive expenditure required for these functions allows minimal opportunities for NASA to undertake other space research and a very small amount of aeronautical research on new aircraft. Big ventures such as the ISS and Artemis dominate NASA expenditures, and its decentralized structure and widely distributed Centers—while an excellent “jobs program” – allows little opportunity for the financial and programmatic efficiency often displayed in “NewSpace” industries such as Blue Origin, Space X, Sierra Nevada/Sierra Space and Northrop Grumman Innovation.

The goals and objectives with regard to space safety and risk reduction are not clearly expressed, and most of the activity seems to address and fix safety concerns and problems rather than design and engineer space systems and transportation that are safer and lower in risk.

This mindset leads to a systems design process that has weaknesses in safety and sometimes also limits true innovation. Design engineers undertake the task of creating the most capable space systems to take a crew, of a specified number of astronauts, to the Moon or Mars. Once designed, as a later step in the process, others are then assigned the task of increasing safety and addressing mission assurance. In short, they are tasked with determining how the approach can be modified or re-engineered to lessen risk. This is not the optimum approach. Rather, safety design engineers with knowledge of dangers, risks, liabilities, and associated trade-offs should be a part of the envisioning process. They should

also contribute to the conceptualization of the design and the safety implications of the design or mission goals as they are first being developed. In other words, safety design engineers should be involved at step one and not step seventeen.

Further, their role should be to question not only initial mission goals but weaknesses in the conceptualization of mission goals and to question premises. If space safety engineers had been involved in formulating the architecture of the Artemis Program, they could well have identified safety and programmatic reasons as to why astronauts being sent to and from the Moon might have been planned on the basis of starting and returning to a location in low Earth orbit rather than starting from the Kennedy Space Center. Likewise, they might have been able to present the advantages of a transport system optimized for three or four astronauts and not eight. The low Earth orbit origin of the mission would have created a transport system that could be performance and safety tested before astronauts ever went on board, allowing escape systems to be much simpler and less demanding in terms of propulsion and size than those associated with the Space Launch System and its abort system. This would not only have been safer, but also have the bonus of being less costly to create.

Integration of Safety Optimization with Systems Engineering and Mission Goal Definition

Essentially, the recommendation is that the NASA Office of Safety and Mission Assurance should, like NASA, be slimmed down and become more geographically and mission-focused. Its most important function would be to provide significant input into the planning and definition of new missions to make them safer and better designed. Safety and mission optimization should be undertaken as an integrated activity. This involves the input of the world's most accomplished and well-trained space safety design engineers. It also involves the

use of artificially intelligent computer programming to undertake modeling and simulation exercises to consider hundreds of different mission architectures that produce dozens of design scenarios as to how future space systems programs might be implemented in an improved and safer manner. The problem with the Artemis Program is that it represents a linear progression from the Apollo Program. It involves a launcher that is simply a bigger version of the Saturn V to be launched from the Kennedy Space Center, with the ability to launch more astronauts to the Moon in a larger capsule. In the course of fifty years, however, a wide range of new system design architecture has been enabled with new technology, new infrastructure, and capabilities on the ground and in space.

Since the Apollo Program there are reusable rocket launchers, including those that can be refueled in space, Earth orbiting space stations, reusable space planes, advanced space navigation, telecommunications and networking satellite systems. There are also artificial intelligence systems with a wide range of applications and advanced robotic systems that have been tested in many on-orbit applications. It is critical that future astronaut mission planning activities utilize all of the important new technological advances.

Key among these advanced planning options would be an in-depth and analytical analysis of possible mission architectures. This process would begin with detailed modeling and simulation, as well as computer analysis. Such an exercise to identify the best possible space mission architecture would allow the creation of at least ten different scenarios for sending astronauts to the Moon that would present significantly different mission architectures than the one now being employed for the Artemis Program. These solutions would be rated first and foremost on the basis of astronaut safety, but also in terms of reliability, resilience, cost, schedule, optimum

use of reusable rockets and overall viability and feasibility. There is little reason to believe that the top ten identified solutions would produce anything like the Space Launch System or the Orion capsule. The primary launcher system would certainly not expend four reusable RS-25 rocket motors that were developed for the Space Shuttle. These reusable and expensive motors are being completely expended with each and every launch of the Space Launch System. This computer simulation and modeling exercise would likewise not produce anything like the oversized Orion capsule with a questionable thermal protection system. The massive size of this capsule leads to the need for an overly large launcher and requires an expensive and high-thrust abort system with many complicated and questionable design features.

The U.S. Human Space Flight Review Committee, or what was often referred to as the Augustine Committee, was empaneled when President Obama took office, but it was asked the wrong question. They were asked to review the Constellation Project, the Ares 1 and Ares V launchers, the Orion capsule, and the current NASA programs and priorities. Instead, they should have been asked to evaluate not only the nature of NASA space programs, especially astronaut exploration programs, but also if they felt these were deficient and to recommend a process to replace or improve the nature of these programs.

To a certain extent, they did this anyway. Their top recommendations in this 2009 Augustine Commission's report, as noted in summary form below, were analyzed and reviewed again in 2020 during the first Administration. Their various recommendations were summarized as follows:⁴⁹

⁴⁹ *Review of U.S. Human Space Flight Plans Committee; Augustine; Austin; Chyba; Kennel; Bejmuk; Crawley; Lyles; Chiao; Greason; and Rid, "Seeking A Human Spaceflight Program Worthy of a Great Nation", Final Report to NASA, April 2020.*

- Complete the International Space Station
- Safely fly the Space Shuttle but end its operations as soon as year-end 2010.
- Develop and fly the Crew Exploration Vehicle (Orion) no later than 2014 (**Author's Note:** This capsule was initially expected to be ready for flight testing as of 2005, or some 20 years ago. The Orion has still not been fully qualified due to heat shield problems. The 2009 report also suggested that a four-passenger capsule might well be a better solution that should be considered as an alternative to the giant Orion capsule, but this was not a firm recommendation and was essentially not addressed in great detail in further NASA review.)
- Return to the Moon no later than 2020 (**Author's Note:** In recent years, this date has fluctuated between 2024 and 2027)
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

The specific findings by the 2009 Augustine Commission report observed that the Ares launcher was simply too expensive, and the program development objectives were too vague. They also were not enthusiastic about the Orion capsule. The Committee suggested a four-passenger vehicle might be a better choice for several reasons. They did note that there had been so much money invested in this development that it might be hard to backtrack. Since there was at the time strong backing in Congress for the Lockheed Martin designed Orion vehicle and the Augustine Commission report signaled at least lukewarm support to

including this astronaut capsule design, that had been advanced by NASA as a crew transport vehicle that could carry astronauts to the Moon and ultimately on to Mars its subsequent inclusion in the Space Launch System launcher design as the astronaut capsule was included in NASA's response to the Augustine Commission's findings that led to the end of the Ares launch vehicle design.⁵⁰

The Augustine Committee was right on both points about the ARES launcher and the Orion capsule, but unfortunately, the NASA response was to replace the Ares launcher with the Space Launch System and to keep the Orion capsule. If anything, it was an even worse solution. The SLS launcher and the Orion are oversized for the Artemis missions. This gives rise to questions about cost, over-complex design issues, and serious safety concerns. These issues will be set forth in greater detail in later chapters, but the takeaways are the following: (a) do not design launcher and capsule systems that are over large and complex for immediate programmatic needs; (b) do not design advanced launcher and capsule systems for service over periods that last twenty to thirty years because of technological obsolescence.; and (c) NASA can often perform the best through the development of "performance specifications" rather than developing "technical specifications."

There are many technical and even safety and resilience issues that come from NASA developing detailed "technical specifications" for astronaut exploration vehicles, especially if this involves launch systems and capsules for future

⁵⁰ Amy Klamper, "U.S. Human Space Flight Plans Review Committee, Norm Augustine", *Space News*, August 24, 2009, <https://spacenews.com/norman-augustine-chairman-review-us-human-space-flight-plans-committee/>

mission needs. Experience with commercial service operators of space application satellites and with NASA missions have shown this to be true. Don't develop systems for the long term because of the rapid state of innovation that is now possible in the aerospace field. Thus, the focus should be on specifications for near-term performance requirements. NASA has seen improved results with commercial transport of astronauts and cargo to and from the ISS using "performance specifications." Today, this "performance specifications" approach has even been employed in the specification process with space suit design. Thus, in terms of timetable, cost, simplicity of design, safety, and risk minimization, NASA can have an advantage by developing "performance specifications" and allowing commercial aerospace companies to develop competitive designs for selection by NASA evaluation teams.

Enhanced Use of AI and Increased Processing Power in Systems Design and Risk-Related Analytics

At the mission definition stage, AI, simulation, and modeling tools should be employed to examine the various goals to be pursued. This would consider the collective needs over the time of the mission. This would assess the needed personnel, life support systems, robotic and automated systems and test facilities, transportation capabilities, habitat/storage/logistics/supply capabilities, duration of mission, support infrastructure in terms of telecommunications, navigation, search and rescue systems, energy/ electrical systems/computing, lighting and heating/cooling, medical plus the health/exercise equipment, etc. This assessment of perhaps thousands of component needs and millions of options would use system simulations and modeling to identify the top ten alternative approaches. This effort might well end up with unexpected answers. This might produce an "optimized mission profile

that involved perhaps two or three astronauts, plus a fully capable humanoid robot, a number of other robotic scientific, measurement, testing, and measurement capabilities, including a down-sized version of the VIPER rover automated mining system—optimized for a suitable landing craft. Such a mission requirement might involve launcher and capsule transportation systems that are significantly reduced in size and cost, able to accomplish 50% more of the mission, and have a projected safety rating that is significantly higher than that associated with the current Artemis mission profile. Also, the mining and analysis part of this system might be a modularized unit that could be attached to an all-purpose mobile platform. This carrier platform with a crane system could be used for multiple tasks. (See Chapter 8).

Any truly objective and critical analysis would certainly show that a launcher, a capsule and a human landing system that is designed to support the launch of eight astronauts was significantly more expensive, and certainly a higher risk profile than that defined for the current program which anticipates a maximum of four astronauts for any mission. It is at this early stage that the most intensive assessment of so-called “requirements” should be examined.

Once mission requirements were optimized and performance specifications were developed, contractors would be solicited to develop their own competitive and detailed technical design proposals for evaluation. Again, there is a strong role for AI capabilities and computer-based qualitative and quantitative assessments. This would allow the evaluation teams, for technical systems design, cost and management planning, and safety, risk minimization, and resilience, to probe much more deeply into the contractor proposals. This process of AI-augmented assessment would involve a much greater number of considerations to be

included and rated in the evaluation and decision process. It is also important to note that this AI assistance would only be used to help NASA engineers and scientists focus on the design strengths and weaknesses. Through this process, they can more easily target design, engineering, and safety strengths and flaws.

When NASA undertakes a “performance specification” process for a new mission, the intense evaluation of contractor proposals becomes of utmost importance. The use of AI and specially designed algorithms as key analytical tools can assist NASA’s evaluation team and particularly aid in the identification of safety concerns. If this AI support capability had been in place, and if safety and risk reduction had been established as an independent and free-standing evaluation standard, separate from the two established for cost and management on hand and technology on the other, this might have made a big difference. It might have led to alternative decisions on the design and engineering for the Space Launch System, the Orion capsule, the Human Landing System, and the lunar Gateway station.

In short, NASA needs to use strengthened capabilities with regard to AI-assisted modeling and simulations. Such capability will be increasingly important in undertaking procurement processes and expert evaluation of contractor proposals. This is especially true in the case when performance specifications are to be used. Such expert tools can provide key assistance both in the development of performance specifications in the first instance and again in the assessment and evaluation of the commercial designs submitted.

Enhanced Integrated Systems Risk Analysis (STAMP and STSP)

The test launch of the Boeing CST-100 Starliner capsule on December 20, 2022, which failed and almost crashed due to software failure, is one of the key examples of how faulty software can lead to a catastrophic failure of a space mission. In this case, a number of software routines had been successfully developed and tested, but the entire end-to-end software system had not been tested on a complete sequence basis, either by Boeing or NASA. In this test, the software commands and instructions were out of sequence. As a result, there could have been a firing of thrusters at the wrong time that could have damaged the International Space Station or the capsule or both. Only emergency development of a new software patch allowed the Starliner to return safely to Earth. After this failed test, an internal review team (IRT) with both NASA and Boeing members found a total of 61 programming errors, some of which were considered of major importance.⁵¹

For some time, researchers in safety engineering have understood that for both mechanical systems and software programming, various component parts of a complicated system, whether this is hardware or software, may all seem to work well. However, overall systems testing of all the parts of subroutines in the right sequence is also important. There is a need to test all the component parts of a mechanical device or computer program to make sure the complete system functions flawlessly. In short, systems engineering and performance testing require fully integrated systems testing to make sure that the component parts link together without malfunctioning and are properly sequenced. Mechanical systems must mesh together safely and reliably, and software

⁵¹ Joseph N. Pelton with Peter Marshall, *Safety First, A review of NASA Spacecraft for Astronaut Missions*, 2nd edition (2024) PMA, Washington, D.C. pp 257-263

systems must link together with exactly the right sequencing, timing, and feedback of corrective verifications that are a part of error correction systems. All of these parts of the whole are key to digital processing systems and their proper functioning.

This form of integrated systems risk analysis has now matured into well-proven systems. Two of the most well-known of these systems are STAMP and STPA. Professor Nancy Leveson of MIT was among the first to champion the idea of testing the performance of entire systems to determine the ability to perform correctly and reliably as an integrated whole. She demonstrated that techniques such as process hazard analysis (PHA), Failure Modes and Effects (FMEA), Hazard and Operability (HAZOP) analysis, and Layers of Protection Analysis (LOPA) all had a common weakness. Each of the PHA assessments tended to divide complex systems into component parts to understand possible faults or hazards, rather than assessing the combined functionality of the overall system or software program as a whole. This led to the development of Systems-Theoretic Accident Mode and Processes (STAMP). The key strength of this type of STAMP analysis was that it provided a means to assess the overall functionality and correct sequencing of software programs as a whole. This methodology can also be applied to physical components of a complex system, as well as to see if the sub-systems, or sub-routines, work correctly, but also to see if the overall integrated system also works correctly and well as a unified whole.⁵²

Subsequent to the development of the STAMP methodology, a further extension of this comprehensive fault analysis was called System-Theoretic Process Analysis (STPA). This hazard

⁵² (“Applying System-Theoretic Accident Model and Processes (STAMP) to Hazard Analysis” (Last access Feb 12, 2025)

<https://macsphere.mcmaster.ca/bitstream/11375/11867/1/fulltext.pdf>

analysis combined the ability to detect hazardous design components and proper sequencing and synchronization flaws that could create systems breakdown.⁵³

The main takeaway in this regard is that as space transportation vehicles and other mechanisms for space stations, life support, and deep space operations become more sophisticated and complex, fault detection may also become much more difficult.

Potential hazard analysis must examine not only the subsystem design and possible failure modes, but also the integrated whole. This problem and issue are compounded as complexity is added. Likewise, fault detection capabilities must be designed to become more adept at ruling out faults and identifying corrective actions.

The experience from “NewSpace” industries to seek to find new solutions that avoid over complexity and overly multi-purpose systems can be one of the key ways forward to success.

Lessons Learned from Past Space Mission Program Experience and the “NewSpace” Industry

There are important lessons to be learned from difficulties experienced in NASA’s major programs, such as Apollo, the Space Shuttle, the International Space Station, and most recently with the Artemis Program. These new approaches can often lead to innovation and new efficiencies. This can lead to new modeling and simulation analytics and programing practices and systems testing and fault identification to build on for the future. There are also lessons to be learned from “New Space” Industry that come

⁵³ “STPA: A Systems Approach to Process Hazard Analysis”, Arrow Technical Analysis, (Last accessed Feb 12, 2025) <https://www.gate.energy/the-brainery/stpa>

from simplification, modernization, uniformity of automatic production, vertical integration, and other innovations in hiring, compensation, and labor management. These key innovations are discussed later in this chapter.

Experience and Possible Reforms for NASA Derived from Past Programs

NASA was a brand-new organization when John Kennedy took office as President in January 1961 and he charged NASA to create launchers that could safely take astronauts into orbit and then to deep space to walk on the Moon. In a remarkably short time, NASA evolved from the Mercury Program to the Gemini Program, and then to the Apollo Program. In order to accomplish this task to take astronauts to the Moon and safely return them to Earth, huge new appropriations of money were given to NASA and a sprawling network of NASA Centers grew up from the original Center in Ohio. The Apollo Program in particular led to massive expenditure of funds, the expansion of NASA Centers and their staff, and the growth of large aerospace corporations with large facilities and staffs often near these Centers. The NASA of the mid 1970s was in many ways oversized for the post-Apollo program. The Nixon White House and the U.S. Office of Management and Budget cancelled the last few Apollo launches after the Apollo 17 launch in 1972 and sought to focus NASA's mission on the Space Shuttle which they also scaled down in size.

The NASA 1958 Act that was hurriedly enacted in response to the USSR's Sputnik launch. During the 1960s, NASA Budget increased by a factor of 35 times. In terms of real year appropriation dollars, between 1958 and 1969 NASA appropriations soared from its budget of \$88million (or \$940 million in current valuation) to a 1969 budget of

\$4.251 Billion (or \$35.320 Billion in current valuation). At its maximum rate of appropriations in terms of its impact as a percentage of the U.S. governmental budget, this represented in 1966 some 4.4% of the entire Federal Budget.⁵⁴

Over time NASA has consistently contracted out a good percentage of its budget to contractors or to NASA Act Agreement partners under Next Steps procurement methods. Over the last few years NASA's appropriations have been relatively flat at between \$21 billion and \$24 billion and this means that a growing percentage goes to support a relatively stable NASA employment base. In order to keep its quite expensive Artemis Program funded, it has had to string out its payments to contractors and make its schedule for Artemis launches extend further out in time.

The bottom line is that NASA has never quite recovered from the swelling of staff and facilities that exploded during the Apollo Program years. Closing down of the Shuttle Program and its massive staff needed to repair the thermal protection system after each Shuttle flight provided some fiscal relief, as did the completion of the ISS construction. Only actions such as moving a number of NASA Centers to a FFRDC status and off the NASA payroll would allow a "right sizing" of NASA and free up the needed resources to complete the Artemis Program and complete its other missions. The details of this possible change by NASA in the Artemis Program were discussed earlier.

The current tightness of NASA funds was most recently shown by the July 2024 decision to halt the VIPER robotic vehicle, which was considered to be a key part of the Artemis Program until this unexpected action was taken. This key

⁵⁴ Ozgur Nevres, *"Budget of NASA, Year by Year (1958-2024)"*
<https://ourplnt.com/budget-of-nasa-year-by-year/>)

programmatic cut was apparently taken to cope with its major cost overruns. Congressional appropriations for the next fiscal year might allow the VIPER to be restored to the Artemis program.⁵⁵

The lesson here is that NASA needs to be restructured to lessen its overheads, centralize its operations to be much more vertically integrated, and to not be dominated by massive programs with costs in the range of \$100 billion plus. Also cancelling obsolete systems such as SLS and the Orion capsule for more modern and less expensive and reusable rocket launchers and capsules would provide additional budgetary leeway.

Another change would be to spin off the aeronautical R&D in advanced aviation to the FAA. NASA is clearly a Space Agency and its lack of clear and effective focus on aviation advances would be better served if this function were transferred and the FAA is the most likely candidate to assume this role.

Lessons from the “NewSpace” Industry

There has been a wide range of innovations, new cost-efficiencies, and breakthroughs in technological design and innovation from the so-called “NewSpace” aerospace companies. One of the biggest innovations has been the new approach to the exacting manufacture of rocket motors that can be re-used multiple times. This type of innovation from these “NewSpace” companies offered not only cost reduction and efficiency but also contributed to greater safety, risk reduction, and resilience. The divergence between the “NewSpace” industry capabilities and

⁵⁵ Ashim “NASA Cancels VIPER Moon Rover Mission” Space & Telescope, July 18, 2024 https://spaceandtelescope.com/nasa-cancels-viper-moon-rover-mission-due-to-budget-concerns/#google_vignette

traditional U.S. aerospace companies became apparent to the U.S. Congressional oversight committees that held hearings as to why the models used by NASA to predict costs were so far off target. These studies found that costs in the more established aerospace companies that were developing new rocket systems or capsules were much higher than the costs of those from developments by SpaceX, Blue Origin, Sierra Nevada, and Orbital Sciences (now Northrop Grumman Innovation). There were questions as to why the costing models could be off by a factor of two, three, or even four times.⁵⁶

The answers as to why “New Space” companies seem to be more cost-effective and produce new space systems at lower prices came from a wide range of answers.

These efficiencies included aspects common to the computer industry in Silicon Valley:

- a. Vertical integration to produce as many elements as possible in-house and with the highest possible quality. (This removed supply chain issues and the costs associated with subcontractors’ profits and overheads, as well as eliminated shipping costs and the risk of damage during shipment.)
- b. Developing parts and subsystems needed to meet exacting specifications for optimum performance and compatibility with the overall design.
- c. A different approach to staffing, recruitment, performance, and compensation. There was an approach to seeking the best and brightest who were committed to the mission and willing to work long hours with modest pay compensation, but with their reward coming from

⁵⁶ Michael Smart, “Old vs. New: The next generation of the space industry” *The Conversation*, Sept. 25, 2016, <https://theconversation.com/old-vs-new-the-next-generation-of-the-space-industry-64793>

stock options and the gains in value of the corporation's stock. (The young, dedicated staff members that were able to be managed through computer links and associative management techniques - sometimes described as "disintermediation" - allowed these companies to avoid being staffed with highly compensated management systems with large offices and excessive overhead costs.)

- d. A strong focus on developing key new products that were the corporation's prime mission and not burdened with large building complexes, research labs, unneeded test facilities, or a large management overhead, and
- e. Perhaps the prime mover has been the constant pursuit of breakthrough advances in technology, design, and performance equivalent to a "Moore's Law" type of progress. These firms have possessed a driving mentality to seek exponential advances. Instead of 5% improvements every year or two, the objective has been 50% to 100% gains and true breakthrough advances. Examples of such advances include such results as: (i) reusable rockets boosters with precise landing capability; (ii) seeking of 100% precision in state-of-the-art manufacturing systems; (iii) progressing through the use of an increasing number of clustered-rocket motors of proven reliability rather than seeking to always develop a new rocket motor and launcher for different missions; (iv) vertical integration; (v) innovative employee, compensation, and administrative practices.

In short, these firms have thrown away the conventional practices of long-established aerospace companies, born of the post WWII era and the so-called military-industrial complex. Instead, they pattern themselves after the new corporate practices developed in Silicon Valley. Jeff Bezos, who pioneered Amazon and Blue Origin, is known for such sayings as: "The great thing about fact-based decisions is

that they overrule the hierarchy.” And “Frugality drives innovation.”

⁵⁷There is no doubt that “NewSpace” companies have revolutionized the aerospace industry and greatly impacted how NASA uses their talents. SpaceX is providing a significant number of its Falcon Heavy launchers in support of the Artemis Program. NASA is also using Dragon Capsules and Falcon Heavy launchers in support of the Gateway lunar space station, starting with the combined launch of the Power and Propulsion Element and the HALO habit unit. The Lunar Gateway Space Station is to be launched by just one highly cost-efficient Falcon Heavy launcher. At a launch cost of about \$400 million, this is some ten times less costly than one Space Launch System launch.

A modified SpaceX Starship is the basis for the Human Landing System that will carry astronauts on Artemis III. This is to be the first astronaut landing on the Moon in over half a century. Blue Origin is leading a team of “established” aerospace companies to create the other version of the Artemis “Human Landing System” and Blue Origin’s Space Reef design was selected to be one of three contenders for the NASA backed private space station for low Earth orbit for the future when the ISS is retired. Sierra Space is involved in designing the HALO space habitat unit, and Sierra Nevada’s Dreamchaser is key to NASA’s planning for resupply of the ISS, along with capabilities provided by SpaceX and Northrop Grumman Innovation’s capsule. But the question remains? Have these lower-cost and more innovative technologies and reusable spacecraft that these

⁵⁷ Joshua Smith, “172 Powerful Jeff Bezos Quotes on Innovation and Leadership” *Executive Resources*, May 19, 2021

<http://executiveresources.com/jeff-bezos-quotes/>

“NewSpace” companies have pioneered also led to increased space safety?

Certainly, SpaceX Falcon launchers and Dragon Capsules have had enormous reliability, and they have confirmed the safe functionality of both Falcon launchers and Dragon capsules, plus the safety of their reuse after refurbishment. Blue Origin’s reusable BE-4 is being used for both the Vulcan Launcher (2 BE-4 engines) and the New Glenn (7 BE-4 engines). Their reliability was demonstrated in the first Vulcan Launch, although the lunar lander itself failed. The importance of reusable launchers and capsules is going to be increasingly demonstrated in the coming years. This is a capability born of the “New Space” industries.

In the arena of space habitats, Orbital Science (now Northrop Grumman Innovation), Sierra Space, and SpaceX are leading providers of this technology today. Only Thales-Alenia from the conventional aerospace industry is a leading contender in the space habitat field, and it is not really a “conventional” aerospace company. It has proven its finesse to bring innovation into play over the last two decades as well. Today, Axiom Space, another new innovator, is not only developing a new private space station and providing private space adventure flights, but has also developed new Axiom space suits. These commercially developed space suits are for use in the Artemis Program as well as to support its private space station operations. The Axiom private space station is being designed and deployed with perhaps about 40% to 50% of the support being provided by NASA as an anchor tenant, but the other revenues are planned to be provided by paying customers.

The safety record and source of safety innovations is still in process for so-called “NewSpace” companies, but to date the record has been remarkably good.

In contrast, the problems with the Boeing developed Starliner capsule and the Lockheed Martin developed Orion have continued for over a decade. There have been problems in terms of being over budget, behind schedule and subject to testing problems and safety issues.

One of the key fallacies of the past that has been exposed by the “NewSpace” industries is that the expenditure of more time and money by NASA to design and build new space transportation systems and life-sustaining technology for astronaut exploration increases safety. The past use of cost-plus fee contracts has been demonstrated to be in some ways counterproductive. This type of contract, which represents the traditional DOD development model, has been awarded to conventional aerospace contractors by both DOD and NASA for decades.

This contracting approach, which is often based on technical specifications, has actually created incentives to build systems more slowly and add alterations that increase complexity, but do not necessarily achieve better or safer performance. The new model that NASA has followed in the past decade, under the “Next Steps approach, has sought to create partnerships with “NewSpace” companies under NASA Space Act Agreements. Conventional aerospace companies are now adjusting to follow suit. These Space Act Agreements are usually based on fixed cost arrangements. This approach can produce better results. Under these partnership arrangements, NASA and the contractors, together, have strong incentives to create the best product as soon as possible, with the highest degree of resilience, lowest risk, and greatest safety.

Under this arrangement, contractor partners are sharing costs to achieve the development, but with the hope and expectation of selling future services if the launcher,

capsule, or other product is safe, resilient, and works smoothly and effectively. Further, the fixed cost contract and the shared cost arrangement gives incentive to do the job well, quickly, and also fully achieves the performance specifications in order to be fully paid. It also creates incentives to work faster and produce better products that are safer and lower in risk. Under partnership agreements to develop new launchers, capsules, and even space suits, these arrangements to date have generally worked well in partnership with SpaceX, Blue Origin, Sierra Nevada, and now a growing number of smaller “NewSpace” companies, which are participants in the Commercial Lunar Payload Services program.⁵⁸

Improved safety does not depend on price, timetable and contractual schedules, but rather on incentives to produce a safe and serviceable product.

Conclusions

NASA’s efforts under the Constellation Program morphed into the Artemis Program and then led to the Space Launch System rocket launchers and the Orion capsule. These key elements of the Artemis program, unfortunately, provide good examples of NASA program developments that have involved serious cost overruns, major schedule delays, and contractual arrangements with the wrong incentives and provisions to produce the results NASA needed to succeed. These past decisions by NASA in the 2010s produced problems of cost overruns, schedule delays, and specification of potentially obsolete technology. In the case of SLS and Orion, the specifications were developed for vehicles that could go to both the Moon and then to Mars,

⁵⁸ (NASA Use of Space Act Agreements. <https://oig.nasa.gov/wp-content/uploads/2024/02/IG-14-020.pdf> (Last accessed Mar 14, 2025))

but this launcher and capsule have proved to be very cost-inefficient, and there are even concerns about the safety of the Orion capsule.

There seem to be benefits from using the best and brightest ideas from “NewSpace” industries. These include new contractual arrangements, improved management techniques, and effective use of performance specifications. We are seeing advantages from not using technical specifications. Instead, there seems to be an advantage from the use of performance specifications and operating under partnership arrangements with contractors. This has allowed NASA to move forward to recover from difficulties and contracting arrangements made over a decade ago. The hope is that these changes create new partnership opportunities, fixed cost contracts, and improvements that encourage new systems that are safer, reusable, lower in risk, more resilient, and allow for longer-term partnership arrangements between NASA and innovative contractors.

There are many lessons to be learned by NASA from the various issues discussed in this chapter about NASA’s approach to systems engineering, expanded use of performance specifications, improved systems risk assessment processes, and expanded use of the talents of “NewSpace” industries. There is also evidence that conventional aerospace companies are learning from these new circumstances as well. They are finding ways to use these innovations to compete for NASA contracts in these areas in the future. In some cases, they are already effectively partnering with the “New Space” industry. This could lead to a “win-win” result for all concerned.

Chapter 5

Promising New Systems to Support Astronaut Safety, Health, Exercise, and Medication

Introduction

Humans have been flying in space for almost 65 years. During this time, a great deal of knowledge has been accumulated about how to sustain human life in space and to keep astronauts safe and healthy. Key lessons have been learned. If we can learn how to sustain humans in space and do so for many life cycles, this can have significant consequences. This is no easy task. There are a host of concerns that include the need to provide astronauts through resupply a significant amount of food and water. The longer-term goal would be self-sufficiency and effective farming in space. Astronauts in space in a weightless or low-g environment actually require more calorie intake than on Earth in normal gravitational conditions. Diets and vitamin intake must also be increased to cope with such aspects as bone loss, reshaping of the skull that could risk adverse pressure on the optical nerve and possible blindness, and a number of other health issues.

The functioning of the cardiovascular system in the human body is greatly different in the microgravity environment

experienced in outer space. The amount of blood supplied to the brain, the body, and the extremities of the body of an astronaut in space is significantly different from what is the case on Earth with a one-g gravitational force. The effects of this altered blood flow on the heart, the brain, and other parts of the body by the cardio-vascular system in a weightless condition are a health issue of ongoing study that still requires significant further research and development. Medication levels needed for astronauts in space typically requires a doubling of the dosage. Likewise, astronauts are also asked to double the time of their exercise to help maintain muscle tone. There is also clearly elevated concern with regard to radiation exposure and related protective measures. These elevated radiation exposure levels are particularly of concern for women of childbearing age.

The ability to grow food in space through either aeroponics or hydroponics is of significance, not only because it assists with resupply but also because such food sourcing has been demonstrated to provide greater health value. Despite the significant amount of psycho-physical research now completed on the well-being and sustenance of astronaut health in space, there is much more to do. We need to know much more about the future possibility of achieving increased levels of medical and dental care in orbit, especially for deep space conditions. In short, much more research needs to be done, especially if the prospect for the future envisions extended trips into deep space, such as trips to and from Mars and long-term living by astronauts on the Moon and Mars. This chapter seeks to explore the future of health care and life support systems in space for humans.

This examination of the research and development agenda to lower risks to astronauts and improve their health has now been intensively studied for many decades. The physiological and psychological research agenda for increased and improved

human health in outer space has now been divided into four different areas of investigation.

- i. Medical and health strategies and systems, including needs for vitamins and medication.
- ii. Supply of food and nourishment
- iii. Medical equipment, operating and treatment facilities, protective equipment, and space suit innovations
- iv. Recycling, purification, and advanced concepts in space agriculture (e.g., Aeroponics)

This is not necessarily an exhaustive list, but it is sufficient for this analysis of progress to date. Certainly, there are also other relevant areas of investigation such as recycling of waste (including human waste), alien viruses and non-carbon-based life forms, and radiation sickness in terms of treatment and its prevention. Other parts of this book examine some of these issues elsewhere since these are also issues that can and do impact the design of space habitats and their proper functioning.

The physiological and psychological research agenda for increased and improved human health in outer space

Most of what is known about human health in outer space has come from astronauts and cosmonauts aboard the International Space Station during its nearly 30 years of continuous occupancy. Clearly additional health and safety information has also come from those aboard the Mir and its earlier manned probes, plus the Chinese Tiangong space station and its predecessor units have also provided and is now providing useful data as well.

Very little is known about astronaut health and living concerns in deep space since all data available to date has come from the

Apollo Program. The Artemis Program will provide new information with the astronauts' exploratory missions beginning in 2026 or 2027. Subsequent missions involving Chinese and Russian space explorers and the Chinese International Lunar Research Station are also now planned. This medical research of astronauts in space has covered many areas with regard to maintaining the health of astronauts in outer space, including systems to provide for food and nourishment, water, and medication.

Improved systems to provide for the astronauts' needs for food and nourishment

The conditions of living in space for an astronaut are significantly different from the conditions of living on Earth. The elements of change primarily involve levels of microgravity and near-weightlessness conditions. Yet, it also involves a number of other concerns. There are issues with different sleep cycles and circadian rhythm sleep disorder, as well as concerns about a lack of access to natural lighting, altered atmospheric conditions, and limited access to fresh fruits and other foods. There is a clear need for frequent physical exercise to cope with muscle tone loss, among other conditions.

Medical research for astronauts in space and in microgravity conditions on the ISS, in particular, has revealed many medical and physiological conditions that are quite different as a result of being in these outer space conditions. It was expected that the cardiovascular system would be different, but perhaps not so dramatically as experience has revealed. Indeed, many other differences also occur. These include physiological effects such as muscle deterioration, bone loss, shrinkage of legs, kidney stones, and changes to its filtration rate. This has increased the likelihood of infection, genetic disorder due to radiation exposure, and enlargement of the heart, as well as

cardiovascular adaptation and redistribution of fluids. In particular, the redistribution of blood from the bottom to the top of the body creates head congestion that can lead to headaches and other concerns. The amount of plasma is reduced by 10% to 15% within the human body, which also impacts the functioning of the heart and lungs. There are also neurological changes and alterations in sensation. This can lead to a sense of isolation and various reactions to living continuously with artificial light, insomnia, and many other medical reactions as described in the referenced article below.⁵⁹

Some of the key findings have been that astronauts need to eat essentially twice the amount of calories while in space to overcome infections and maintain health. They need this additional food intake to cope with other physiological adaptations of the body. Further, as noted above, there is a need to essentially double medicine dosages that are equivalent to a single dose on Earth.

Bone growth is particularly affected. Even with calcium supplements and food diets designed to compensate, there is not only a loss of bone density but also a loss of muscle. One of the most serious is the subtle but important reshaping of the skull. This can lead to serious pressure on the optic nerve that could, if sustained over a long time, even lead to blindness. The increased blood flow to the brain and face heightens this problem.

This is not only a function of weightlessness, but also the lack of lower back pressure, which creates further danger of the

⁵⁹ Ashwini, Wani, Bala Prabhakar, and Pravin Shende, "Strategic Aspects of Space Medicine: A Journey from Conventional to Future Requisites" *Science.org*, June 24, 2024, <https://spj.science.org/doi/10.34133/space.0123>

optical nerve receiving increased pinching, a condition known as spaceflight-associated neuro-ocular syndrome (SANS)⁶⁰.

The issue of microgravity problems and their problems for astronaut health, bone loss, muscle tone, and even potential blindness has provided support for the development of a space station that, through rotation, can provide some degree of artificial gravity. The Vast space corporation has even proposed a configuration of a rotating space station design that could provide microgravity at the central hub and some element of artificial gravity at the extended parts of the platform. This type of design could potentially serve to alleviate some of the adverse health effects of extreme microgravity.

This Vast Space Company's design of modular elements joined together demonstrates a design of modules that could be joined together over time. This could allow the creation of a rotating space station habitat to create artificial gravity. This design is significantly different in its architecture from the planned Axiom Space Station and the competitive designs that Northrop Grumman, Blue Orion, and Nanoracks have proposed to NASA in their space station designs. None of these planned or proposed space stations envision designs that would provide the possibility of both artificial gravity and microgravity conditions within a single integrated space station design. Additional extension modules could increase the effectiveness of the artificial gravity and allow the speed of rotation to be reduced. This type of design, deemed as Haven 2 and shown below, could mitigate the health and fitness issues related to microgravity addressed above. (See **Fig. 5.1**)

⁶⁰ K. Patricia Bouweraerts, *Spaceflight*, July 7, 2022 "In Spaceflight, Lengthier Lower Body Negative Pressure
<https://www.opthalmologyadvisor.com/news/lengthier-countermeasures-needed-to-prevent-ode-in-spaceflight/>

Despite the various negative medical issues and concerns discussed above, the special microgravity experienced in outer space can have benefits. One of these is that microgravity can help grow and create almost perfect crystalline medicines that might help bring new healing capabilities, and this is particularly true of crystalline proteins. This is perhaps the most promising area for microgravity-based medicine research. This capability to grow such crystalline protein medications is now being seriously undertaken. This is just one of several space-based industries that will be particularly explored in planned private commercial space stations in the next few years. This is a current top effort.



Fig. 5.1: The VAST space platform design that could provide artificial gravity for astronauts in space (Graphic courtesy of the VAST space corporation)

That has been described by researchers as a beneficial aspect of crystalline structures growing in a microgravity environment, which tend to grow in a more perfect manner

and thus can and do grow to a much larger size. This has been described in the following manner.⁶¹

Proteins are involved in every aspect of our lives, including as essential components of our immune system and as parts of viruses that can make us sick. When we take a medication, it tends to bind to a specific protein in the body. This process typically changes the protein's function. Some years ago, astronaut scientists and medical researchers discovered that protein crystals grown in space were more uniform and perfectly formed. One of the results is that they tend to be larger than those grown in Earth's gravity."

Since then, drug companies and academic researchers have conducted hundreds of protein crystal growth (PCG) experiments. Indeed, these medication-related PCG experiments represent the largest single category of experiments conducted on the ISS. The importance of PCG medication has been increasingly described as a sort of a key that unlocks almost natural cures and with little or no adverse results to a patient's health.

"In many diseases, the proteins that can trigger the disease state fit into very specific locations, like a biological keyhole. The protein of a potential drug for treating that disease must be designed to fit that keyhole. A good key and keyhole fit results in a more effective medicine with fewer side effects, but to achieve that fit, scientists need detailed knowledge of the structure of both proteins. One of the best ways to analyze a protein structure is to grow it in crystalline form. Clearly, this is a key area for continued R&D that could

⁶¹ Melissa L. Gaskill, "Creating New and Better with Protein Growth Experiments" NASA Release April 25, 2023
<https://www.nasa.gov/missions/station/iss-research/creating-new-and-better-drugs-with-protein-crystal-growth-experiments/>

benefit astronauts and an expanding space economy, but also many people on Earth.”⁶²

This type of research should be particularly encouraged on board the ISS and the now-planned private space stations. The pharma industries will likely be encouraged to explore these new space-based medicine developments, and there may be the possibility of joint ventures between the private space station operators and the pharma-industries to these ends.⁶³

There are many needs for astronauts in space in terms of foods, water, medicine and vitamins. These are met by resupply missions to the ISS and the Chinese Tiangong space stations that are between 200 and 280 miles (or 320 and 450 km) high in their low Earth orbits. In the case of the Artemis Program to the Moon, resupply is still a costly enterprise, with annual costs of operating the ISS calculated in the billions of dollars. Missions to Mars are, of course, a much greater challenge. When Mars is on the other side of the sun, it can be some 200 million miles (320 km) away. Mars resupply becomes exponentially greater and thus a much, much bigger challenge.

Future Supply of Food and Water to Meet Future Astronaut Needs for Deep Space Exploration

If supplying astronauts in deep space with needed medicine and vitamins represents a challenge for the Artemis Program, then subsequent missions to Mars represent difficulties that are of a larger order of magnitude. When the distances involved with deep space resupply space capsule missions begin to seem overwhelmingly inadequate

⁶² *Ibid*

⁶³ *Creating New and Better Drugs with Protein Crystal Growth Experiments*, Space News, <https://spacenews.com/creating-new-and-better-drugs-with-protein-crystal-growth-experiments/>

economically and operationally, then alternatives must be considered. This means creating systems that are able to create such critical supplies from a localized supply capability, either on the Moon or, more importantly, on Mars. This is not an issue that pertains to the production of medicines and vaccines. The production of food and water represents the alternatives. This means either very expensive, lengthy and difficult resupply missions or finding a way to achieve a way to produce and grow and/or recycle food and water.

In all these cases is key to create the ability to create a localized means to undertake some sort of agricultural or organic growth production of food, water, or medicines. In all cases this likely involve having access to sources of water that are recyclable. This again would be desirable for the Moon but even more essential for Mars because of the vast distances between Earth and Mars.

Conceptually, these requirements suggest that an optimum approach would be to send a variety of systems, materials, and machines, plus smart robots, to create this type of production or farm production capability on the Moon. In the movie “The Martian,” the idea of how this would be done was very simply presented, but in the laboratory, and for real, this is thought to be much, much harder.

Nevertheless, if it is possible to formulate and then create this type of remote organic and water production, then the actual development and deployment of this type of remote infrastructure would be the less difficult part of the task.

This type of remote lunar or Mars-based life-sustaining capacity could likely be created with a minimal number of astronauts sent on such a mission. Only after this lunar infrastructure was in place, including perhaps the

production of rocket fuel, material processing systems, plus the ability to create recycled food and water supplies, would a significant number of astronauts be sent to occupy sustainable habitats.

This development of viable habitat systems involved robotic production and processing systems where food, water, and sustenance were not only available, but human patterns of eating, drinking, breathing, and waste disposal were organically combined with the production cycles in an organically sustainable way. This would not require a 100% recyclability, but it would still be highly effective with an 80% to 90% efficiency rate. Otherwise, the processed frozen water in the Lunar South Pole area would be consumed in a period of only a few years.

This whole system includes the use of human waste as a source of plant fertilizer and water supply, as well as aeroponic systems, and builds on the Environmental Control and Life-Support Systems (ECLSS). These were developed for the ISS and the Lunar Gateway to create even more circular resource-using systems that include the use of carbon dioxide and human solid waste as integral parts of a circular and sustainable life-supporting system. The challenge would be to develop, test, and perfect such a sustainable and circular ecosystem on the Moon so that an even more efficient resource re-utilization system could be employed on the surface of Mars.

The scientific research and bio-engineering needed to accomplish such a sustainable bio system are, of course, enormous. The movie, *The Martian*, suggested such a possible make-shift system to grow crops on Mars. An entertainment science fiction film fantasy is one thing. The actual accomplishment of this in reality is something

entirely different. There is a tremendous set of challenges to find the best way forward.

One clear-cut research agenda is determining whether aeroponic, hydroponic, or even conventional agriculture is the best way forward, or whether it is some combination. Pluses and minuses of different types of agricultural practices in microgravity or simulations of something like farming on Mars have been under study for some time. These include experiments in space on the ISS, the Mir Space Station, and active research now underway on the Chinese Tiangong Space Station. Also, devices such as clinostat (2D and 3D), Rotating Wall Vessels (RWVs), and Random Positioning Machines (RPM) have been used to simulate a lack of gravitational pull inward toward Earth's center.

A broad-based major review of agricultural tests and experimentation has reported that despite significant research on microgravity-based raising of agricultural crops and seed to seed growing, success with crops such as peas, wheat, rape and lettuce are a long way from a fully sustainable system. The reported conclusion was: "...the use of plants as a sustainable bio-regenerative life support system (BLSS) to produce fresh food and O₂, reduce CO₂ level, recycle metabolic waste, and efficient water management for long-duration space exploration missions requires critical gap-filling research." In short, there is a long way to go before this can produce fully practical results on a spaceship going to Mars or to produce appreciable amounts of food and a full-on ability to sustain astronauts at a space habitat on the Red Planet.⁶⁴

⁶⁴ (M. Sathasiva, R. Hasamani, B. Swamy, and R. Kumaran G, "Plant Responses to Real and simulated Microgravity" *Science Direct*, Feb 18, 2021 <https://www.sciencedirect.com/science/article/abs/pii/S2214552420300730>

There have been experiments with growing plants and even vegetables and lettuce on the ISS. Fresh produce grown on the ISS has been demonstrated to be healthier and more nourishing than dehydrated food mixed with water. Experiments on the Chinese Tiangong II vessel have reported that lettuce grew to a greater height and developed a richer green color and responded favorably to lighting and demonstrated phototropism.⁶⁵

There have been many attempts to test conventional dirt-based agriculture, hydroponics (growing in water) and aeroponics (growing with roots exposed to the air) with a variety of experimental systems tested on the International Space Station.

Sierra Space has developed a number of agricultural plant test beds that have tested plant activity and growth on board the ISS. The first of these was the so-called “VEGGIE”. This testbed provided an environment that promotes biological growth of intended species by providing a programmable light source, ventilation with the cabin environment, and a passive means to provide water to plants. This provided an integrated growth environment that allowed on-board growth of selected plants in 2014. This growth platform was designed to support selected species with a light source that was programmable, suitable ventilation, and a watering system.

The Advanced Plant Habit (APH) was installed in 2017 and represents a plant growth chamber with increased capabilities. This plant chamber, also developed by Sierra Space under NASA contract, included some 200 sensors. This provided

⁶⁵ (Y. Shen, S. Guo, P. Zhao, L. Wang, X. Wang, J. Li, and Q. Bian, “Research on Lettuce Growth Technology onboard Chinese Tiangong II Spacelab”. *Acta Astronautica*, Mar 2018, <https://www.sciencedirect.com/science/article/abs/pii/S0094576517307646>

APH with a wide range of controls and also included the ability to acquire and record data concerning plant growth in microgravity. Its capabilities included the ability to control temperature, humidity, oxygen, light quality and quantity, and photoperiod. It also included a filtering system to remove liquid and gaseous contaminants. The growth of red and green chiles in the APH allowed the astronauts to create their own tacos. It was “crops” from the APH that were first consumed by astronauts. This was part of the so-called Plant-Habitat-04 Study.

The XRoots aeroponics test bed facility on the ISS has proven the feasibility of this type of agriculture in space.⁶⁶ (See **Fig. 5.2**)



Fig. 5.2: XROOTS aeroponic test bed facility on board the ISS

(Graphic courtesy of NASA)

⁶⁶ Space Station Payloads, Sierra Space, <https://www.sierraspace.com/space-technology/microgravity-environmental-systems/space-station-payloads/> (last accessed March 13, 2025)

The progress made to develop viable aeroponic crop growing chambers on the ISS and parallel research and development aboard the Tiangong space station represents significant progress. These results are still a long way from a truly integrated and fully functional sustainable bio-regenerative life support system (BLSS). This would be an integrated human and biological plant life and atmospheric interaction system that would be self-sustaining in terms of oxygen and carbon dioxide interactions, and cyclical use of water to the maximum degree possible.

There have been attempts to achieve this type of interactive stasis here on Earth with the notable failure of the Biosphere II experiments in Arizona. In this experiment, the life-protective experimental controls eventually required emergency venting of carbon dioxide gases that were becoming increasingly life-threatening to the biosphere participants. There were other difficulties as well. These included issues related to the adequacy of the water supply, as well as destructive tribalism disputes and antagonisms formed by hostile groups within the experimenters. Clearly, there is a need to create a sustainable bio-regenerative life support system (BLSS) in Earth-based conditions before being able to do this in space.

The Gerard K. O'Neill book *The High Frontier* was an attempt to describe the scale of a giant rotating cylinder to create a sustainable form of artificial gravity, as well as the scope of farming and other essential activities to create a viable space colony. He envisioned the need for resupply missions to support this daring and technologically ambitious activity. The Earth has been a successful and sustainable biosystem for many millions of years, yet large-scale pollution and the generation of greenhouse gases could ultimately threaten its interactive and bio-regenerative capabilities. The challenge of creating a

mutually interactive organic process that provides stasis between humans and other organic vegetation with regard to nutrients, water, carbon dioxide, oxygen, light and darkness, heat and cold, and energy supplies is a difficult balance to achieve and sustain. The Biosphere II experiment failed, and no similar experiments have yet to achieve long-term sustainability. It seems that human industrialization and ecological practice might even challenge the Earth's own biosystem through climate change, altering practice. (See **Fig. 5.3**)



Fig. 5.3: The BioSphere II Experiment Failed Due to Carbon Dioxide Buildup

The development of a “Bio-regenerative Life Support System (BLSS) would be a critical capability for life sustenance on a long-term MARS habitat and would indeed be quite valuable for a Mars space transport vehicle. It would also likewise be useful in a wide variety of applications here on Earth.

Medical equipment, operating and treatment facilities,

It might seem clear that going from astronauts on the ISS in low Earth orbit to exploration and creating habitats on the Moon to serious efforts to go to Mars for extended habitation is an increasingly difficult activity. The challenge is much more than spaceships that are able to make longer-range trips. The biggest challenges are coping with radiation that will be addressed in the next chapter, but also there is a need for increasing self-sufficiency. This ranges from access to doctors and dentists, the ability to create food and recirculate and preserve water, to reuse and repurpose waste materials, and have access to complex equipment and tools. It is possible to send a team of healthy astronauts to the Moon or to Mars for a relatively short stay and then return to Earth. But it is another thing to contemplate long term living in these remote places for the longer term.

It is possible to send small medical instruments along with astronauts, but currently we are not able to send MRI (Magnetic Resonance Imaging) and CT-Scan (Computerized Tomography-Scan) equipment into the compact confines of astronaut spacecraft. Even or it even conventional X-Ray equipment is quite difficult. Nor do we have medical labs that can examine blood, urine, or stool samples or examine biopsy samples that are easily deployed into deep space. In the days of cave men and cave women, there were communities of hunter-gatherers with a roaming existence. Everything that was needed to support their existence could be carried with the migratory group. There was no need for refrigerators, power plants, or even seeds, plows, harvesters or silos. Modern society is very tool and infrastructure dependent. Astronauts have access to electrical lighting, telecommunications, and very complex and expensive toilets, but not sophisticated medical equipment to support astronauts long term stays in space.

Let's start with the challenge of the supply of vitamins and medicines to meet astronaut needs. Currently NASA maintains a pharmacy on board the ISS of about 100 different types of vitamins, medications, and medical supplies. These supplies for the ISS typically have a shelf life of a year, before resupply is needed. For resupply of these to the Moon, the Gateway, or Mars we must consider the added issues of much longer radiation exposure, plus the much greater difficulty of resupply and associated costs.

One possible pathway to the future, especially for the Mars Mission, is to seek a way for astronauts to manufacture vitamins and medicines in space. This would require the development of a process whereby astronauts would be taught to grow and produce "gene-edited" natural organisms that could then produce a range of pharmaceuticals and vitamins. This would require a so-called "library of modified DNA" to be developed that could be sent into space. This specially designed DNA would allow the astronauts to produce, on demand, the needed medications or vitamins. This appropriate DNA "key" or "keys" needed to create pharmaceuticals could, in theory, produce a number of required pharmaceuticals and vitamins. In theory, with aeroponics, this process might well be used to advance the growing of a variety of foods and agricultural products as well.⁶⁷

There are expanding efforts to explore and develop in-space production of stem cells into heart, brain, and blood tissues in support of regenerative medicine uses on Earth, as well as many other medicines as noted above. In April 2022, NASA announced eight different research and development

⁶⁷ Min Read, "NASA Selects Proposals to Enable Manufacturing in Space" NASA Release, April 15, 2025

<https://www.nasa.gov/missions/station/nasa-selects-proposals-to-enable-manufacturing-in-space-for-earth/>

awards to different institutions to develop various initiatives to produce medication in the microgravity environment of the ISS.⁶⁸

This expanding effort is to produce new medications and stem cell therapy- related medications for use on Earth, and the possible future ability to generate a wide range of medications for astronauts use for true deep space missions to Mars. These production capabilities would be based on using specialized “DNA keys” to create a remote pharmacy in space.

Space suit innovations

One of the areas where there is continuing progress is in the area of design and fabrication of space suits. We have come a long way from the designs that were used for the Apollo Space Suits. The space suits being used for the Artemis III astronaut landing are actually being designed, engineered, and fabricated by Axiom Space. These are intended to be used as astronauts on the ISS, the Lunar Gateway, the Moon surface during the Artemis program, and also used by NASA astronauts and space adventure visitors to the Axiom Space private space station. The terms of the NASA Space Act Agreements with Axiom Space are that NASA will, in effect, rent or lease these space suits for astronauts to wear during the Artemis exploration. When NASA decided to go to a commercial developer for its future space suits development, the original plan was to award contracts to two suppliers so that there were alternative suppliers and competitive sources of supply.

⁶⁸ Megan Tatum, “Drugs in Space: The Pharmacy Orbiting the Earth” *The Pharmaceutica Journal*, July 2020, <https://pharmaceutical-journal.com/article/feature/drugs-in-space-the-pharmacy-orbiting-the-earth>

In that process, Axiom Space was chosen, but the alternative commercial supplier of these new xEVA space suits (Extravehicular Vehicular Activity) would be Collins Aerospace. This decision was announced by NASA in June 2022. The plan was for these new commercial space suits to be used on the ISS as well as for the Artemis Program, and that NASA would be able to have alternative suppliers of these space suits that they would “lease” from these vendors. As late as February 2024, Collins Aerospace had reported successful testing on their space suit prototype design in a parabolic microgravity flight for a 20-second test of their new space suit. On June 26, 2024, however, NASA issued a statement that the contract with Collins Aerospace had been “de-scoped” and that the fixed price contract under a NASA Space Act agreement would no longer continue to provide for a space suit. The reasons were not given, but speculation by industry observers indicated that there were significant cost overruns and that Collins had signed a fixed price contract for this space suit development.⁶⁹

As of this date, NASA has not issued another contract for a new alternative supplier. The Axiom Space developed Extravehicular Mobility Unit that is to be used for the Artemis III astronaut Moon landing continues under an exhaustive testing program.

Although Axiom Space has conducted its own testing program, this was only the first step in a safety testing program. NASA has retained the role of testing and certifying the Axiom Space spacesuits, and elaborate and extensive testing is now underway. The tests at Johnson Space Center, pictured below, were designed to test mobility and dexterity to perform various

⁶⁹ (Jeff Foust, “Collins Aerospace Pulls Back from NASA Space Suit Contract”, *Space News*, June 26, 2024

<https://spacenews.com/collins-aerospace-pulls-back-from-nasa-spacesuit-contract/>)

tasks on the Moon. Additional tests have been conducted at NASA's Neutral Buoyancy Laboratory that can simulate a partial gravity environment. The ultimate test will involve testing in outer space. (See **Fig. 5.4**)

The new suit is less rigid and gives astronauts much greater mobility and flexibility of action. Yet, there is clearly some concern that there is only one source of supply and the lack of a backup capability. Currently the SpaceX developed Human Landing System and the Axiom Space ax-EMU space suit together constitute two of the more important critical path elements for the successful achievement of the planned 2026 Artemis III Moon landing.

The space suit will have completed extensive testing, but the Human Landing System will have much less testing and safety compliance testing that the Command Module and Lunar Module had prior to the Apollo 11 touch down.

The success of this design is key not only to the upcoming series of astronaut missions to the Moon under the Artemis Program, but also to support astronaut missions associated with the ISS, and to support the Axiom Space commercial space station that is now planned. The first components are to go up to connect to the ISS as early as 2027. Several additional components are to be added and connected to this new system. When the ISS is deorbited in 2030, the Axiom Space commercial space station will disconnect and become a free flyer. This system will have a space hatch so astronauts can access space for extra-vehicular activities. After the multi-ton ISS system is de-orbited, NASA astronauts undertaking research in low Earth orbit can access the Axiom Space facility under the Space Act Agreement terms agreed with NASA.



***Fig. 5.4; The Axiom Space developed axEMU Space Suit under Testing at the Johnson Space Center
(Image courtesy of NASA)***

Conclusions

Challenges of space exploration remain significant despite years of orbital operations by astronauts. This chapter has addressed the many health and medical challenges that astronauts face in terms of vitamins and medications, and how these will become more difficult as astronauts seek to explore even further into deep space, especially when missions to Mars are undertaken. Next, the difficulties of providing food and water to astronauts were examined.

Microgravity provides a number of health challenges and difficulties. The examination of future spacecraft that might be used for a Mars mission could perhaps even consider a rotating platform that could offer artificial gravity that could mitigate these health issues, such as bone loss, muscle tone and strength, and even such problems as pinching of the optic nerve and threats to vision.

This is not only a matter of providing the necessary supply of water for a variety of purposes, but also food that provides essential nourishment and necessary sustenance for health and vitality. Next addressed were the many medical facilities and equipment that are difficult to provide within the confines of launchers and space capsules that limit the range and quality of health care that can be provided in outer space, and how this complicates the opportunity of truly deep space operations without risking astronaut health and well-being.

The next area addressed was the difficulty of growing agricultural plants in space and the progress that was being made in various techniques that can be employed that range from conventional dirt-based farming with fertilizers, to hydroponics, to the very promising field of aeroponics—all of which have been explored on board the ISS with some success.

The final aspect addressed was the challenge of developing the latest generation of space suits, and the NASA decision to contract out the design and fabrication of the latest systems to the contractor Axiom Space.

Chapter 6

Radiation Protection for Astronauts

Introduction

The number one health and medical concern for astronauts regarding the safety of their living in space involves radiation protection from the Sun. This requires, at a minimum, the creation and enforcement of appropriate radiation exposure standards. In 2021, the National Academy of Sciences, Engineering, and Medicine conducted a major review of human radiation standards for astronauts. This study proposed, in its report in June 2021, that NASA revise its radiation exposure standards for astronauts. It particularly addressed the elevated radiation exposure levels that astronauts will encounter during exploratory missions to the Moon, to Mars, and other deep space locations. The prime conclusion from this study was that NASA should update its radiation exposure standards for a dose limit that would be a universal career-long radiation dose limit of ~600 millisieverts (mSv) that would apply to men and women alike.⁷⁰

⁷⁰ National Academy of Sciences, Engineering, and Medicine, “SPACE RADIATION AND ASTRONAUT HEALTH: MANAGING AND COMMUNICATING CANCER RISKS” June 24, 2021 <https://nap.nationalacademies.org/resource/26155/Space-Radiation-Study-Recommendations-and-Conclusions.pdf>

(Authors' Note. A millisievert (mSv) is defined as the average accumulated background radiation dose to an individual for 1 year, exclusive of radon, in the United States. The National Council on Radiation Protection NCRP now recommends that the annual effective dose to an individual from occupational exposure should not exceed 50 mSv and that the cumulative lifetime effective dose for an individual from occupational exposure should not exceed 10 mSv multiplied by the individual's current age in years).⁷¹

This report noted that NASA's current standard for NASA Astronauts is based on older radiation exposure studies. It thus stated:

"NASA currently uses a 3 percent REID to set the limit. However, the occupational hazards that initially informed the selection of this metric are relatively outdated. Upcoming planned missions into deep space present an important, near-term opportunity for NASA to reassess whether 3 percent REID is the most appropriate metric to use in setting the dose-based space radiation health standard."⁷² (Note: REID stands for "Radiation Exposure Induced Death")

It further indicated that there were a number of reasons to explore this standard as follows:

"Astronauts who travel on long-duration spaceflight missions, such as missions to Mars, are likely to be exposed to radiation levels that significantly exceed the proposed new standard".⁷³

⁷¹ National Academies of Sciences, Engineering, and Medicine. 2021. *Space Radiation and Astronaut Health: Managing and Communicating Cancer Risks*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/26155>

⁷² *Ibid*

⁷³ NASEM, News Release, June 24, 2021, <https://www.nationalacademies.org/news/2021/06/nasa-should-update->

(Authors' Note: NASA's current standard is a 3% Radiation Exposure Induced Death (REID). Unless technological advancements and engineering controls provide improved protection to astronauts for missions into deeper space, NASA would need to seek waivers to the radiation health standard to pursue these future deep space missions. While NASA may need this flexibility to pursue waivers, there is also a need for an explicit and public framework for how the agency will consider both mission and individual waivers.)

So far, NASA has not altered its standards and instead has continued a policy of granting waivers on radiation standards for individual astronauts on an as needed basis. It has also continued to have women of child-bearing age undertaking shorter mission duration stays in space to limit their radiation exposure.

This means that astronauts going to the Moon will be limited in how long they can remain on the Moon and that Mars missions as now envisioned are outside the current limits—and by a sizable margin. As a consequence, either standards will have to be changed to offer lesser protection, or the phrase used above becomes quite key. This phrase was: “Unless technological advancements and engineering controls provide improved protections to astronauts...”

In short, there needs to be focused attention on material research or magnetic diversion technologies to offer astronauts increased radiation protection for deep space missions.

Lead is the best protector against high energy radiation for Earth based radiation exposure, but not necessarily for cosmic radiation. Plus the fact lead is quite heavy.

[astronaut-radiation-exposure-limits-improve-communication-of-cancer-risks](#)

There are so-called Faraday materials that also provide protection. These are typically composed of polyester fiber, copper, and nickel, which have good conductivity and effectiveness in reducing radiation penetration and magnetic and electrical waves. There are other materials involved, such as cotton and silver, that can aid in forming radiation-inhibiting cloaking materials. Research into improved radiation protection materials to help protect astronauts continues to be a key medical and materials research area to develop improved astronaut radiation protection.

The best way forward might well be an interdisciplinary research team that could consider a number of strategies and potentially identify a combination of protective strategies for astronauts.

The various strategies and mission architectures that might be considered include:

- a. Expanded use of robotic systems and capabilities that reduce the number of astronauts needed to carry out a significant amount of work. This might particularly focus on the construction of suitable radiation-protective, human-friendly habitat facilities on the Moon or Mars that could then be available for subsequent astronaut habitation.
- b. Use of magnetic systems for diversion of ionic cosmic radiation to better protect rocket launch systems, and especially astronaut capsules, space stations, habitats for astronaut living quarters, and lunar and Mars rovers. Such possible electro-magnetic protective as protective systems for astronaut while on the Moon, Mars, the lunar Gateway space station.
- c. A variety of improved radiation protective materials for astronauts that could be used in space suits, flight suits,

sleeping quarters, etc., as well as emergency protective facilities on spacecraft or habitats on the surface of the Moon or Mars.

- d. Suspended animation astronaut flight systems of compact size that allow increased protective cladding and/or electromagnetic shielding against radiation dangers.
- e. Dietary vitamins and supplements, and other protective medication practices, to offer some level of protection and physical responsiveness against radiation exposure.

It may well be that some combination of these strategies and mission architecture represents the ideal solution in terms of overall mission safety, efficiency, and cost savings, as well as the highest level of radiation protection. Often, the design of a space mission is a combination of parts that are planned, designed, fabricated, tested, and assembled into an overall system, but in this case, an integrated approach could produce an overall best integrated design. The integrated and interdisciplinary design team might be small in number, and each team member is linked to larger units with expertise in robotics, magnetic field research and development, radiation protective materials, space suit design, suspended animation research, and doctors involved in diet and medication research related to radiation diseases.

Such research teams could help to produce a better overall design for deep space research and exploration. Outcomes from this integrated R&D could improve the overall system architecture for Artemis, the Lunar Gateway Space Station, and future Mars exploration missions.

Astronaut Radiation Safety Standards

One of the key needs for safety with regard to future space exploration activities will be updated safety standards. This will particularly include radiation safety exposure

standards, not only for NASA astronauts, but also for what might be called “citizen astronauts. Up to this point in time, only hundreds of humans have ventured into space, but in the 2020s and 2030s, the number will increase to thousands. More and more people will venture into space above the so-called Von Karman Line, which is considered to be the edge of outer space where airplanes cannot fly. Certainly, there will be increasing opportunities for sub-orbital flights at lower and lower costs. There will be chances to visit private space stations, and perhaps two will be available within the next five years. There may even be a chance for “citizen astronauts” to venture even into deep space above Earth orbit.

These safety risks and appropriate safety standards for radiation exposure may be different for those going on sub-orbital flights, for those visiting space stations in low Earth orbit, for those explorers that may go to the Moon, and, most daunting, for those going the furthest by traveling to Mars and then returning. Such journeys to Mars that will extend over many months and involve travel over millions of miles/kilometers will, of course, pose by far the greatest risks. Suitable health standards and devising the needed protective shielding requirements will be the most challenging of all. One would want to send experienced astronauts on such a long and hazardous journey through deep space, but on the other hand, you would want such space travelers to have the least amount of previous radiation exposure. It is a difficult issue to address and find a good answer.

Risks associated with travel into space, or even very high-altitude flight, involve the threat of cancer of various types, radiation sickness, and also mutation of genes, which would be of particular concern to women of childbearing age.

Currently, NASA radiation risk health standards are set on the basis of lifetime exposure limits. These are thus dependent on age, specifically on age for female astronauts who are of childbearing age. Based on this sliding scale formula and sex, the allowed limit might be as low as 180 mSv for a 30-year-old woman of childbearing age and up to 700 mSv for a 60-year-old man. A mSv stands for milli-Sieverts”

(Note: mSv represents a milli Sievert, which is an international unit of radiation exposure. A Sievert, named after Swedish scientist Rolf Sievert, represents the equivalence of the biological effect that would occur when one joule of gamma ray energy is transmitted into one kilogram of human tissue. A mSV is one thousandth of a Sievert.) A typical human is exposed to a natural radiation level in the range of 2.4 to 2.7 mSv a year, but a similar amount from microwave ranges, viewing of television and computer screens, dentist X-rays, and security checking systems. Thus, the total amount of exposure humans have in modern society is about six mSv per year. A similar term is a “Gray,” which is also a unit of ionizing radiation dose in the International System of Units. It represents the absorption of one joule of radiation energy per kilogram of matter of any type, rather than just human tissue.⁷⁴

The NASA radiation exposure health standard seeks to limit astronauts to being overly-exposed to harmful effects. The maximum level of exposure for an astronaut is based on a 3% REID (or Risk of Exposure Induced Death) with an upper 95% probability of accuracy.}

There is no universally agreed-upon standard for the limits that are most appropriate for radiation exposure for

⁷⁴ “Know your dose”, *University of San Francisco University*, <https://knowyourdose.ucsf.edu/> (Last accessed Mar 17, 2025)

astronauts at this time among the space agencies of the world. The current limit that NASA has at the time of the report is based on a 3% chance of a cancer-related death based on age and previous space missions. Thus, the exposure limits are geared to each astronaut on an individual basis.

As noted earlier, the National Academy of Science, Engineering, and Medicine undertook an in-depth study in 2021 of astronaut radiation exposure and recommended changing the approach that NASA uses. The report's conclusion was that NASA should adopt a single and common standard for all astronauts, regardless of sex and age, and instead allow astronauts to engage in medical counselling to determine in a clear fashion the level of risk that they wish to take on from a personal health viewpoint.

Thus, a female astronaut who is not anticipating having children may well be willing to assume a higher level of radiation exposure up to 600 mSv. A male astronaut may be willing to assume a higher risk level of 5% REID and so on. The National Science, Engineering, and Medicine concept advanced from their study was that a 600 mSv was a reasonable level of risk for an astronaut to take on, in that astronauts already knew they were taking on a high-risk occupation.

For instance, 600 mSvs would be the risk that an 84-year - s-old person would experience in normal life when combining natural radiation on Earth and manmade radiation exposure from dental and other X-rays, security scans, etc. (based on the 6.7 mSvs/ year equivalence for someone living in a U.S. city.) in any event. Astronauts could, with proper medical counselling, individually assess the level of risk and make their own informed decision.

The NASEM study also suggested that there have been more recent studies of radiation exposure and its effects, and that NASA might wish to update its current 3% REID guideline based on the latest medical data. Recent studies suggest that man-made radiation sources now well exceed natural radiation exposures.⁷⁵

Radiation Concerns and the Artemis Program

The Artemis Program is intended to have astronauts staying for longer on the lunar surface than was the case with the Apollo Program. These missions were designed to explore extraction of volatiles and water from the ice frozen in the Moon's craters in its Southern polar regions.

To assist this process, lessen the safety risk of this mining and extraction process, and limit exposure to radiation, one of the key elements was to have been the VIPER mobile robotic system that could largely undertake this extraction and testing process on nearly an autonomous basis. The overruns in the cost of the VIPER robotic rover have led NASA to cancel this key element of the program, unless it is restored by Congressional appropriations for 2025-26.

NASA has developed a number of tools to model and measure the risks of radiation exposure. This has particularly focused on the occurrence of so-called Solar Energetic Particle Events (SPEs) that can come from solar storms.

⁷⁵ "NASA Should Update Astronaut Radiation Exposure Limits, Improve Communication of Cancer Risk", National Academies of Science, Engineering, and Medicine news release, June 24, 2021, <https://www.nationalacademies.org/news/2021/06/nasa-should-update-astronaut-radiation-exposure-limits-improve-communication-of-cancer-risks>

There have been many specific recommendations as to how NASA should address radiation research with regard to astronaut exposure and limitations to its harmful impact. The following list has been developed as a list of promising areas.⁷⁶ (See **Table 6.1**)

There are many sources of radiation dangers from the Sun and cosmic ray space radiation, but one of the greatest concerns is atoms that have been stripped of their electrons. An atom stripped of its electrons does not last long in the Earth's environment, but in outer space, ionic nuclear particles do exist, and these are quite dense and destructive to the human body. An atom with its electrons has a diameter of about 10^{-8} centimeters, but a nucleus, stripped of its electrons has a diameter on the order of 10^{-12} cm or even 10^{-13} cm and is thus at least 10,000 times denser and more destructive than an atom that is not in ionic form. Within the magnetic forces of the sun or other stars, or even experimental accelerators, denser elements can be stripped of their electrons. It is such ionic particles that can cause the most harm to astronauts.⁷⁷

⁷⁶ Dr. Martha Cloudsley, *Protecting Astronauts from Space Radiation on the Lunar Surface* NASA Presentation at Langley Research Center, Feb 9, 2021, [Cloudsley Lunar Radiation Talk v2.pdf](#)

⁷⁷ University of Toronto, "Cosmic Radiation Hazards"

<http://www.ehs.utoronto.ca/services/radiation/radtraining/module1.htm>

• <u>Key Areas of Research on Astronaut Radiation Exposure & Reduction</u> • Improved modeling of human risk • Biological countermeasures • Improved Dosimeters • Space weather forecasting tools for operations – • Improved methods for estimating astronaut risk based on onboard measurements • Improvements to NASA's radiation transport code • Pion transport – Cross section measurements to improve physics mode • Measurements for code validation • Uncertainty modeling and integration of radiation uncertainty with other design uncertainties • Development of wearable protection • Novel storm shelter approaches • Logistics tracking for reconfigurable shielding • Habitats and vehicles designed using the ALARA process • Active Shielding

Table 6.1: Research Areas Related to Astronaut Space Radiation Protection (Source: NASA Presentation cited above)

The terms used to measure radiation threats to humans, such as “grays” and “sieverts,” are consistently used to measure radiation dangers here on Earth. However, in outer space, the nature of the radiation damage is quite different, because ions stripped of their electrons are not found outside of linear accelerators or atomic bomb blasts. In outer space, however, there are also dangerous Galactic Cosmic Rays (GCRs) and solar storms that create Solar Energetic Particle Events (SPEs). This makes deep space a very dangerous place. An atom stripped of its electrons in ionic form is up to a million times denser than a bullet. A solar or any stellar CME event can have quintillions or more “ionic bullets” within a mass ejection.

It is these dangers that astronauts will primarily need to be protected against during trips to the Moon or the Lunar Gateway. And in the case of journeys to Mars, the dangers become much larger because of the duration of the trip to Mars or the trip to return. The type of radiation that comes from television sets, microwave ovens, dentists, or body X-rays can be shielded by lead shielding, but the powerful ions traveling in outer space, known as GCRs and SPEs, need to be addressed in other ways. These speeding nuclei can set off chain reactions in lead shielding, which is dangerous to astronauts. In deep space, the shielding strategy must be different. This is accomplished by creating what are called cosmic “storm shelters” and protective wearable gear.⁷⁸

⁷⁸ Amy Blanchett and Laurie Abadie, “Positive, Negative, or Neutral: It All Matters: NASA Explains Space Radiation”, NASA Article, Sept 21, 2017, <https://www.nasa.gov/humans-in-space/positive-negative-or-neutral-it-all-matters-nasa-explains-space-radiation/>

Level of Radiation Exposure for Astronauts on the Moon

Astronauts have been constrained to working in low Earth Orbit since the end of the Apollo program with the last Apollo 17 mission in 1972. Missions to the International Space Station are a few hundred kilometers above the Earth and below the protective Van Allen belts that serve to shield astronauts from the Sun's solar wind and solar flares. The shielding of the Van Allen belts provides significant protection, but astronauts still encounter greater radiation exposure than someone on Earth's surface with the additional protection of the atmosphere and the ozone layer. Based on significant measurements over time, it is estimated that an astronaut during a six-month stay on the ISS would be exposed to about 72 millisieverts (mSv). This estimate, however, is based on the premise that astronauts would be able to be largely in a habitat that provides a reasonable level of protection.

This amount of radiation exposure would total 144 mSv in a year, or over 50 times the natural radiation exposure that would occur on Earth. This is a significant amount of exposure, but still quite manageable. Under current NASA standards, astronauts could spend several such stays and still be within specified risk levels.

Travel to the lunar surface is a whole new ballgame when it comes to radiation dangers. The radiation levels to be experienced by astronauts in the basecamp location in the South pole area of the Moon are not well understood in terms of solar and other deep space radiation. The landing site for Artemis III was chosen for landing safety and relatively even ground without regard to radiation impact. Further, the great height of the SpaceX Human Landing System likely increases the exposure levels for the

astronaut habitat living quarters during the Artemis III stay on the Moon. This is because the capsule area where the astronauts will likely operate stands well over a hundred feet off the surface of the Moon. This compares with the much lower profile that will apply to the Blue Origin consortium design used for the Human Landing System, which is currently slated to be used in the future, but not before the Artemis V mission.

At this point, there is limited information available about the protective shielding that the Orion Capsule will provide to astronauts. Passive and active measurements of the level of radiation experienced both on the outside and the inside of the Orion capsule were taken during the Artemis 1 flight. More measurements will be taken during the Artemis 2 flight. During the Artemis 1 flight, radiation impact was a key focus. Thus, in addition to the collection of data from radiation dosimeters, there was the specific Matroshka AstroRad Experiment that provided much more finely-tuned data. This activity, which was a collaboration between the German Space Agency DLR and NASA, placed radiation sensors at various locations on two human-like dummies to record detailed measurements.

This Matroshka AstroRad Radiation Experiment involved placing sensitive radiation sensors both outside and inside two life-sized manikin torsos. The idea was to record the adverse impacts of radiation on human tissue through this simulated radiation exposure exercise.⁷⁹ (See **Fig. 6.1**)

⁷⁹ Laura Sorto, “Artemis 1 Radiation Measurements Validate Orion Safety for Astronauts” Oct. 09, 2024, NASA Release, <https://www.nasa.gov/humans-in-space/artemis-i-radiation-measurements-validate-orion-safety-for-astronauts/>

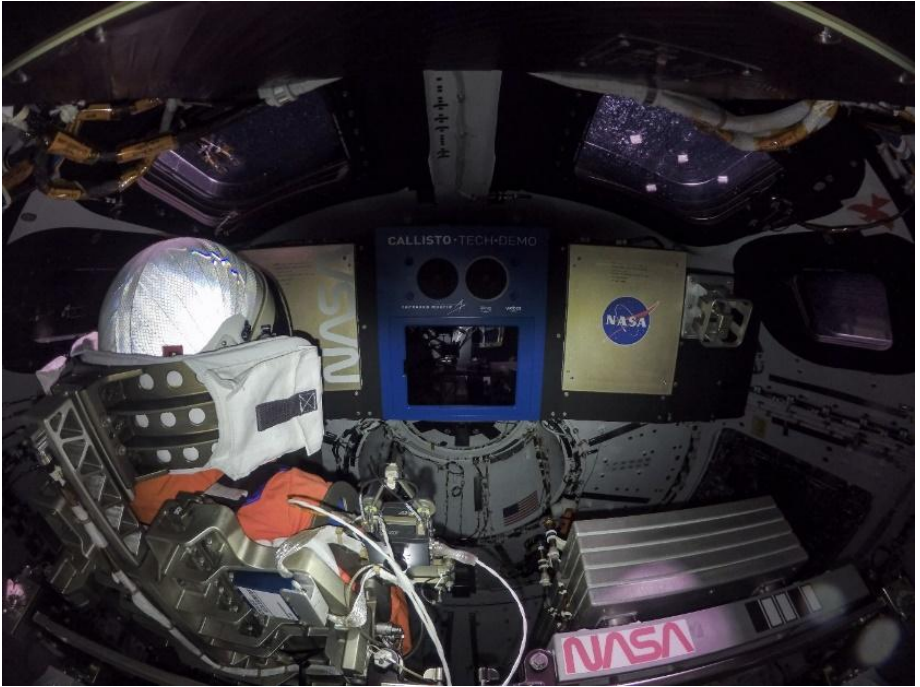


Fig. 6.1: The Radiation Measurement Experiment on board Artemis 1 flight
(Graphic courtesy of NASA)

During Artemis II, additional radiation exposure will be acquired with astronauts aboard the Orion Capsule during the ten-day mission that is now likely planned for September 2025. These experiments will provide information about radiation doses received for various body parts during the Artemis 1 launch by the sensor-equipped manikins and then compared with results related to those of the astronauts aboard during the Artemis II flights. The time aboard the Orion Capsule for Artemis II will be similar to the time involved with the Artemis III lunar landing, but not the time they will be on the lunar surface or the times when they will be residing inside the Human Landing System capsule. This capsule will be mounted on the top of the SpaceX modified reusable StarShip launch vehicle

during a stay that is up to 1 week or more. In short, astronauts will be exposed to high radiation for significantly longer during the moon landing and perhaps for as much as twice as long if their stay should extend to two weeks.⁸⁰

Extensive data from various scientific missions in deep space are available to collect information on solar radiation and interstellar radiation. This has been collected by NASA and other space agencies over the decades. This has allowed for a model to be built for the levels of radiation that astronauts will experience during Artemis II and Artemis III. However, the Artemis II and Artemis III missions will be the first since late 1969 through 1972 that astronauts will be in a high radiation environment outside the protective magnetic shielding of Earth. This will allow actual dosimeter data to be collected outside of the Orion spacecraft and inside for Artemis II and Artemis III flights. This will include data from both outside and inside the Orion spacecraft and the Human Landing System. When the HALO habitat is available in lunar orbit, it will be especially equipped for this purpose.

The ultimate level of space radiation protection is provided by specially designed materials for astronauts to wear to protect them and their most sensitive organs. These need to protect the entire body and the head. These are similar to hazmat suits that have been developed for work in hazardous areas around radioactive sites.

⁸⁰ Shaowen Hu et al, “Real-time dose prediction for Artemis Mission” *Journal of Space Weather and Space Climate*, Jan 7, 2025 [Real-time dose prediction for Artemis missions | Journal of Space Weather and Space Climate](#)

The figure below (See **Fig. 6.2**) shows the Orion space capsule with astronauts wrapped in protective gear. The purple suiting is known as an “Astro Rad” vest.⁸¹

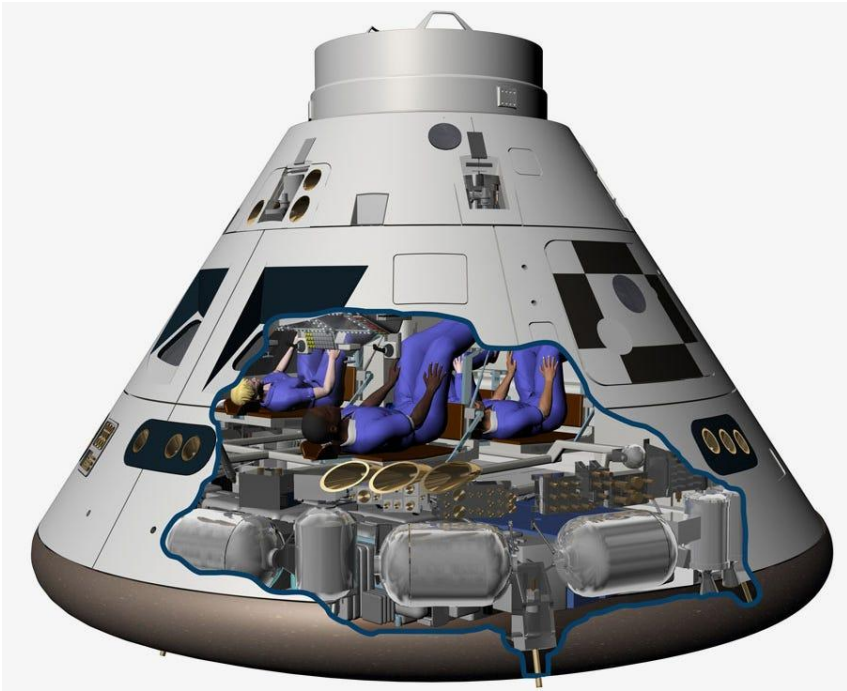


Fig. 6.2: The Astro Rad Vest Developed for NASA Astronauts to Wear on Orion Space Capsule
(Graphic courtesy of NASA)

This is only the last layer of protection. There is also intensive study of what are known as “storm shelters” for astronauts to be protected against Galactic Cosmic Rays (GCRs) and Solar Energetic Particle Events (SPEs). The

⁸¹ Astro Rad Vest, NASA radiation protective suiting, (Last accessed March 12, 2025)

<https://www.bing.com/images/search?view=detailV2&ccid=z4na7Kxo&id=67295B821067E5F305E0D921BAA1DC9B82678oEC&thid=OIP.z4na7KxodMfb7Qorq4x9vgHaGA&mediaurl>

shelter shown is a specific place to find protection against hazardous space weather storms, but there are efforts to design ways to store supplies and specific elements, such as water supplies (known as “water walls”), to provide additional layers of protection against space radiation. These will likely not be used during the Artemis exploration, but an optimized craft for Mars missions might well have water walls and supply chambers designed to also serve as space radiation protective shielding.⁸² (See **Fig. 6.3**)



Fig. 6.3: NASA Design for Astronaut “Storm Shelter” for Radiation Protection
(Source: NASA)

⁸² NASA Astronaut “storm shelter” design for cosmic radiation protection,
NASA<https://www.bing.com/images/search?view=detailV2&ccid=IkCnpusb&id=3C23CA1052FE44ACC78F74C4FF7411C91312857F&thid=OIP.IkCnpusbkH2olrMY9pCwuAHaGo&mediaurl=https>

Gateway and Radiation Protection

The earlier recommendation that more radiation protection should be added to the HALO element is indeed important. The lunar Gateway needs special emergency radiation protection chambers, or “storm shelters.” This is an important added key safety measure. Currently, the HALO unit is configured for launch, and it is too late to configure the supply for what would be superior water systems to create a more effective “storm shield.” This should be considered a vital design feature that should definitely be included in the design for future habitats in deep space in all astronaut living quarters.

It would also be useful to add other special life-sciences experiments, such as a small yeast sample as a substitute for a human body, that would stay on the HALO and be monitored over the lifetime of the Gateway for radiation effects. Yeast, in fact, is a reasonably good stand-in for the human body in seeking to understand the likely effect of radiation over time on human physiology. Wherever possible, the following approaches are recommended with regard to harmful radiation impacts on the human body and on astronauts while in space and aboard the Gateway:

- Use substitutes for humans in the study of radiation effects (i.e. measuring the effects of radiation on yeast or other substitutes for the human physiology).
- Operate the Gateway autonomously, where possible, without astronauts on board.
- Limit the number of crew on board to the minimum necessary and use “smart robots” and AI systems to substitute for astronaut capabilities where possible and effective.

- Limit extravehicular activities (EVAs) to the minimum required and use the Canadian arm, when available, for repairs or system maintenance.
- Upgrade the design of the HALO unit and also the design of the International Habitation Unit to add greater radiation protection. This should include an emergency “storm shelter” chamber where astronauts can obtain added storm protection during major solar flares.
- Coordinate NASA radiation exposure research with the other space agencies that are participating in the Artemis program and sending astronauts to the Gateway during the many years of this Moon exploration program.

Radiation and Solar Storms

The other concern, beyond solar and cosmic radiation, involves not only cancer and genetic mutation but also the issue of a specific type of solar storm, known as a coronal mass ejection. These solar events are not high-energy releases of radiation, but rather the ejection of super-accelerated ions. The ejected ions travel not at the speed of light, as is the case with radiation, but at less rapid velocities. These are still very high-speed velocities that would be found in an ion generator—i.e., around one to three million km/hour. Such events can thus be detected by a solar telescope, and alerts can be sent to astronauts with perhaps hours to spare.

It would be hoped that astronauts would be able to seek cover in protected locales such as below-ground shelters in time, but for the first few missions, the astronauts would have limited protective sheltering options. On Earth, humans are protected from CMEs by the Earth’s atmosphere and its electromagnetic shielding, but on the Moon, they will need shelters that offer protection from

both radiation and ionic bursts from the sun. Thus, spacesuits should have special alert signals to take cover when any sign of danger from radiation or CMEs is detected or anticipated by unusual sunspot activity. Off-Earth exploration should be planned for Solar Minimum rather than Solar Max periods to the extent possible.

The timing of the Artemis missions to the Moon is not entirely auspicious. January and early February 2023 represented the onset of the Solar Max period. Thus, solar flares at the X.2 and X.3 intensity range are now occurring. These flares are expected to rise in number and intensity during this period of solar radiation through 2026 in Solar Cycle 25, which appears to be emitting more intense flares than in Solar Cycles 23 and 24, which turned out to be less severe. If Artemis III actually occurs around its latest announced date of mid-2026 or even later, this would be a period where the Solar Max radiation would begin to decline. Artemis II will likely experience some high radiation levels and could also experience a CME ionic burst.⁸³

At a minimum, NASA should continue its solar research to understand the patterns of the Solar Max/Solar Minimum 11-year cycle and the why and how of the differences in the 11-year cycles. This research should be intensively directed at understanding the electromagnetic phenomenon of connecting and splitting apart magnetic loops in the corona and photosphere to better predict when the most violent of these events are likely to occur. About half the time, when solar radiation flares occur, there are also Coronal Mass Ejections. The reasons why these radiation flares are accompanied by CMEs should also be a key area of emphasized study.

⁸³ Abbey Interrante "Sun Releases Strong Solar Flare" January 2023
<https://blogs.nasa.gov/solarcycle25/>

This effort should particularly investigate the latest data from the Hermes experiment and the various NASA satellites now studying the sun's scientific behavior, as well as new data developed during the Artemis Program and the Gateway Space Station's research operations.

The Lunar Gateway and Its Role in the Study of Radiation Hazards

The Artemis Program will provide information on solar radiation and its impact on the Southern Pole locations of the Moon and help identify a suitable location for a permanent base in this sector of the Moon. There are additional dosimeters and measurement systems that will be available on the Lunar Gateway, which is planned for launch and deployment in a special Near-Rectilinear HALO orbit. The decision to deploy this Lunar Gateway facility in this special orbit was a matter of some controversy due to the high degree of radiation that astronauts would be exposed to in this location. Critics such as Robert Zubrin have noted that the purpose of the Artemis program is to study the Moon and that a permanent facility there could be subterranean in nature and thus shield astronauts much more effectively than would be the case in Lunar Orbit.

The planning of the Lunar Gateway, in light of this concern, designed the facility so that it could operate autonomously and without astronauts on board for a significant period of time. This facility is designed to play a critical role in telecommunications and networking relays to reach difficult locations at the Moon's South Pole with a broadband signal. This facility and its special orbit are also designed to facilitate logistical resupply and to serve as a safe haven in the event of a need to vacate the lunar surface. Finally, and perhaps least convincingly, it might provide logistical

resupply and support for future exploratory missions to Mars.

In terms of radiation research, the various measurement devices external and internal to the Gateway will provide very useful data on the nature of radiation dangers to astronauts, since they can gather important variations in radiation exposure over time.

Counter Measures

The even greater challenge for NASA with regard to its current standards is the issue of astronaut travel not to the Moon but to Mars. Even with the shortest known travel routes to Mars and back the 3% REID lifetime limit would certainly be well exceeded with current levels of protective suiting and storm shelter designs.

Part of this standards-making process for radiation risk exposure is now focused on countermeasures to protect human tissue from these radiation dangers and chances of cancer. One such countermeasure is a combination of aspirin and warfarin. It is thought that such Medical Counter Measures (MCMs) can work for at least some specific tissues and for relatively small periods of time measured in weeks or perhaps even months.⁸⁴

Medical research has revealed yet another vexing problem. Radiation effects can compound the problems of bone loss associated with weightlessness. The result of this research has been reported as follows:

⁸⁴ J.S. Alwood et al, "Simulated Space Radiation and Weightlessness: Vascular-Bone Coupling Mechanisms to Preserve Skeletal Health" NASA Technical Reports, <https://ntrs.nasa.gov/citations/20120011349>

“There are especially serious risks for long-term exploration class missions when astronauts will face the challenge of increased exposure to space radiation and abrupt transitions between different gravity environments upon arrival and return.” This research suggests that one cannot look at medical dangers and problems associated with radiation, abrupt changes in gravitational effects, and other factors such as changes to the human circadian rhythms in isolation, but also in terms of their total systemic impacts.”

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Conclusions and Recommendations

The dangers of free space radiation to astronauts while traveling into deep space above the protective atmosphere and magnetic shielding of Earth are quite real. The microgravity environment is also a challenge, and the two issues together can have a compounding effect.

The prime research areas are largely summarized in **Table 6.1** above, and protective strategies for the radiation are provided in the listing in the section on the Gateway Space Station.

New materials suited to protective defense against free space radiation should receive special attention. The deadly ionic nucleus stripped of their electrons are 10,000 times more dense and therefore more deadly than anything people experience here on Earth with dental and body X-rays. The lead shielding pads used here on Earth do not provide the needed protection against cosmic radiation.

The results of the coming Artemis missions, the Lunar Gateway dosimeter readings, and the research agenda (outlined in **Table 6.1**) should provide a better basis for

⁸⁵ Abbey Interrante “Sun Releases Strong Solar Flare” January 2023
<https://blogs.nasa.gov/solarcycle25/>)

designing spacecraft to travel to Mars. For reasons of space radiation protection alone, the Orion spacecraft does not seem to be an optimum design for a mission to Mars, even if other issues, such as its heat shield and excessive costs, were not considered.

There is insufficient information to make a detailed judgment about the designs of the two configurations of the Human Landing System regarding the adequacy of these spacecraft in terms of radiation protection. Clearly, the best option for lunar astronauts would be to move from using the Human Landing System as their short-term habitat on the Moon to a permanent habitat facility below the regolith of the Lunar Surface.

Chapter 7

Protection of Astronauts from Space Debris and Cosmic Hazards

Introduction

In the case of astronauts at the International Space Station, as well as those at the Chinese Tiangong Space Station, there is ever-growing concern about space debris, orbital collisions, and the implications of the increasing deployment of large constellations in low Earth orbit. The bottom line is that there is now an ever-widening amount of space debris in Earth orbit, with an astonishing 40,000 debris elements larger than 10 cm in diameter and being actively tracked. There are also some 300,000 that are 1 cm or larger in size.

The private space stations that are now planned with NASA as a partner organization will, of course, have similar concerns about space debris when they are deployed in the next few years. The ISS and the Chinese space station now have to be routinely maneuvered to avoid space debris. In an interview with former Canadian astronaut Robert Thirsk, he was asked what particular concerns he felt while being aboard the ISS. He responded that he had not had any specific health concern or specific threat concerns, but that concern about a possible space debris collision and related hazards certainly came to

mind each time the ISS had to be repositioned to avoid a projected possible debris collision.⁸⁶

This problem of space debris is certainly a valid safety concern for astronauts. This risk factor associated with space debris continues to increase due to the deployment of so-called mega-LEO satellite constellations. This threat seems likely to become worse without specific action. The SpaceX Starlink constellation, which is in a lower orbit than other LEO constellations, is perhaps of the greatest concern to astronauts on the ISS and Tiangong. The Starlink constellation concern is, however, not unique. A growing number of large-scale constellations are being deployed and launched into orbit. Each satellite maneuver, initial insertion, and deorbit operation can lead to orbital collisions. In addition, there are over fifty large-scale debris objects in low Earth orbit that have been identified as prime debris concerns. Most of these large and dangerous big cross-section debris objects involve defunct upper-stage launchers and large-scale non-operational satellites. Such massive and multi-ton debris elements represent the most significant sources of potential major collisions. If these very large debris objects collide with another piece of debris with a large kinetic energy, this could potentially create many thousands of new debris elements.

There are a variety of ways forward to protect astronauts, crew, and passengers on public or private space stations. These measures include changes to regulatory practices, changes to international law and regulatory reform, specific actions with regard to restrictions on mega-Leo constellations, and new specifications as to collision avoidance capabilities that need to be placed on most new satellite launches. This is particularly

⁸⁶ Zoom Panel Interview with Robert Thirsk on Feb 13, 2025 on the Living-in-Space Zoom event which had participants from well over 30 countries and hundreds of participants)

so with regard to satellites being deployed in large-scale constellations. Thus, there are a number of regulatory changes plus R&D activities that are needed to help achieve improved safety capabilities in Earth orbit. The most important step forward would be an international agreement on space traffic management that would be observed on a systematic basis and include some form of enforcement of this process. This effort should include an active debris removal campaign, stricter due diligence procedures prior to launch, and specific requirements for active collision avoidance of satellites. Unfortunately, agreement on space traffic management within the United Nations Committee on the Peaceful Uses of Outer Space and the Working Group established to address this topic has made slow progress in this regard. The approved COPUOS Debris Mitigation Guidelines are not mandatory and have no enforcement process behind them.

One of the key steps needed to minimize debris and allow key progress in this area would be to incentivize active space debris removal. This effort to encourage debris removal would likely also require a revision to the so-called Liability Convention. This would particularly require a new provision to create “absolute liability” associated with space debris collisions on the part of “launching states.” Since Russia, China, and the U.S. are responsible for the most space debris, such a revision is difficult to negotiate and agree on. Without such a provision, there is limited economic incentive to undertake active debris removal, which is technically difficult and expensive to achieve.

In light of the situation described above, the problem of space debris in Earth orbit, and especially in low Earth orbit, has continued to increase in recent years. This problem has been especially driven by three major space debris collisions and projections by NASA and ESA that every five to ten years, there will likely be another major debris-generated collision. As this

problem and concern increase in all types of Earth orbits, especially low Earth orbit, there are plans to place more and more satellites in orbit. These are not only being launched by the thousands into Earth orbit, but now increasingly around the Moon and Mars.

At least two space stations are planned for the Moon. These are both conceived as being able to accommodate astronauts. One is known as the Lunar Gateway, and is now planned to be deployed by the U.S. and its international partners within the next two years. The second is to be deployed by China, Russia, and other partners, and it is part of the so-called International Lunar Research Station initiative. As the problem of space debris worsens in Earth orbit, it is important to make reforms in practice with regulations, preferably with enforcement provisions, to address not only the issue of debris in Earth orbit but also for the Moon and Mars as well.

This chapter thus addresses the extent and nature of space debris and potential collisions in Earth orbit as a hazard to astronauts in orbital space stations. It goes on to ask what technological capabilities, regulatory reforms, improved practices, and incentives might be created to address the space debris problem and especially the danger to astronauts on space stations. These are not only those operated by the U.S. and China and their international partners, but now there are also plans for privately-owned commercial space stations. One of these is known as the Axiom Space Station to be created in partnership with NASA. A second one, which NASA will also help sponsor, is pending a decision. Both are to be deployed before the ISS is deorbited at the end of 2030.

A Better Understanding of the Nature of the Threat of Space Debris to Astronauts

The rapidly growing danger of space debris as a threat to astronauts and vital operating satellites and spacecraft is not well understood. If some type of small object, such as a tomato or even a rock the size of a baseball, were to hit an automobile, it could certainly do some damage, but it would not likely be a lethal event. But something that is traveling at an orbital velocity of 17,000 miles per hour (mph) or around 27,000 kilometers per hour (kph) and has a diameter of 4 inches or 10 centimeters would have the force of a powerful hand grenade. Even some debris elements as small as a chip of paint flying at orbital speeds can crack the window of a space vehicle.

A collision between two sizable space debris elements can create an avalanche of new debris elements. There have been three notable collisions in Earth orbit and each of these major collision events created thousands of new debris elements.

And space debris is not always generated from collisions. Satellites that are not decommissioned correctly can also blow up and create significant debris. This decommissioning process is sometimes called “passivization”. It involves releasing liquid or gases from tanks that might explode, and complete deactivation of electronics and batteries. This proper decommissioning is clearly key to do properly, as shown in the chart below. The most protective step of all, of course, is de-orbiting of satellites at the end of life if at all possible. The chart 7.1 below shows recent new sources of space debris that were created between 2018 to 2025. This generation of new debris came from many sources, such as anti-satellite tests, collisions, and improper deactivation of satellites at the end of life.⁸⁷

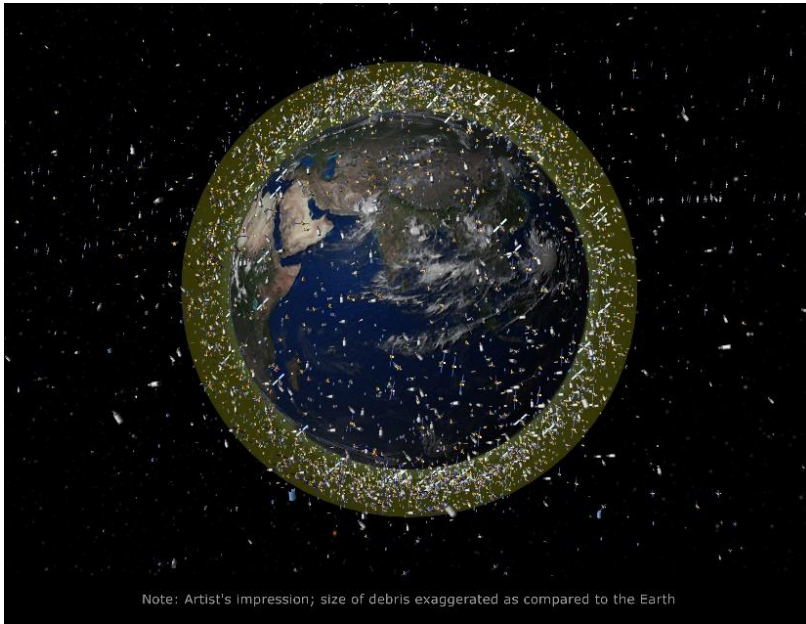
⁸⁷*“Listing of space debris producing events” (Reference Spirce to Table 7.1)
(This site was last accessed on March 18, 2025)*

The start of a new era of major new space debris generation occurred when the Chinese military tested their missile firing and accuracy against a defunct Chinese weather satellite in 2007. This test generated over 3500 debris elements. This one event increased the number of debris elements over 10 cm in diameter by 20%. This was followed in 2009 by a Russian defunct weather satellite Kosmos 2251 colliding with an Iridium satellite. This event created over 1700 debris elements over 10 cm in size.

Then, in 2021, a Russian missile intercepted a defunct Russian weather satellite, Kosmos 1406. The result of this unfortunate missile test was over 1550 new debris elements. These occurrences are the most damaging of space debris triggering events, but there is now a steady stream of accidents and satellites that have not been properly disposed of at the end of their lives, which are contributing to the buildup of space debris. The result has been an ever-rising amount of space debris. See **Fig. 7.1** to see a representation of current space debris in low Earth orbit.

Table 7.1 is revealing as to the diverse nature of debris creation events and the fact that this is an ongoing process that is generated by more than collision events. The lack of degassing of fuel tanks and making sure battery systems are fully deactivated at the end of life are the most common debris-generating occurrences. Over time, it is now clear that these events can rival the debris caused by an in-orbit collision. It can even come from an astronaut losing a tool on a spacewalk.

https://en.wikipedia.org/wiki/List_of_space_debris_producing_events



Note: Artist's impression; size of debris exaggerated as compared to the Earth

Fig. 7.1: The rising amount of space debris is particularly increasing in Low Earth Orbit
(Graphic courtesy of ESA)

Most debris does indeed come from collisions, inadequate decommissioning measures, lack of effort to remove defunct upper stage rockets and satellites from orbit, and other causes such as unsuccessful rocket staging, explosive bolts, discharge of waste, accidents from docking with spacecraft, and unsuccessful rendezvous and proximity operations (RPOs). All of these actions and a lack of preventive actions can lead to pollution of Earth's orbit. This creates dangers to satellite operations and, most critically, can lead to specific dangers to astronauts while they are in orbit.

Most space-faring nations now have specific due diligence reviews prior to launches to make sure that launch operations will not lead to the creation of space debris. Past types of debris problems, such as the use of explosive bolts for launcher stage separation, have been largely eliminated. Yet there are

continuing concerns. One of the major concerns is for all satellites launched in low Earth orbit to be equipped with active debris removal capabilities if at all possible. Even one or two-unit cube satellites can create problems, and the smallest satellites should have at least some sort of passive de-orbit capability if at all possible.

TABLE 7.1: RECENT EVENTS CAUSING NEW SPACE DEBRIS 2018-2025					
Date	Object	Designation	Cause	Pieces	Pieces in Orbit
Aug 31, 2018	Centaur V upper stage	2014-055B	Unknown	107	107
Dec 22, 2018	ORBCOMM FM-16	1998-046E	Energetic fragmentation, due to leftover propellant	13	5
Jan 24, 2019	Microsat-R	2019-006A	ASAT (Anti-Satellite) weapon system test	129	0
Feb 6, 2019	H2-A 202 Rocket Body	2018-084L	Unknown; Third known breakup of an H-2A Rocket Body	6	0
Feb 6, 2019	H2-A 202 Payload Adapter ^[41]	2018-084E	Energetic fragmentation event; Cause Unknown	3	0
Apr 2019	Centaur V Rocket Body ^[12]	2018-079B	Energetic fragmentation event; Cause Unknown ^[12]	193	192
May 7, 2019	Titan IIIC Transtage rocket body	1976-023F	Energetic fragmentation event due to leftover (N ₂ H ₄) Monopropellant	Not Known	Not Known
August 19, 2019	SOZ (Sistema Obespecheni ya Zapuska) ullage motor	2010-041H	An energetic fragmentation event is caused by leftover fuel in the ullage motor.	23	23

	from a Proton Block DM 4th stage				
August 13, 2019	Ariane 42P third-stage rocket body	1992-052D	Unknown	10	10
December 23, 2019	Kosmos 2491	2013-076E	Unknown	~20	~20
May 8, 2020	Fregat tank	2011-037B	Unknown, possibly an explosion	346	280
July 12, 2020	H2-A 202 Fairing	2018-084C	Collision with untracked debris	123	5
March 18, 2021	Yunhai-1 02	2019-063A	Accidental collision with a fragment from the Zenit 2 rocket body that launched Tselina in 1996.	39	20
November 15, 2021	KOSMOS 1408	1982-092A	ASAT (Anti-Satellite) weapon system test	1787	394
November 12, 2022	Long March 6 upper stage	2022-151B	Unknown, but may be related to upper stage “passivization” or insulation issue	781	722
November 17, 2022	H2-A 202 Payload fairing	2012-025F	Energetic fragmentation event; Cause unknown	50+	50+
January 4, 2023	Kosmos 2499	2014-028E	Unknown	85	85
March 11, 2023	Orbcomm F3 6	1999-065E	Unknown; likely energetic fragmentation event caused by a malfunction in the hydrazine orbit adjustment system	7	7
August 21, 2023	Vega VV02 VESPA adapter	2013-021D	Unknown; likely debris impact	7	7

March 26, 2024	Long March 6A upper stage	2024-058B	Unknown, but may be related to upper-stage passivization or insulation. ^[26]	~60	~60
June 26, 2024	Resurs-P No.1	2013-030A	Unknown, but may be related to improper spacecraft passivization	100+	100+
July 4, 2024	Long March 6A upper stage	2024-126C	Unknown, but may be related to upper-stage passivization or insulation.	Not Known	Not Known
August 6, 2024	Long March 6A upper stage	2024-140U	Unknown, but may be related to upper-stage passivization or insulation.	700–900+	700–900+
September 6, 2024	Atlas V Centaur upper stage	2018-022B	Unknown;	40+	40+
October 19, 2024	Intelsat 33e	2016-053B	Unknown; potential threat to all spacecraft in geostationary orbit, including a number of Russian Sats	700+	700+
February 9, 2025	New Glenn upper stage + Blue Ring	2025-011A	Energetic fragmentation event; Cause Unknown, but may be related to upper stage passivization or insulation.	67	67
Source: “List of space debris producing events” (site last accessed on March 18, 2025) https://en.wikipedia.org/wiki/List_of_space_debris_producing_events					

Table 7.1: Space Debris Creation Events from 2018-Mid 2025

Technical Innovations to Cope with Space Debris

The tracking of satellites and debris in orbit has been undertaken by military systems for many years to detect the possibility of a hostile missile attack, as well as to keep track of satellites in orbit and space debris. The U.S. Space Surveillance Network (SSN) is now tracking some 40,000 satellites and space debris larger than 10 cm in diameter with an S-band radar tracking system in the South Pacific. The largest amount of these tracked satellites and debris objects (i.e., almost 50%) are in Low-Earth Orbit. This tracking capability is augmented by a number of commercial tracking systems using both optical and radar tracking capabilities. A number of governments and space agencies also have independent tracking systems. These include Russia, China, and the European Space Agency, among others. An entity known as the Space Data Association, which is a group of companies, space operating entities such as Intelsat and Inmarsat, and space agencies with operational space networks, also provides a key service. It provides warnings of possible conjunctions between satellites or between satellites and debris, so that maneuvers can be taken to avoid collisions.

Operators generally set specific collision probability thresholds for close approaches to be warned about. When threats of crashes are more serious, they have a process for determining when to take evasive action. These thresholds for undertaking a maneuver to avoid a crash tend to trade off the seriousness of the potential collision against the costs of such action and the potential of human error moving into an orbital location that actually encounters a crash.

There are several conditions that apply. One is where two satellites might potentially have a conjunction, and active control is possible. Another is where there is a satellite with

active control, and the other object is essentially debris or an inoperable satellite without any possible capability for control. Finally, there could be two objects in orbit without any degree of control, where evasive action is not possible except for some sort of ground-based directed energy system or laser that might alter an orbit to prevent a collision.

In a situation where it seems likely that an operational satellite could collide with another space object, a satellite operator can fire on-board thrusters to change the orbit to avoid the collision and, as required, fire thrusters again to return to the desired orbit.

This involves calculating what is called the minimum delta change in speed to avoid the crash and thus using the minimum amount of fuel required to alter the satellite's orbit and avoid the conjunction. Then, afterwards, there may be a need to return the satellite to its operational orbit for telecommunications, remote sensing, or its other operational duties. This approach to detecting the danger requires someone to calculate the needed thruster firings and someone to send the needed commands to the satellite. This approach worked when there were only relatively few satellites or space stations in service and not a great deal of space debris to avoid. The current space environment, where there are an increasing number of large-scale constellations of operational satellites in low Earth orbit, has made this type of avoidance process increasingly unsustainable. It is now increasingly necessary to use computer-based algorithms to detect a likely conjunction and to send commands to avoid the collision.⁸⁸

⁸⁸ "Space Collision Avoidance Technology: An Overview" *New Space Economy*, (last accessed March 20, 2025 <https://newspaceconomy.ca/2023/11/03/satellite-collision-avoidance-technology-an-overview/>)

The increasing number of possible conjunctions has thus led to the development of automated collision avoidance systems. These specially developed algorithms and machine learning concepts are used to review and instantly analyze incoming conjunction data and to instantly assess the risk of a collision. When it seems necessary, a decision is made by this set of algorithms as the action to be taken. This 'decision' is based on the level of risk that is expected to be exceeded, and appropriate firing of jets is made to undertake what is called automatic orbital evasive action. This automation of the collision avoidance capability is increasingly important to employ for evasive actions with regard to very large constellations of satellites, especially those in low Earth orbit. In the current space environment with a number of constellations with thousands of satellites in orbit, or shortly planned, manual monitoring of possible conjunction risk would be impractical. Also, having calculations made and then having spacecraft engineers devise commands developed to avoid the collision by maneuvering around the debris threat would be equally impractical in terms of time constraints.

Avoidance technology must be programmed to be able to detect or learn whether the threatening space object is a non-cooperative space debris object or a satellite that is able to maneuver away from a collision itself. Active satellites, with automatic collision avoidance software and appropriate algorithms, can communicate and coordinate evasive actions. Non-cooperative objects, like debris or defunct satellites, cannot avoid collisions. Satellites must be programmed to avoid collisions from both cooperating and non-cooperating satellites or space debris elements.

One of the most critical elements in successful collision avoidance is the accuracy of orbital data. Over the last few decades, there has been a continuous development in the

accuracy of space surveillance technology. Unfortunately, at the same time, there has been an increasing number of space debris elements that need to be tracked. The U.S. Space Force S-band radar system in the South Pacific, known as the “Space Fence”, has now been operational for several years. Studies for another S-band radar system, possibly in Australia, have been undertaken, but no final decision has been made. (See **Fig. 7.2**)

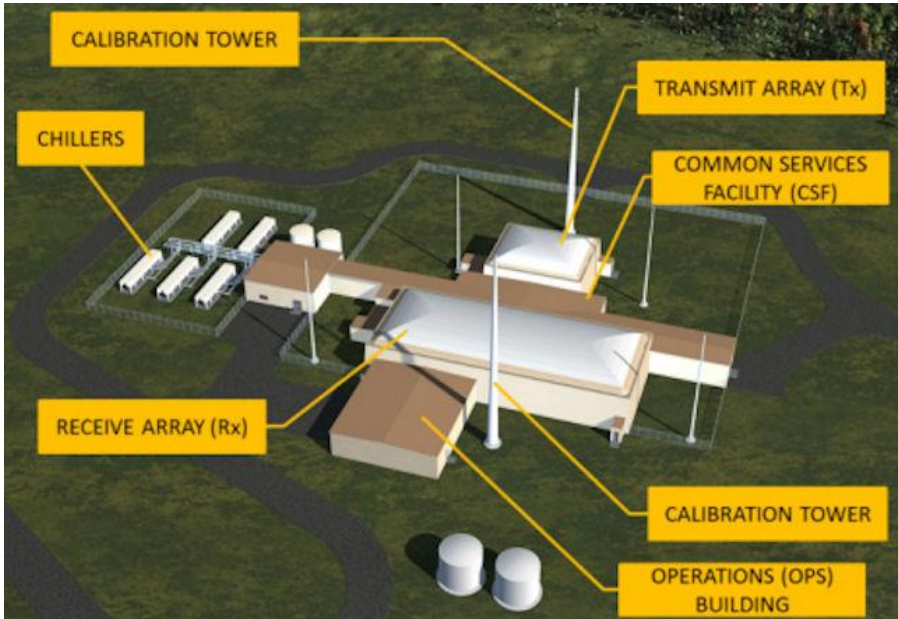


***Fig. 7.2: The S-Band Global Fence System
Operated by the U.S. Space Force
(Graphic from the U.S. Government)***

The Lockheed Martin Corporation manages the operation of the Space Fence under contract with the U.S. Air Force. There are over a dozen commercial tracking capabilities operating on a global basis. These commercial systems use both optical and radar tracking systems to monitor satellites and space debris in orbit. Some of these firms include Astrodynamics and LeoLabs, as well as the Lockheed Martin

iSpace system. The iSpace system's SPACETRACK website indicates that it now is tracking 300,000 space debris elements and that its customers include space agencies such as the German space agency (DLR).⁸⁹

These additional capabilities include the tracking capabilities of the European Space Agency, and other governments such as Russia and China. These systems can not only track space debris, but also detect missile and rocket launches as well.

The augmented capabilities are required to track smaller debris with greater precision. Additionally, as the number of satellites grows, especially with the deployment of large constellations, there is a need for more advanced coordination and communication mechanisms to manage operations in orbit. Most of the large constellation satellites have machine language and algorithms that can be used to avoid collisions. This capability and its accuracy are still being tested. There are many concerns and operational conditions that must be addressed with regard to large-scale constellations. These include precautions taken to ensure safe initial launch to orbit, initial insertion, orbital insertion into a constellation, or even into some sub-orbital pre-operational status position prior to insertion into the constellation proper. There is likewise a need for careful operation of all elements of constellation configuration, as well as de-orbiting at the end of life. All of these orbital conditions could potentially lead to a collision with other satellites in a large constellation or other debris elements, or operational satellites or space stations of other countries, or some other operational satellite or space debris element. The very fact that 300,000 orbital elements down to 1 cm in

⁸⁹iSpace SPACETRACK, *Keeping an Eye on Space*, May 4, 2021

<http://www.lockheedmartin.com/en-us/news/features/2021/keeping-an-eye-on-ispace.html>

diameter are now being tracked reveals the degree of difficulty involved in seeking to avoid collisions and how threat alerts have to be strategically and selectively initiated when a significant threat level is reached.⁹⁰

Due Diligence Prior to Launch

There are specific U.S. requirements to be met to qualify for approval for a launch in the U.S. There are processes for governmental and military satellite operations, as well as others that pertain to commercial launch operators. There are Federal Communications Commission space debris standards and requirements. There is also the due diligence review process undertaken by the FAA-AST prior to a licensed commercial launch authorization. There is, in most cases, also a requirement for an officially filed and approved environmental impact statement associated with a space launch, as well as a process for clearing aircraft flying in close proximity to a space launch operation. In a number of incidents, U.S. commercial launch operations have been put on hold until revisions are undertaken to ensure that there is a clean launch that does not produce space debris elements.

In the case of U.S. Governmental launches, NASA, NOAA, and the U.S. Air Force provide their own review processes to ensure a clean and safe launch operation. The French Space Operations Act (FSOA) specified a number of ways to prevent space debris from occurring. This includes pre-launch due diligence, safe launch operations, and even fines for not removing satellites from orbit by the specified time of safe operation standards. The trend is for governments to set standards for due diligence prior to launch, but there are no

⁹⁰ (European Space Agency, Web site article on Space Safety, “Automating Collision Avoidance”, (last Accessed March 2, 2025)
https://esa.int/Space_Safety/Space_Debris/Automating_collision_avoidance

uniform international standards for due diligence prior to launch. Such an international “best practices” standard would be useful to develop and agree on. It is particularly important for national governments to create national laws with safety standards, infraction fines, etc. Safety standards for launches, protection against the creation of new debris, and strict national space safety laws and regulations remain the most important part of the process of creating safe and clean launch operations.

Needed International Regulatory Reform and Changes to International Space Law to Address Space Debris

The most important regulatory issue that is truly central to the control of space debris is the implementation of the concept of space traffic management. The hope is that space-faring nations would agree to a worldwide regulatory system concerning the safe launch, orbital deployment, operation, and deorbiting of all spacecraft. This would ideally cover not only all types of Earth orbit, but also include spacecraft in orbit around the Moon, Mars, and other celestial bodies. Further, it would also create an agreed system for the safe operation of all high-altitude platform systems and hypersonic craft reaching altitudes above aircraft operations and below orbital altitudes. This would cover every aspect of a launch, from pre-launch due diligence and strict safety engineering to all launch and operational activities (including collision avoidance capabilities) and also enforcement penalties to ensure timely and complete de-orbiting operations.

The UN Committee on the Peaceful Uses of Outer Space created a Working Group on the Long-Term Sustainability of Space, and after many months of deliberations, drafting, and compromise, it reached agreement and full consensus on 21 voluntary guidelines. These guidelines addressed four broad

areas, with ten of the guidelines explicitly addressing space safety. These guidelines, as noted below, include such topics as accuracy of orbital data, improved information on possible collisions (known as potential conjunction events), processes for collision avoidance, pre-launch safety assessments, improved information sharing with regard to space weather events, and a number of other points.

The titles of the ten guidelines on space safety are provided here, and the full text is provided in Appendix 1:

B.1 Provide updated contact information and share information on space objects and orbital events

B.2 Improve the accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects

B.3 Promote the collection, sharing, and dissemination of space debris monitoring information. B.4 Perform conjunction assessment during all orbital phases of controlled flight

B.5 Develop practical approaches for pre-launch conjunction assessment

B.6 Share operational space weather data and forecasts

B.7 Develop space weather models and tools, and collect established practices on the mitigation of space weather effects

B.8 Design and operation of space objects regardless of their physical and operational characteristics

B.9 Take measures to address risks associated with the uncontrolled re-entry of space objects. B.10 Observe measures of precaution when using sources of laser beams passing through outer space

B.10 Observe measures of precaution when using sources of laser beams passing through outer space⁹¹

Despite the progress achieved through these 21 Guidelines, the process of moving to agreement on a true space traffic management process has stalled. The representative of Russia has insisted that seeking agreement on the next step beyond to develop true space traffic management arrangements was, essentially, “premature.” Even the 21 Guidelines, as agreed within the Working Group in 2019 and within the Committee on the Peaceful Use of Outer Space in 2020, were only “voluntary guidelines” with no explicit enforcement processes. This is why national regulations, backed with enforcement provisions, are particularly key.

With more and more satellites launched for so-called mega-LEO constellations for telecommunications and other purposes, there needs to be agreement about deployment, de-orbit, on-orbit servicing safety standards, rendezvous and proximity operations procedures, and space safety practices. Such ultimate space traffic management processes would, in theory, closely follow the model for aircraft safety, where national oversight would observe and enforce international safety standards.

These space traffic management processes in theory would be similar to those now implemented through agreements reached within the International Civil Aviation Organization (ICAO). This organization, which is located in Montreal, Canada, was established under an international Convention agreed in 1948. It has served to coordinate international safety standards for commercial and private aircraft. These agreements are reached through new or updated safety

⁹¹(“Guidelines for the Long-Term Sustainability of Outer Space Activities” Nov. 2020 https://spacesecurityindex.org/wp-content/uploads/2020/11/IssueGuide_LTS.pdf)

standards established under a process known as Standards and Recommended Practices (SARP) regulations.⁹²

There is an ultimate need to create a systematic way to control the safety of launch operations, spacecraft deployment and operations, and disposal of space debris. And if there is not active space debris removal in all instances, there is an alternative need to employ passive debris removal systems for small satellites or have firm agreements and regulatory oversight for the repurposing of space debris and non-operational spacecraft in a safe and secure way.

Safety Reform Related to High Altitude Operations for “Proto-Space”

It is likewise important for these space traffic management agreements and processes to cover all high-altitude activities above commercial air traffic altitudes and below orbital altitudes. This area is often known variously as sub-space, near space, or even sometimes called “Proto-Space.” This term has been defined as the region above commercial “air space” and below the altitude needed for long-term sustainability for a satellite in low Earth orbit. This is thus the region above 21 kilometers and below 160 kilometers in altitude. Although for many years there were no particular uses for this region of the atmosphere, there are now such possible uses as for “Dark Sky” research stations, parabolic flights for hypersonic aircraft, high altitude platform systems, and various possible military applications. The increasing activities in these altitudes will give rise to a number of safety concerns. One of the main concerns is the relative speeds that are involved. In the case of high-altitude dark sky and high-altitude platform systems for telecommunications, broadcasting, earth observation, and

⁹² ICAO Standards and Recommended Practices (SARP)

<https://www.icao.int/safety/safetymanagement/pages/sarps.aspx>

weather uses, these are very close to motionless. Hypersonic aircraft, however, would be operating at speeds such as Mach 3 to Mach 6. This is clearly a dangerous mix of relative velocities.

Even officials who are close to the COPUOS discussion and agreement procedures have sometimes become pessimistic about the effectiveness of this U.N. Committee in reaching firm and enforceable processes on a range of increasingly urgent space safety agreements. They note that these processes, which require unanimous agreement, are very slow and thus take years to achieve, and then end with only “recommended or voluntary” guidelines. Without mandatory force and no enforcement processes, they are not effective means for enforcing effective space and “Proto-Space” flight safety provisions. Such slow and non-binding guidelines are inadequate, unsafe, and place at risk all forms of space operations. Today, there is vital modern infrastructure operating in Earth orbit on which billions of people’s lives depend. There are now billions of dollars of space-related commerce and vital infrastructure for communications, broadcasting, navigation, Earth observation, weather observation and forecasting, military defense systems, automatic identification systems, and other applications on which billions of people rely. In short, this is not only a matter of the safety of astronauts, but also public safety for a growing number of people here on Earth, as well as aircraft passengers, whose lives could be at risk since safe air travel now relies heavily on satellite systems.

Conclusions

There is increasing interest in seeking new space safety actions to control the creation of new space debris and find improved ways to address what is a mounting problem due

to the creation of more and more large satellite constellations, particularly those in low Earth orbit. Areas that need action in this area include:

- **Finding a way to amend the so-called “Liability Convention” to Incentivize Space Debris Removal:** This would seek international agreement to create “absolute liability” responsibility for space debris-triggered accidents and collisions that occur in Earth orbit. Ideally, this would also cover collision in “near space” and for other celestial bodies (such as the Moon, Mars, etc). This amendment process should also address incentives to encourage end-of-line deorbit through active debris removal. Such efforts should also address other concerns, such as repurposing and salvaging defunct satellites or defunct launch motors, as well as suitable provisions related to on-orbit rendezvous and proximity operations (RPO).
- **Revised and Updated Space Debris Mitigation Guidelines:** The U.N. COPUOS and the Inter-Agency space Debris Committee (IADC), were, in a way, both responsible for developing what eventually became the official U.N. Committee on the Peaceful Uses of Outer Space officially adopted “Space Debris Mitigation Guidelines. This process was a long and complicated process. The space agency collaborative process developed their proposed guidelines and the COPUOS, with a few modifications, and agreed to a somewhat simplified version. The problem is that more and more satellite launches, especially the deployment of thousands of additional new satellites in low Earth orbit and the lack of a mandatory requirement with enforcement provisions, have made the risks of the so-called “Kessler Syndrome”—or runaway buildup of space debris even more likely.

- **A Systematic and Mandatory International Process for Space Debris Mitigation and an Agreed Space Traffic Management Process:** An improved mitigation process that includes a means of undertaking systematic and ongoing active space debris removal or repurposing of space debris that incentivizes debris removal, encourages active collision avoidance capabilities (and especially for large constellations in low Earth orbit, seeks to removal the largest of defunct payloads and upper stage rocket engines from Earth orbit are prime goals to be agree on in establishing a new Space Traffic Management Process. It would be ideal if this could be agreed upon using the mechanisms available through the IADC and the UN COPUOS Processes. If this is not possible, perhaps a number of countries could agree together on such a process based on mutual understanding of a “best practices” approach that could lead to such an ultimate STM approach that evolves from a growing national consensus.
- **Development of New Technologies to Aid Space Debris Removal and Collision Avoidance:** All of the above efforts to create new agreed-upon processes and ways to achieve global cooperation to remove space debris from Earth Orbit are important to pursue with a sense of urgency because of the increasing risks. These agreements also need to move to cover parallel measures to prevent this debris from building up around the Moon, Mars, other celestial bodies, and to provide safety protections for so-called sub-space, near-space, or Proto-Space. This is a key new area of space safety concern because an increasing number of possible applications are now developing in this once-unused “Protozone” region of Earth’s upper atmosphere. As this regulatory and space traffic management process is developed and hopefully agreed upon by all space-faring

nations, it is also important to develop new technology and operational systems in this area as a high priority.

This technical research and development agreement should include such provisions as follows: (i) AI augmented and optimized automated collision avoidance systems; (ii) improved and augmented technology for active debris removal systems (including systems that derive electro-magnetic systems power from the Earth's magnetosphere to engage in debris removal processes); (iii) improved technical capabilities and maneuverability capabilities to enhance orbital safety operations; and (iv) improved technologies and oversight provisions related to rendezvous and proximity operations (RPO).

These technical and enhanced engineering agreements on new capabilities and safety regulations should include not only active space systems to conduct these actions in space, but also seek the development of various laser or directed energy system capabilities that could under international safety regulatory controls might be used to aid in necessary orbital changes to avoid collisions between space debris and operational satellites or space stations. It might even be possible to reach an international agreement on the possible use of Earth-based capabilities to undertake future space debris removal operations.

- **Development of International or Regionally-Agreed Plans to Develop a Systematic Scientific, Technical, Operational, Regulatory, and Space Safety Plan for Avoidance of Collisions and Removal of Debris from Earth Orbit, High Altitude and Sub-Space Regions of Earth, as well as for the Orbital Safety from Debris for the**

Moon, Mars and other Celestial Bodies: All of the above objectives need to be pursued with urgency and the basis of international agreement and cooperation. Ideally, the international agreement needs to be reached as soon as possible on all of the various goals identified above. Urgent steps forward are needed to act to remove or at least reduce the threat of space debris. Today, this is an increasingly dangerous condition that serves as a safety threat to astronauts, space stations, space commerce, and all forms of space applications, scientific research, and exploration.

The above five areas of required action as enumerated in these recommendations should be considered integral parts of an agreed action agenda. Agreement in all of these areas are need to achieve a workable international “Space Traffic Management” process. This needs to be viewed as an urgent global safety issue. As such it is urgent that the five actions as outlined above be pursued and implemented as soon as possible.

The key to this being achieved is an international agreement on a systematic, interdisciplinary, and comprehensive means of achieving increased safety with regard to space debris mitigation, as well as new attention to space safety concerns with respect to the “Proto-Space” region above commercial air space and below outer space. The above five interrelated goals and objectives are thus only the key area that would become the start of such a space safety standards process and the implementation of a “Space Traffic Management” system, such as we have for national and international aircraft safety. The sense of great urgency involved here would dictate that all of these safety, regulatory, and technical development goals need to be accomplished no later than year-end 2030.

Chapter 8

Deep Space Support Systems for Advancing Astronaut Safety

Introduction

The nearly thirty years of experience of living in space that the International Space Station provides clearly represent a head start in learning how to support astronauts living on the Moon or on Mars. The additional experience gained from the MIR space station and the Chinese Tiangong Space Station has also provided quite useful information on which to build as well. These many low Earth orbit experiences, plus the additional information derived from the Apollo Program lunar exploration visits, all help to provide knowledge about resupply services, key infrastructure systems for astronauts' environmental controls and life support systems, and key health and medical information.

We know how things can go wrong, what support systems are critical, and how they perform in the space environment. There is information about how to discover and recover from a variety of issues. These include air leaks, spacesuit problems, telecommunications and navigation issues, and hazards that range from noxious gases to fires, power outages to solar storms, and space debris to urgent problems such as radiation flares or medical issues for astronauts in space. Decades of

astronauts living and coping with issues in space, however, have been largely confined to living in low Earth orbit.

The difference between living in low Earth orbit and living in deep space is numerous and significant. The requirements for NASA astronauts to carry out their activities in deep space are significantly different in dozens of ways in terms of resupply mission difficulties, health challenges, risks and dangers, and many different infrastructure requirements. This chapter addresses key support systems and requirements in terms of the infrastructure that is needed to support astronauts' needs as they are sent on missions to the Moon, Mars, and other deep space locations.

Seven specific needs are addressed in this chapter that are broken down into: (a) telecommunications, navigation, search and rescue, and related services; (b) energy, power and lighting; (c) robotics; (d) material processing and additive manufacturing /3D printing systems; (e) Transportation Systems and Mass Driver Concepts for the Moon & Mars; (f) AI-enhanced systems; and (g) space systems and their international compatibility.

Navigation, Telecommunications, Tele-Location, and Rescue Operations

It is true that we know a great deal about highly efficient navigation, telecommunications, tele-location, and search and rescue systems, not only for remote areas on Earth but also for links to the International Space Station. However, the creation of systems for telecommunications to link Earth and the South Pole region of the Moon has special challenges. The extreme South areas of the Moon do not connect easily back to NASA ground control because there is no clear line of sight back to antennas operated by NASA on the Earth's surface. What NASA has done to provide connections is to deploy the Gateway lunar space station in a special orbit that has

continuous connectivity to the Moon's surface facing Earth, as well as the lunar North and South Poles. The special, highly elliptical, eccentric orbit around the Moon is known as a near-rectilinear halo orbit, which has a perilune of 10,000km and an apolune of 70,000 km. This special orbit avoids the need to place three satellites in orbit to provide constant coverage of the entire Moon, but the disadvantages are twofold. These are added delays to broadband telecommunications signals from Earth, plus the lack of backup if this gateway-mounted relay system should fail. At its greatest distance from the Moon, at apolune, almost a second of delay would be added to a round-trip communications exchange.

This lunar gateway space station will also have both optical coverage and broadband telecommunications links to the entire visible surface of the Moon from Earth and both polar areas. It can thus provide telecommunication relay services to Earth, as well as support for tele-location, search and rescue, and navigation services. It can thus support resupply missions going from Earth to the Moon's surface and return trips as well. The lunar Gateway will also undertake scientific research of the sun, as well as radiation exposure for astronauts. It will also provide a safe refuge for astronauts if they encounter difficulties on the lunar surface or their return to Earth is for some reason delayed.

Critics of the lunar Space Station suggest that the space station should have been created on the lunar surface and that an antenna relay on the lunar surface located at a more Northern position above the South Pole area could have been created to connect the astronaut back to Earth. This could have been created at much less cost but again there would have been maintenance, reliability, and access problems issues to address.⁹³

⁹³ Joseph Pelton and Peter Marshall, *The Gateway Lunar Space Station*, (2024) PM Associates, Washington, D.C. pp. 235-50.

Telecommunications, navigation, tele-location, search, and rescue issues for Mars are raised to a completely new level. All of these capabilities will be much more difficult.

There is only a few seconds delay for the links to the Moon and back, and even when the lunar Gateway is furthest from the Moon, a round-trip would be under four seconds. The round-trip connection to Earth to cope with emergencies or routine items varies very little because the Moon is in a relatively stable orbit around Earth. The connection with Mars is quite another matter. The shortest time for round-trip communications there and back is about 6 minutes as the signal travels over some 110 million Kilometers for the complete round trip. When Mars is opposite the Earth on the opposite side of the Sun, the direct link is 250 million kilometers in distance, but one must also consider the relay length needed for a satellite link, since you cannot send a signal through the Sun. The complete relay length might extend to 350 million kilometers, or a round-trip link that might extend to 700 million kilometers. A round-trip transmission to Mars might thus be as long as 44 minutes, or 22 minutes one way. This means there is no near-real-time connection to the Moon, but a round-trip delay of 4 seconds is close. But, for Mars, there is a long link delay associated with asking an emergency question and getting a quick reply. By this time, an astronaut in distress gets an answer; he or she might well be dead.

Further, a broadband telecommunications system to link Earth to Mars would require a significant new capability to create a network of satellites to relay messages around the sun and then to relay the signals going to and from the surface of Mars. This network would likely depend on an optical network that would be a focused laser beam in order to be able to provide a tightly focused broadband link over this great distance. A combination space navigation and telecommunications network for Mars, plus a broadband

optical transmission system to support telecommunications and video transmission from Earth to Mars and from Mars to Earth, would require a significant investment to plan, devise, manufacture, deploy, and operate. Such a system would likely have only about a twenty-year lifetime and thus would also need to be replaced or refueled, as well as undergo serious servicing to maintain such a satellite network.

The current Mars orbiters that relay signals back to Earth, namely the Mars Odyssey and the Mars Reconnaissance Orbiter (MRO), plus the ESA-developed Mars Express, can send radio signals back to Earth, to be received by the NASA Deep Space Network. This system would not be of sufficient bandwidth to support astronaut exploration missions. The system designed to send back communications from Mars from the Curiosity rover would likely be inadequate to support a longer-term astronaut mission and the rapid sending of video images. The current capability can take 12 to 24 minutes just to send one video image back to Earth. Since NASA's current Deep Space Network can only transmit and receive microwave signals, a new system would be needed to transmit and receive optical signals. This would also require finding three suitable desert locations, with virtually no rainfall, at suitable locations around the globe for the transmission and reception of such high-powered and concentrated optical signals.⁹⁴ (See **Fig. 8.1**)

The above discussion of telecommunications, navigation, and related needs all add up to the likely need to spend billions of dollars to create a high-speed transmission system to send and receive optical signals back and forth between Earth and Mars. It would also likely require the creation, deployment, and

⁹⁴ "How long does it take to transmit a picture from a spacecraft", *Astronomy*, Nov 24, 2024

https://www.answers.com/astronomy/How_long_does_it_take_to_transmit_a_picture_from_a_spacecraft_on_mars_to_earth

operation of a multiple-use satellite network around Mars. This might be designed so that it could provide space timing and navigation services, broadband telecommunications, and perhaps even support remote sensing services, search and rescue services. This would likely require replacement within twenty years or extensive servicing, refueling, and refurbishment.



Fig. 8.1: The Three Giant Deep Space Network Antennas Located in the U.S., Australia, and Spain That Span the Globe
(Image provided courtesy of NASA)

A short mission for astronauts to land on Mars and do some exploration and scientific missions could likely be supported by current capabilities for communications. However, any serious attempt to create a permanent habitat site on the Martian surface would require a much more expensive and much higher throughput system, such as described above. There is a need to research the development of a reliable, deep space broadband, interplanetary telecommunications system

to Mars that can support video and broadband data. It would have a sustainable design so that it can reliably operate over decades to come if there is to be a viable, longer-term human presence on Mars. Such a truly broadband connection is essential to any longer-term habitat capability for astronauts on the Red Planet. Such a facility is a pacing item in establishing a permanent presence. The use of optical wavelengths, perhaps blue or green lasers, to use the highest frequencies or the smallest wavelengths for the greatest intensity of signal with the broadest bandwidth may be the most optimum design.⁹⁵

This will be an expensive facility that will take time to design and deploy in terms of costs and time to plan, build, and operate. This will involve not only the relay satellites, likely at L4 and L5, but also creating a design for the part of the telecommunications system on Earth, to supplement the existing Deep Space Network. It might, however, be designed to operate in Earth orbit, and for Mars, the transmission or reception for the Mars orbit. In short, this will be a very demanding network to build and deploy. The satellite orbiters for Mars might, however, be designed to be multi-purpose and thus support other services from orbit. Such services include remote sensing, search and rescue, and navigation capability without necessarily adding great cost to the satellite telescopes equipped to receive and send information to the optical relay facilities.

The priority research objective would be to design an optimized optical transmission system for a very broadband link between Earth and Mars.

⁹⁵ Katia Moskvitch, "Mars to Earth: How to send a HD video between planets," BBC News, <https://www.bbc.com/news/technology-19950183> (Last accessed Mar 22, 2025)

The prime research and feasibility investigation would be to examine whether the best design for an interplanetary broadband relay system would be to have satellite facilities located at the Lagrange Point L₄ and L₅. Once this critical design was chosen, there would then be the further design of optimal connection designs for continuous linkage over the entire surface of Mars and the entire surface of Earth without connection interruptions.

This consideration would include considering whether the optical transmitters and receivers to the L₄ and L₅ relay stations could be piggybacked on existing satellite systems used for Earth-based services. There would be similar considerations with regard to Mars-based services. There would be a question as to whether a satellite network or ground-based system would be the best design, and if a satellite network could also provide navigation, position location, search and rescue, tele-location, or other capabilities in addition to links back to Earth.

In-Situ Energy and Power Systems

The landing and return vehicle for a short astronaut visit to Mars will likely have sufficient electrical power and lighting capability to support the visit to the Martian surface and any short-term habitat that might be set up there.

The design of a viable power supply and distribution system for a permanent living community of people is another matter. Much more electrical power and lighting would be needed for a longer-term presence. Much higher levels of power would be needed for some medical applications and equipment, mining operations, material processing and manufacturing/construction, and scientific applications. These types of power levels will not likely be met by solar cell illumination. This suggests that new capabilities will be

required, such as nuclear fusion power systems that could be connected to electric generators. Research is needed into what other power sources might be used beyond solar energy systems. Such sources that are used on Earth, such as geothermal, wind-powered generators, or hydroelectric dam-powered turbines, are not available on Mars. The planning for energy systems must consider the architecture of settlement facilities in terms of whether they would be underground or above-ground systems.

In the long term, there could be other possibilities, such as whether it might be possible to create electromagnetic systems to protect Mars from the solar wind. The creation of magnetic shielding for the entire planet of Mars might, in time, allow the development of an atmosphere. This might even lead to cloud systems and even to wind that could enable wind turbines. There might also be lakes and rivers, but hydroelectric dams and power systems currently seem unlikely.

Clearly, solar power systems backed up by rechargeable batteries will be needed. There continue to be opportunities for higher efficiency systems, such as quantum dot technology or ultraviolet multi-junction photovoltaic cells, to be examined by NASA.

Currently, the most likely high-power sources may be what are called Small Nuclear Reactors that can operate in the range of 10 to 20 megawatts of output power. These systems are small enough that they could be transported on a Falcon Heavy launcher. These small nuclear reactors have been licensed by the Nuclear Regulatory Commission and are designed so that they can be transported on trucks and do not require elaborate cooling systems such as large nuclear plants that generate gigawatts of power. The figure provided here shows the scale of such a generator. Nu-Plant is a new company backed by Westinghouse and Bill Gates, and it is one of the leading

suppliers of this new type of mobile nuclear reactor. Such systems might be optimized to power remote habitats on the Moon or Mars. (See **Fig. 8.2**)



Fig. 8.2: A Small Nuclear Reactor that has advantages of new design and compactness. These have been licensed by the Nuclear Reactor Commission.

(Image courtesy of U.S. Nuclear Reactor Commission)

There are various energy and electrical power sources that should be examined with short-term, medium-term, and long-term planning processes in mind. In this area, research based on Earth-based energy needs and by corporate research might well lead the way. Thus, in this area, NASA might monitor research rather than feel compelled to lead this research effort, except in terms of an electromagnetic shielding system for Mars, which might lead to new ways of providing for power in the very long term.

Robotic Systems

Robotic systems are not normally thought of as a crucial part of any normal urban architectural infrastructure. The domain of deep space exploration and the needs associated with planning and executing sustained habitation for either the Moon or Mars are different. Survival of astronauts on the Moon on a longer-term basis requires augmented power and manipulative skills and ability to withstand a variety of dangers and hostile environments.

Robotic systems will provide essential capabilities to support mining of resources, building of habitats, construction of distribution systems for electrical power, and recycling of waste. They could be key to providing support services, such as for the smooth operation of environmental controls and life support systems, such as the development of exhaust systems, lighting systems, etc. Astronauts on their missions to deep space are needed for scientific investigation, planning and programming, reporting on activities, and problem solving, but they are not needed as work minions or for menial tasks. There are quite a large number of jobs that various types of robots can do well, and indeed better than astronauts. Robots have the advantage of strength, endurance, and resistance to the harsh conditions of outer space. They have the capabilities to engage in hazardous activities such as mining and operating various types of equipment for long periods of time without needing food or water. There will be activities associated with creating a permanent habitat or research center that involve risks, dangers, or needed skill sets associated with working under the conditions represented by the harsh environment of either the Moon or Mars, or operating for very long periods of time.

In many cases, astronauts will need work partners, whereas robots can simply turn on special software applications that

are especially suited to such operations as the creation of lighting systems, installing heating or exhaust systems, to housing or storage units, and even such tasks as gardening activities in support of hydroponic or aeroponics vegetable gardens. Initial visits to the Moon and Mars will have prefabricated systems for habitats and life support. For longer-term stays, however, there will be a need for sustained excavation activities of the lunar regolith to obtain icy volatiles to be used to create water that can be used in electrolysis units to produce oxygen, or to help to extract materials that can ultimately be processed to be used in 3-D printers. These materials will then be used to create structures and other infrastructures. This will enable the creation of buildings, the formation of conduits, and more. Robots will be able to support transport operations, mining, and construction, among other tasks.

Looking at robotic assistance as key infrastructure support is different from other utilities such as telecommunications or energy. In this case, there are possibilities that range from nanotechnology to full-scale mining robots, such as the 300-pound (136 kg) R5 Valkyrie robotic system currently in testing in Australian mines, or autonomous mobile vehicles such as the VIPER system that was designed for the Artemis Program.

The Valkyrie robot is the next generation of the R2 Robonaut series with upgraded actuators, improved electronics and sensing systems, as well as improved machine learning capabilities. Its appearance is almost like a superhero from the pages of a comic book, and it certainly has a range of impressive capabilities. It is currently being tested in actual mining operations after its latest upgrades. After the DRC competitive trials in 2013, it has been modified to improve the reliability and durability of both its hands and ankles. Its software has been reprogrammed in such areas as its walking algorithms to achieve greater dexterity.

This imposing, all-electric R5 series NASA Robot stands an imposing six feet (or 1.9 meters) tall.⁹⁶ (See **Fig. 8.3**)



Fig. 8.3: The R5 Robonaut series known as Valkyrie, after Norse Legend
(Graphic courtesy of NASA)

The design, deployment, range of robotic capabilities, and key operational issues of repair and maintenance of robotic assistance are a critical part of planning for deep space missions. The range of capabilities by robotic systems continues to improve to perform a range of capabilities requiring strength, dexterity, hazardous undertakings, and many skill sets requiring sophisticated sensing and logic-based operations, as well as a wide range of applications and algorithms.

⁹⁶ Bill Stafford, James Blair, and Regan Geeseman, “The R5” NASA Technology Development Program Release, (Last Accessed Mar 20, 2025) <https://www.nasa.gov/technology/r5/>

There is strong logic about the replacement of one or even two astronauts on a deep space mission with one or two astronauts. Astronauts require food, water, sophisticated environmental control and life support systems, and a significant amount of resupply operations. In contrast, a highly capable robot does not. It only needs electricity, some temperature control, and perhaps lubricant. Robots of varying designs can provide transport, strength, dexterity, and many skill sets and capabilities that include physical and sensing capabilities, memory, observational and measurement skills, and even intellectual functions. The logic of using extensive robotic skills for deep space capabilities becomes increasingly the case for very deep space missions when resupply becomes more and more difficult. The early stages of exploration to create truly sustainable and habitable base camps and more permanent types of habitats would particularly benefit from the use of robotic labor over astronaut builders.

The other consideration is the longer-term resilience and faultless operation of such robotic capabilities. Astronauts could be trained or be given repair advice or manuals to address minor issues of robotic problems or failures, but serious failures or breakdowns would require a return to Earth or abandonment. There will not be robotic repair shops in deep space for some time to come. Ultimately, the consideration will hinge on the fact that robotic devices can be left behind, but astronauts cannot be abandoned. Their health and well-being must be assured.

This is not to say robots should replace astronauts, but rather, astronauts should be supplemented by one or more robots that can provide a range of key capabilities. Such systems are much easier and more efficient to sustain and operate at great distances away from Earth. The more durable, resilient and capable such robotic systems are, with the least maintenance

and repair needs, the better suited they are for deep space operations.

NASA developed many types of robotic devices, such as Dextre for repairs and refueling, Astrobee for free flying, and R2 robots that have been tested on the International Space Station. Canada has developed several versions of the Canadarm, and the European Space Agency has developed its own mechanical arm - the European Robotic Arm (ERA) and the CIMON Crew Interactive Mobile Companion (CIMON), which was developed by Airbus and the German Aerospace Center.

These various capabilities, however, are only just a starting point. The future development of robotic systems by commercial developers can likely produce smaller, smarter, and more versatile capabilities for a host of applications that can support future space exploration mission. NASA, ESA, CSA and JAXA, in particular, should redouble their development efforts to support missions to Mars and other deep space missions.

Smaller and more compact robotic systems, such as CIMON and Astrobee, are highly mobile and versatile. They also have high levels of memory and versatile programming and algorithms. As described later in the discussion about how it might be possible to create very capable planetary habitats for Mars or elsewhere in deep space with the use of ‘smart’ robots that can be mobile broadband telecommunications and networking facilities, database access points, and also serve as sources of hundreds of computer applications. These electro-mechanical resources can evolve from ‘smart’ robots to quasi-astronaut-like aides when Mars exploration missions are planned for real within the next decade. Such versatile and mobile support capabilities can have huge potential applications for future deep space exploration. See **Fig. 8.4**

below for the CIMON mini-robot on the left and the Astrobees mini-robot on the right.

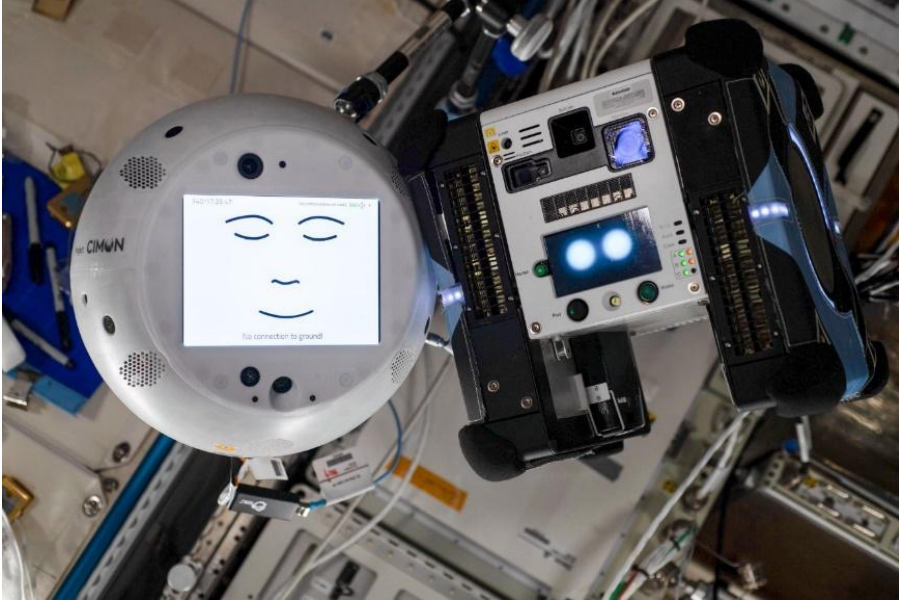


Fig. 8.4: The CIMON (left) and Astrobees (right) small robotic devices developed by the European Space Agency and NASA
(Image courtesy of NASA)

Additive Manufacturing, 3-D Printing, and Material Processing Capabilities

Another unusual “infrastructural support” that is needed to support astronauts in their deep space exploration is known as additive manufacturing or 3D Printing. These printing devices and associated material processing systems are critical capabilities for the use of local materials on the Moon and Mars to construct permanent base camps in which astronauts can reside for long periods of time. Additive manufacturing/3-D printing and material processing capabilities provide essential capabilities for creating permanent facilities, such as a Base

Camp facility, either on the Moon or Mars. Innovative thinkers such as Robert Zubrin and Gerard O'Neill have explained how the planning for a permanent human presence off-Earth will be most efficient, safe, and cost-effective by creating machinery, fuel supplies, a robotic workforce, and mechanisms as the first stage of such deep space activity.

In the case of Robert Zubrin, he has suggested that it would make sense to send automated machinery to Mars first to capture methane gas to create rocket fuel for return trips to Earth and other preparatory activities. Gerard O'Neill, in the *High Frontier*, explained the necessary steps needed to create lunar machinery to mine regolith materials, process it, and then use a mass-driver system that could transport materials into outer space.⁹⁷

This would all be precursor activity to support the construction of mass rotating cylinders that could become the home of a space colony many kilometers in diameter and much longer in length. This rotating cylinder would be sufficiently large that it could generate a viable artificial gravity that could sustain human life and support farming and a myriad of human activities.

These initial steps in robotic operations and systems would provide flexibility to construct permanent habitats that can provide astronauts with safe and secure quarters that are protected from solar flares and coronal mass ejections. They would also provide the needed sophisticated environmental controls, life support systems, and room for growing plants. Although there is logic in using such robotic systems for early operations and building of structures on the Moon, Mars, or elsewhere, there is also good reason to support astronaut

⁹⁷ Gerard O'Neill, *The High Frontier: Human Colonies in Space*, 1976, William Morrow Publishers, N.Y.

exploration and human travel to these locations in the later stages as well.

NASA has been engaged for at least six years in an effort to develop the necessary technologies to undertake new off-world automated construction. Part of this activity is the competitive “3D Habitat Challenge.” The Colorado School of Mines and ICON, a construction company that is based in Austin, Texas, are among the teams that are most directly involved in advanced R&D in this area. They have also undertaken similar work under a Small Business Development Grant from the U.S. Air Force. NASA's overall effort in this area is known as MMPACT - “Moon to Mars Planetary Autonomous Construction Technologies Program. This activity is being managed under the NASA Marshall Research Center in Alabama.⁹⁸

One of their designs is based on the material processing of mined ore from lunar regolith that has been refined to the extent that it could then be used in a large additive manufacturing process, as is shown in Fig. 8.5.

The prime challenge in this area might be the feasibility of processing materials obtained from the Lunar surface, and specifically, regolith mining, that could be proven to be suitable for additive manufacturing. This is one of the key elements of research and experimentation during the Artemis Program missions.

⁹⁸ Nasa Report, “NASA looks to advance 3D printing construction system for the moon and mars” NASA.com (last accessed March 20, 2025) - <https://nasa.gov/technology/manufacturing-materials-3-d-printing/nasa-looks-to-advance-3d-printing-construction-systems-for-the-moon-and-mars/>

Transportation Systems and Mass Driver Concepts for the Moon & Mars

The development of reliable, efficient and effective transportation capabilities to support NASA exploratory missions are key. This would be for both transport on the surface of the Moon and Mars as well as to accommodate landings and takeoffs. This is another vital service requirement to be addressed in terms of how this would be designed, developed and operated as well as how it would be accomplished safely and effectively.



Fig. 8.5: Concept of Lunar Base Camp, Rocket Landing Sites, and Other Facilities that Might be Fashioned by 3D Printing Systems
(Image Courtesy of NASA)

There are several key considerations that should be broken down into transport systems. These are: (i) astronaut transport on the surface for exploration and scientific activities; (ii) mining operations and transport of mined materials to

processing and additive processing locations; (iii) safe and secure landing and takeoff of resupply craft and transport to storage facilities; (iv) search and rescue operations for NASA related missions and other exploratory personnel by other national astronaut programs. In all of these operations, there are key questions as to how various transport systems will be powered, maintained, and/or repaired, operational safety ensured, and problems and accidents addressed. The most likely designs for vehicles, whether astronaut-driven, AI-operated, or by radio command, will likely be electrical systems with rechargeable batteries. Vehicles supporting mining operations or other dangerous missions would likely be a combination of autonomous vehicles with radio command override controls. Vehicles engaged in activities such as search and rescue or advanced scouting missions might well be supported by a micro-rotor aerial system with a wide terrain video camera such as the Ingenuity. This derives from the Ingenuity rover mission, which has been proven to fly in the Martian atmosphere.

The Artemis program will first deploy simple lunar rovers that can carry astronauts in space suits over relatively rough terrain and accommodate two astronauts. These are under development and may be deployed to the Moon with the Artemis IV mission.⁹⁹

The so-called moon rovers, known in NASA speak as Lunar Terrain Vehicles, will require astronauts to wear space suits. The vehicles are compact, mass-efficient, and minimally equipped. Thus, they are adequate for earlier Artemis missions. Nevertheless, NASA should proceed with the development of a larger vehicle that has a pressurized cabin, environmental controls, life support equipment, and the ability to operate independently on multi-day missions. This

⁹⁹ (Lunar Terrain Vehicle, NASA release, <https://www.nasa.gov/suits-and-rovers/lunar-terrain-vehicle/> (Last accessed Mar 23, 2025))

vehicle would also include radiation protection, medical supplies and equipment, air locks, communications, and power supply. This RV-type conveyance, known as the Space Exploration Vehicle, is under consideration for later Artemis missions or deployment on Mars. It would have the ability to accommodate up to three astronauts and be much more versatile. It could potentially support a variety of tasks. These could include scientific experiments, surveys, scouting operations, sample collection, and search and rescue operations. It should also be supported by a flying Ingenuity-type mini-copter with a terrain camera if it were to be deployed on the Martian surface in the 2030s. (See **Fig. 8.6**)



Fig. 8.6: Possible Prototype RV Type Vehicle for Luna Exploration
(Graphic Courtesy of NASA)

The Space Exploration Vehicle has been fabricated under a development contract with Toyota Corp and is not currently

approved for development for a specific Artemis mission at this time.¹⁰⁰

In planning for the future, NASA might also consider the need to develop what might be called a “multi-purpose trucking platform” vehicle. This would likely be equipped with a crane that would be able to transport various units designed for various functions. These carrier systems for modular units should be able to transport such equipment as material processing units, additive manufacturing units, sample analysis and scientific tests, and even habitat units. The key to transport planning would be to have carrier systems that could carry a variety of modular units and have a crane system for loading. Instead of developing the unitary and integrated VIPER robotic rover for mining, there might be a better solution. This would involve a multi-use robotic platform truck or carrier with a crane to load multiple application packages. Such a multi-use transport system could support multiple systems for mining and analysis of frozen volatiles or to acquire chunks of regolith. This might also be used to transport supplies from the Human Landing System landing site to the base camp or undertake other functions. This is the creation of a modular approach to transport systems rather than integrating all of these functions together as was the case with the VIPER mobile robotic system.

AI Enhanced Systems to Support Astronaut Missions

Finally, let’s address a capability that can be used to augment and enhance the capabilities of almost all of the various infrastructure elements discussed above. All of these deep space systems for telecommunications, navigation, position

*100 Space Exploration Vehicle, NASA Fact Sheet,
https://www.nasa.gov/wp-content/uploads/2015/08/464826main_sev_factsheet_508.pdf
(last accessed Mar 20, 2025)*

location, tele-security, energy production and distribution, robotic systems, transportation, and more can be increased in performance, efficiency, resilience, and reliability. The specific applications of AI to all of these various systems are too diverse and specific to be addressed in detail here for each of these areas. AI software and algorithms to optimize these systems can make a significant positive impact.

The interconnection of these AI capabilities with various sensors, temperature and pressure gauges, electrical usage meters, telecommunications and navigation systems throughput control systems, etc. can be very powerful ways to increase the performance in a variety of ways.

In large modern cities, these types of upgrades are currently being processed. There are smart Internet of Things (IoTs) units installed in appliances, utility facilities that range from elevators, traffic signals, water gauges, electrical power, gas and oil flow gauges, telecommunications, and navigation systems, to carry out a number of vital functions. These “smart” interactive units can detect cyberattacks, distributed denial of service (DDoS), problems with traffic signals, pipeline flow problems, difficulty in elevators or electrical or other infrastructure problems, routing difficulties, and security breaches. The addition of AI capabilities can further increase productivity, security protections, and hazard detection capabilities of these various infrastructure capabilities that are created in the hostile environment of deep space. There are numerous concerns about the various systems established in outer space. There are major fluctuations of temperatures, violent windstorms, radiation flares, and coronal mass ejections to be concerned about. Further, if there are problems in urban areas with vital infrastructure, there are teams of trained personnel monitoring these systems and teams of skilled personnel that can move out quickly to respond to outages from storms, floods, fires, or whatever. In deep space,

there will be only a few astronauts who will need to rely on vital infrastructure to operate flawlessly and with 100% reliability. They will need to rely on AI systems to provide alerts when problems occur and provide help to restore service or fix problems on an urgent basis.

There is a good deal of experience with the International Space Station to optimize the design of “smart” sensors, “smart” gauges and meters more to monitor temperature, lighting, power levels, possible air leaks, and performance of everything from environmental controls and life support systems to issues with waste management systems. The challenges of deep space on the surface of the Moon and Mars provide a much greater range of dangers. Astronauts on the ISS can make an emergency descent to the Earth’s surface, but coping with dangers and escaping to safety becomes increasingly difficult with the Moon and certainly much more so for remote Mars, which can be over two million kilometers away, and telecommunication connection relays are with long delays.

This means that the deep space infrastructure must be engineered to be extremely reliable, resilient, redundant in critical areas, and “smart”. They must also be designed to provide alerts as to dangers, system breakdowns, and optimized through “intelligence” to maximize performance.

The best of the research and engineering technology from the world of “smart” cities needs to be transferred to the system engineering units at NASA so as to develop the best designs for astronaut needs to survive on the Moon and Mars.

Universal Systems Standardization

It is imperative to use the best of the AI Algorithms, “smart Internet of Things units, cyber security systems, and protective electronics, sensors, and gauges in our deep space vital support

systems. These technologies need to be integrated into the various infrastructures examined and discussed in this chapter to keep them safe, reliable, and at peak performance. There is one other key step to take as well. This is to seek to create as much standardization of equipment and interconnection linkages as possible. This is especially true for communications, power, search and rescue systems, and environmental controls and life support systems. It appears that in the context of the world political environment, space activities, whether in Earth orbit or in deep space, will likely continue to be competitive. At the current time, lunar activities and the establishment of bases at the Moon's South Pole will be divided between the activities of the U.S.-led Artemis Program and the Chinese-led International Lunar Research Station (ILRS). This will require agreements on safety arrangements to separate landing sites to minimize the harmful dust and health dangers associated with rocket take-offs and landings.

Although there may be political competition associated with such deep space exploration and subsequent space applications, material processing and construction, there must be mutual respect for the life and well-being of all astronauts who venture into outer space. This means that there needs to be a concerted effort to standardize the interfaces and linkages between as much equipment and facilities as possible. This standardization can save the lives of astronauts and ensure safety to the maximum extent possible.

The Artemis Accords, which the U.S. led the way in drafting and signing up other countries, had 53 signatories as of March 2025. On the subject of "Interoperability," this Accord states:

"Interoperability of systems is critical to ensure safe and robust space exploration. Therefore, the Artemis Accords signatories commit to use reasonable efforts to utilize

current interoperability standards, to develop new standards when necessary, and to follow such standards.”¹⁰¹

This is a useful statement of principle for helping to preserve the safety of astronauts in deep space. Yet, as noted by the Executive Director of the International Association for the Advancement of Space Safety (IAASS), there must be difficult and demanding technical standards work undertaken to ensure that search and rescue systems are designed to be interoperable. This will not be possible without engineers designing truly interoperable systems. And this will also be true of power distribution, all forms of telecommunications, life support systems, and everything that requires power, telecoms, or physical interconnection. Currently, most systems for the Artemis program have already been designed and fabricated. As of yet, there has been little activity in undertaking discussions of design specifications to allow interoperability to be achieved. Without this engineering and standardization effort, the systems that China, Russia, and other participants in the International Lunar Research Station will not be able to achieve interconnection and interoperability with the systems that are to be used in the Artemis Program.

It is not logical to say that this will be their loss. Indeed, it might well be Chinese or Russian-designed equipment that could be used to save astronauts working on the Artemis Program and not the other way around.

Conclusions and Findings

There are a significant number of areas where support systems will be needed to support astronauts as they stay longer and longer in deep space to carry out their missions, create permanent base camps, and engage in space mining, material

¹⁰¹ *The Artemis Accords*, <https://www.nasa.gov/artemis-accords/> (Last Accessed March 30, 2025)

processing, and move from exploration to a myriad of applications. A great deal of research and development needs to be undertaken to develop capabilities in these areas. One of the key aspects to keep in mind is that capabilities developed in these areas for the Moon or Mars might very well be excellent new capabilities to also be used on Earth. The opposite could well be true.

Some of the most important areas that need to be research and developed to support deep space exploration are examined below.

Telecommunications, navigation, search and rescue, and related services

The type of telecommunications systems devised by the Artemis program for Astronauts to communicate back to Earth from the Moon's South Pole, by using the Lunar Gateway Space Station and Ka-band radio communications, will not really be sufficiently broadband as a model for a telecommunications system for Mars. The search and rescue network for the Moon, however, should be easily adapted for Mars. There is the development of an optical communications system, perhaps using blue or green laser-generated signals and an effective relay system for when Mars and Earth are on opposite sides of the sun. This would require a new Earth-based Deep Space Network. Since this is a long lead-time and expensive undertaking, this should be considered a high-priority new capability to research and develop to support a future Mars mission. The optimal satellite configurations required for a Mars-to-Earth broadband relay system should be a starting point.

Energy, electrical power, and lighting

The energy, electrical power source, and lighting for Mars may likely require nuclear power sources. High-efficiency solar cell systems may be appropriate for some of the electrical power supply. New technology, such as quantum dot solar cell systems or ultra-violet multi-junction designs, should be monitored to ensure resilience and power production efficiency. Clearly, there is an active research agenda here, but the latest technology and capabilities might well be generated by corporate research for green energy systems here on Earth. Monitoring new developments in photovoltaics, nuclear energy, quantum dot technology, rechargeable batteries, and so on may be the key path forward to power supply, electrical energy, and lighting systems. Concerns such as temperature extremes and radiation suggest that Earth-based systems still have to be adapted to use in deep space.

Robotics

The future of robotics will also move forward rapidly for Earth-based uses. There are unique conditions of deep space that must be considered. These include weightlessness, micro and sub-g gravity, vacuum or thin atmospheric conditions, radiation concerns, severe temperature ranges, and more. These unique conditions will require NASA to maintain its own longer-term research capabilities in this regard. In addition to technological advances and concerns about adaptability, there are also psychological considerations. These will likely be involved if astronauts find themselves with robotic units that evolve into what are equivalent to close partnership conditions. The social dynamics and partnership dependence that may evolve with close association with “smart” robotic partners must be considered along with the technological development and programming of robots that may be increasingly perceived as “humanoid.”

Material processing and additive manufacturing /3D printing systems

This is one of the areas where very rapid technical development is not only possible but very likely. There is a very rapid technological evolution now occurring with regard to material processing. This relates to the nature, composition, and especially the make-up of deep space materials that can and will be obtained from the Moon and Mars. There is a need to understand more clearly what materials can be obtained from the Moon and Mars, and the ability to process these mined materials to an extent that they can be used for building habitats, creating structural elements with strong tensile or other types of strengths. This then relates to the extent to which these materials extracted from the Moon or Mars might be applied to 3D printing to create a variety of products or structures. This is one of the few areas where new understanding will need to await experimentation, and applications must await the Artemis explorations on the Lunar surface. Simulations and modeling can provide a head start, but actual experimentation and final test results on the Moon must await actual test results.

Transportation and Mass-Driver Systems

Transport systems on the Moon will be key to success. The idea of more modular systems that can serve many purposes could aid research and exploration efficiency. Lunar Transport Vehicles that do not have pressurized cabins increase the risk for astronauts. Space Exploration Vehicles that provide more radiation protection and breathable air are still not developed, and their availability dates are unknown. The systems for Mars, from rovers to micro-rotor flying camera systems, are years away. Experience from the Artemis Program exploration will provide significant input into the planning for Mars missions. Vehicles with rechargeable batteries will be key to

both Lunar and Mars exploration. Robotic transport systems that can successfully navigate the Lunar terrain will be crucial to the future development of vehicles for Mars. Telecommunications, navigation, position location, and search and rescue systems to support the transportation operations for the Artemis Program will likely be replicated for Mars.

One of the key questions is whether the mass driver system envisioned by Gerard O'Neill will actually be designed and built on the Moon and perhaps Mars as well. Certainly, new and more easy-to-construct designs that use fewer materials and new construction techniques make this type of high-efficiency launcher system easier and less costly to build. In light of the much lower gravity of the Moon, such systems might be used to launch astronauts and various things into orbit. There is, in this case, the question of not only how it can be done but also how safe it will be for various types of cargos, including humans. There is clearly a rich research and development program to be developed in this area for transport on both the lunar and Mars surfaces, and also transport of materials to lunar orbit and the safety of these operations.

One of the critical issues is not only the “hows” and “whys” of putting things into lunar orbit, but rather the increasing concern about the safe and secure way of removing them so as to avoid orbital debris issues and concerns not only for Earth orbit that is such a huge problem today. It is odd that humans forget many of their worse mistakes and repeat them over and over again.

AI-enhanced systems;

In all the previous areas of research and development, the deployment, use, upgrade, and even safe retirement of obsolete AI-enhanced systems will be highly relevant. NASA

will need to develop and enhance the performance of all these systems using AI technology. This goes for telecommunications, navigation, search and rescue systems, power, electrical energy generation, energy efficiency systems, robotics, mining, material processing, additive manufacturing, and transportation systems.

This will involve not only the efficiency and effectiveness of their performance, but also their protection against cyberattacks, their maintenance, repair, and upkeep, and their reliability, resilience, and safety of operation.

There is a tendency to let efficiency of operation and productivity drive technology advancement, but in this case safety and protection of the systems in which they are used, and human/astronaut safety should be paramount. The truth is that AI Systems and AI Chat-based capabilities will become a universally used capability that will be key to the efficiency and effectiveness of all the other support systems addressed in this chapter.

Interoperability and Standardization of All Support Systems for Astronaut Exploration

Astronauts are representatives of all humankind. The protection of the health and safety of all astronauts is enshrined in the Outer Space Treaty, and then spelled out in greater detail in the Rescue Agreement and also clearly expressed in the U.S. led Artemis Accords.

This Rescue Agreement is formally known as the “Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space.” This international agreement was negotiated within the U.N. Committee on the Peaceful Uses of Outer Space and its Legal Subcommittee in the 1960s and was then

approved by the General Assembly in 1967 by consensus in Resolution 2345 (XXII). It was quickly ratified by a sufficient number of countries to enter into force in December 1968.¹⁰²

These various commitments and admonitions to protect the health and safety of astronauts are one thing. The actual creation and execution of interoperability agreements that will allow the emergency recovery of space support systems that protect the lives of astronauts and allow their actual rescue is another. NASA, along with other space agencies of the world, needs to actually cooperate with other space agencies to ensure that all spacecraft, launchers, space suits, and support systems, as discussed in this book, are designed to be interoperable with various linkage systems used by all space explorers from around the world. These standards are for interoperability that would support the rescue of all astronauts operating on the Moon, Mars, or wherever else they may be in the realm of outer space.

R and D in all of these support areas addressed in this chapter are key to astronaut safe travel and exploration and should be pursued so that these systems perform reliably, effectively, and most of all, safely. The international Association for the Advancement of Space Safety (IAASS) has sought to champion these interoperability standards and to seek to ensure they are implemented. This is key to the safety of all astronauts of the world.

¹⁰² “*Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space*” December 1968
<https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introrescueagreement.html#:~:text=The%20Agreement%2C%20elaborating%20on%20elements%20of%20articles%205,States%20shall%2C%20upon%20request%2C%20provide%20assistance%20to%20launchin>

Conclusions

This chapter has sought to emphasize that astronaut exploration, particularly in the hostile environment of deep space, involves much more than space suits, rocket launchers, space capsules, and lander systems. There are a wide range of infrastructures to provide key support systems. These are technically complex, expensive to design, build, deploy, operate, maintain and service. These various systems must also be updated and replaced when they become antiquated or no longer function. They must be targeted R&D to develop these support systems, because deep space exploration by astronauts would not be possible without them. The key space system infrastructures that are covered in this chapter and needed new and expanded capabilities include the following seven areas.

- Telecommunications, navigation, search and rescue, and related services
- Energy, power and lighting
- Robotics
- Material processing and additive manufacturing /3D printing systems
- Transportation Systems and Mass Driver Concepts for the Moon & Mars
- A I-enhanced systems
- Space systems and their international compatibility

This chapter addresses many research and development goals and specific technical efforts to create vital infrastructure needed for future deep space exploration initiatives. There are three specifics area that particularly require a focused effort.

First, there is a need for a broadband deep space telecommunications system. This includes the need for an optical broadband relay system for Earth to Mars

interconnection via a satellite relay system plus a supporting Earth-based optical Deep Space Network. This would likely include both an upgraded DSN to support both broadband RF and optical communications. This one new capability involves the most important and needed deep space support development and likely the most expensive capital expenditures.

A second key area is the energy production capabilities to support any permanent lunar or Mars based astronaut living facility. This would very likely be the sort of nuclear power system that was discussed.

Third, and for the longer term, there is the idea of creating an electro-magnetic shielding capability to protect Mars from solar wind that strips away its atmosphere has enormous potential impact implications. This would be an extremely difficult and technologically challenging approach. Yet, if this were to become technologically possible it could change the course of space exploration and what it means for humanity's longer-term future. It is because such a technical capability could be a game-changing new technological capability that could lead to creating a livable environment on Mars, that it should also be given significant support.

There are dozens of other R&D efforts addressed in this chapter, but these three highlighted above are among the top priorities.

Chapter 9

Promising New Launch Vehicles Technology for Human Space Travel

Introduction

Since the first days of rocketry, with the first Goddard rocket launches and then the development of V-1 rocket launchers of World War II, there has been a steady increase in the size, power, and reliability of rocket launchers. The last decade and a half has seen a remarkable surge in launcher and rocket engine development. The development of rocket engine design and production to be reusable has led to a sudden increase in safety and performance, as well as a decrease in launch costs. This increase in performance and decrease in cost has been driven in large part by so-called “NewSpace” industries such as SpaceX, Blue Origin, New Zealand’s Rocket Labs, Northrop Grumman Innovation, and others. They have led the way in what might be called a revolution in rocket launcher design, engineering, reliability, manufacturing, and cost reduction.

There are three key factors that contribute to this rapid rate of innovation. First and foremost has been the development of reusable rocket motor engines. In many instances, they can be returned to precision landing sites so that these rocket stages can be refurbished and reused. In some cases, launchers as well as capsules can be reused some five to ten

times. The Dragon Crew Capsules were designed for possible five times reuse. The Boeing CST-100 Starliner was, in theory, designed for possible ten-fold reuse, but it has not yet been space safety qualified after a series of misfortunes.¹⁰³

Second, there has been advanced in the 3-D printing of rocket motors. This has been pioneered by Rocket Labs, but many others, including NASA, are pursuing seeking to develop this type of capability. NASA has even demonstrated over a year ago the 3-D printing of metal components on board the ISS.

Third, there has been advancement in overall precision and quality manufacturing to critically exacting standards and rapid production of rocket motors of the highest reliability and near faultless performance. The SpaceX high thrust Raptor rocket engines used to launch the Falcon Heavy launcher have proven to be very reliable in performance and of increasingly low cost. The Blue Origin B-4 motors that are being used in the new Vulcan launcher and soon the New Glenn launcher. These two engines have both demonstrated these same quality production and reliability characteristics.

There have recently been issues with the Raptor engines that are now being produced at great speed, with a rate of one engine a day rolling off an assembly line. The failure of six Raptor engines in the latest Starship test flight has led to questions about the production and rapid assembly of the 33 Raptor engines for the Starship. There is now great pressure on SpaceX to be able to develop and deliver the modified Starship as the Human Landing System for the

¹⁰³ (Joseph Pelton and Peter Marshall, *Safety First: A Review of NASA Spacecraft for Astronaut Missions*, (2024) PM Associates, Washington, D.C. pp 261-266.)

Artemis III lunar landing, which is in danger of not meeting its September 2026 launch date. The grounding of the Starship pending investigation of this latest Starship failure clearly threatens the Artemis III planned launch operation in the third quarter of 2026. This launch failure for Starship 8, which is the second launch failure in a row, has prompted the FAA to put a ground stop on further launches until after a full-scale accident review is completed and a clear understanding is reached as to the cause of this latest failure.¹⁰⁴

It has also been suggested that the strategy of clustering a number of very reliable rocket engines together to produce higher and higher performance launchers, such as is being done by SpaceX and Blue Origin. Rather than continuously developing rocket motors, there is a further key element to improve launcher performance, safety, and cost reduction. This strategy, however, may have its limits. If the production rate becomes too rapid with insufficient quality controls in effect, or there are other issues, such as exact sequential firing systems or other simultaneous control issues. These are key but shorter-term development issues. This chapter seeks to examine longer-term research efforts and efforts to create new, safer, and perhaps more cost-efficient ways to reach outer space.

This chapter seeks to find better space transport technologies that can be deployed in the next 10 to 20 years, while the above-noted “NewSpace” development trends with conventional rocket systems continue. It is hoped that the various key advances mentioned above will continue to

104 Mark Moran, “FAA Issues Ground Stop after SpaceX Loses Contact with StarShip 8 Minutes after Launch” *UPI News*, March 6, 2025 <https://www.msn.com/en-us/news/technology/faa-issues-ground-stop-after-spacex-loses-contact-with-starship-8-minutes-into-launch/ar-AA1ApuSz?ocid=BingNewsSerp>

produce even further gains as the pursuit of new launch systems is being researched and perfected.

The goal is to pursue truly new launch capabilities that can potentially support even safer, more reliable, and higher performance capabilities. It is hoped that these new ways to go to space might not only support deep space missions, but might also enable the more economic new capabilities needed in Earth orbit. One goal would be to find more economical means to remove space debris from orbit or to repurpose defunct spacecraft that are no longer able to perform their original intended purpose.

It is to be hoped that some of these new technological options and transport systems might be developed to not only boost reliability, performance, safety, and reliability, but also drive down costs and make launch operations more sustainable in terms of impact on the climate and provide cleaner launches that can help abate climate change concerns.

Optimizing reusable launchers with more sustainable propellants for launch operations and spacecraft maneuvering systems

As noted in the introduction, there has been remarkable progress in developing new and better launch systems. The last few years have seen rapid new developments. These include Falcon Heavy and the Starship by SpaceX, the Vulcan Centaur by the United Launch Alliance, Ariane 6 by Arianespace, and the New Glenn by Blue Origin are significantly more capable than the Space Launch System (SLS) that is currently slated as the prime launch vehicle for the Artemis Program despite its huge cost. The Falcon Heavy was substituted for the SLS in the launch to the Europa moon of Jupiter because of cost and scheduling

issues. This change of launch arrangements represented savings that could be variously stated to be five to ten times, or even more, cost-effective than the SLS. Further, the Falcon Heavy also has a more proven reliability record.

The number one launch issue facing NASA at this time is whether the Space Launch System and the Orion capsule will be phased out of operations? And if so, when and how will this occur. This is a policy issue that is beyond the scope of this study, but it is still a key and important concern. Both the SLS launcher and the Orion capsule, which currently represent technological approaches to astronaut deep space transportation, are two decades old in their design and engineering. Both are extremely cost-ineffective, and there are also safety concerns in their designs. A switch in both the launcher rocket and a suitably sized capsule for the Artemis program to more modern astronaut systems that can be safely verified for future deep space needs needs to be urgently decided by NASA officials and the U.S. Government.

A number of optional capabilities are possible, but the decisions might involve not only the choice of vehicles but even a change in the mission architecture, with flights to the Moon perhaps being initiated from low Earth orbit. This would involve future astronauts boarding their space transport systems going to the Moon or Mars after their launch system has been successfully sent to LEO, refueled, and system tested. These decisions are crucial and should be taken as soon as possible. Possible options of this nature are discussed in the second edition of *Safety First: A Review of Astronaut Spacecraft for Astronaut Missions*.¹⁰⁵

¹⁰⁵ Joseph N. Pelton with Peter Marshall, *Safety First: A Review of Astronaut Spacecraft for Astronaut Missions* (2024) PM Associates, Washington, D.C. Chapter 21 and particularly Recommendation 3.

There are concerns about launcher technologies other than those used in NASA astronaut missions. A number of launch vehicles are now being used for sub-orbital flights with crew and passengers aboard. A number of these launch operations are either quite dirty in terms of releasing metal particulates into the delicate and very thin stratosphere or releasing methane greenhouse gases. It is hoped that future generations of these vehicles will be redesigned to be hydrogen-fueled with liquid oxygen oxidizers or otherwise able to lift astronauts to space in a cleaner way. In addition to greater safety for astronaut and citizen astronaut flights, we need to seek to provide cleaner flights for our own planet's residents as well. We need to seek to find alternative launch systems for NASA vehicles and private commercial citizen astronaut flights that reduce the release of greenhouse gases or even dirtier metal particulates.

From a policy or standards-making perspective, it might be useful for governments to offer financial or other incentives to develop these cleaner fuel systems and/or establish various types of deadlines for cleaner-fueled systems. These new limits would set dates for penalties to go into effect if new cleaner fuel systems are not developed by a date certain.

There might be ways to address such issues in a way to incentivize this transition by committing to a certain amount of launch operations associated with space debris removal that would require the associated launch operations to use cleaner and greener liquid fuels and prohibit dirty solid fuel launchers to be used for such operations.

With this introduction, let's explore key longer term research options for launch systems to Earth orbit and to deep space.

Nuclear Propulsion

One of the technologies that has been studied for decades for launch systems involves the use of nuclear energy. There is a range of ways in which this can be used. It can be used as a power source within a launcher system, and it can be used as a power source for propulsion. Each of these different nuclear systems will be discussed in terms of the potential nuclear application, current state of development, and research and development needed to achieve practical use. Most of these applications and uses are most likely to be applied in the context of deep space exploration and applications in future missions to Mars and perhaps in the longer term for astronaut missions to the Moon, perhaps in the 2040s.

Nuclear power sources

In Chapter 8, it was noted that small modular nuclear power installations might be used as a power source to provide electricity for habitats on Mars. These might be based on smaller radioisotope power generators, up to small nuclear reactors that are based on nuclear fission, or, for the longer term, conceivably based on nuclear fusion. Technical improvements that are ultimately developed in this area might ultimately be applied to space transportation systems. These might be able to generate enough power to provide electricity to a large lunar research and exploration base camp on the Moon or Mars.

Many of the propulsion concepts that have been tested and could be implemented in the short term involve the heat from nuclear reactors to create thrust. Here are three examples.

Nuclear Thermal Rockets (NTR)

This type of rocket power is the result of a three-step process. These three steps are: (i) generate extremely high temperatures by means of a fission reactor, (ii) transfer this generated heat to a liquid propellant such as liquid hydrogen, and (iii) expel the liquid propellant at very high speeds via a nozzle to create propulsion. This type of rocket has been under study by the British Interplanetary Society and DARPA as far back as the 1960s and 1970s. There have been as many as ten different research projects to examine and test the theoretical possibility of this type of NTR propulsion. These studies include the British Interplanetary Society (BIS) Daedalus project and the DARPA Orion project. These have largely been conceptual studies. None of these fission-based NTR systems has flown on an actual rocket system to date. NASA halted its fission-based NTR research program in the 1970s when it began to gear up the Space Shuttle Program after the end of the Apollo Program. More recently, such NTR rocket studies have focused on Fusion reactor-powered NTR-type launchers.

NASA has been working at a theoretical level in this area for many years, as have some research universities, such as Princeton University's Advanced Physics Laboratory. The fuel efficiency that might be achieved makes this type of propulsion technique a plausible approach to long-range interplanetary travel. This could be achieved with either a nuclear fission or a nuclear fusion reactor. This approach of using nuclear reactor heat rather than direct propulsion, from a safety standpoint, seems to have clear advantages.¹⁰⁶ (See **Fig. 9.1**)

¹⁰⁶ NASA release: *Nuclear Thermal Propulsion: Game-Changing Technology for Deep Space Exploration*, <https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/nuclear-thermal-propulsion-game-changing-technology-for-deep-space-exploration/> (Last accessed Mar 30, 2025)

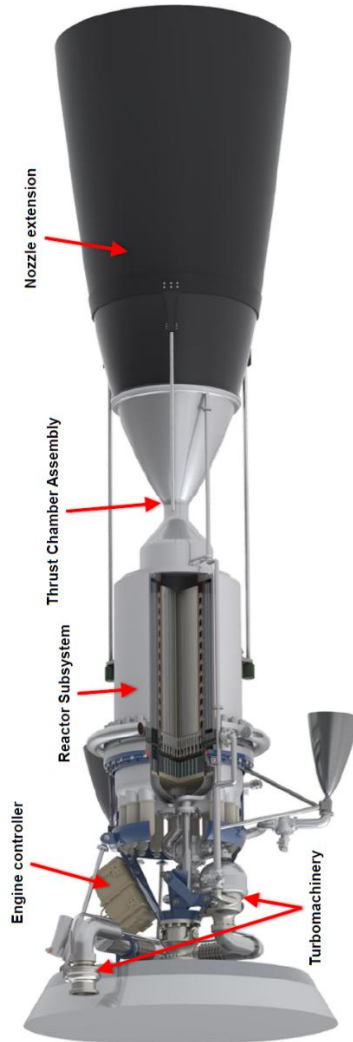


Fig. 9.1: Diagram of Nuclear Thermal Propulsion System being researched at NASA Glenn Research Center
(Graphic courtesy of NASA)

Nuclear thermal propulsion has the advantage over chemical rockets in two ways. First, it can deliver thrust efficiency at twice the effective thrust of chemical propellants. This is because liquid hydrogen is less massive than the chemical explosives and also the burning of hydrogen gas is cleaner than chemical fuels and especially of solid fuel rockets that expel dirty particulates.

Nuclear electric propulsion: A much different type of approach is to use heat from a fission or fusion reactor to drive turbines to generate electricity in a way resembling a nuclear power plant. In the context of propulsion for a rocket system, the electricity that is generated could then be used to ionize a gaseous propellant and electromagnetically accelerate it. This type of ionized thruster unit is being used today to stabilize spacecraft. The Power and Propulsion Element (PPE) for the Lunar Gateway Space Station will use electromagnetic thrusters to propel the HALO and PPE units to their special Lunar orbit around the Moon. The conventional solar power cell generates electricity on the PPE, which means that this trip will take almost a year's time to reach its final destination. A nuclear electric propulsion power set of thrusters, in contrast to solar cell-generated electricity.

Thus, the NEP approach would generate more thrust and a much faster transit time. Nuclear electric propulsion is much more efficient than chemical thrusters, which produce a short burst of thrust, but then they consume a lot of fuel all at once. NEP thrusters, in contrast to chemically fueled thrusters, produce much less thrust. Yet they can build up speed by constant and ongoing acceleration that just keeps building up velocity month after month. The acceleration rate is less, but it is constant, and thus the spacecraft speed builds up over time with the much less energetic ionic thrusters. Thus, NEP thrusters might seem slow “turtles” at

the start, but they will be moving much faster than a chemically fueled “hare” at the end of a race across interplanetary distances. If an NEP launch system is given enough time to build up its velocity, it could indeed reach very fast speeds.

NEP ionic thrusters would not be able to be used for liftoff from Earth. They could, however, be used for true deep space exploration starting from, say, GEO orbit, where the g-force is only 2% of that at Earth’s surface. The speed of a spacecraft using NEP ionic thrusters could steadily build up over a year’s time to reach speeds much faster than a chemical rocket that had expended all of its energy in a quick and exhaustive burn-up of all of its fuel. If one wanted to send a spacecraft from the Moon to go out to the Oort cloud at the edge of our solar system, an NEP thruster system might be the ideal propulsion system. It would also be possible to use chemical boosters with a NEP system to boost speed.

In March 2025, Pulsar Fusion of Bletchley, England, under funding by the U.K. Space Agency, unveiled what they have named the Sunbird Migratory Transfer Vehicle that would be propelled by a fusion-powered nuclear electric vehicle. This vehicle, according to Pulsar Fusion, is claimed to be ready as early as 2027. If it fulfills all of its stated goals, it could reduce the transit time to Mars by half that of conventional chemical launchers, which would require about nine months to reach the Red Planet.¹⁰⁷ (See **Fig. 9.2**)

¹⁰⁷ “Pulsar Fusion’s Sunbird Unveiled: Nuclear Powered Rocket to Slash Interplanetary Travel Times” Globe News Wire, March 10, 2025 <https://www.morningstar.com/news/globe-newswire/9391239/pulsar-fusions-sunbird-unveiled-nuclear-powered-rocket-to-slash-interplanetary-travel-times>



Fig. 9.2: The Pulsar Fusion Concept of a Nuclear Electric Interplanetary Vehicle
(Courtesy of U.K. Space Agency)

Nuclear Ramjet Propulsion: This approach is only applicable to hypersonic transport operations within the realm of the Van Karman line limit of 100km altitude. The idea is to use nuclear reactor to superheat sucked in air and eject in at hypersonic speeds.

All of these concepts essentially use the heat and/or thrust capabilities of nuclear reactors to create propulsion. This could be to heat fuels that can be expelled at high speed through a nozzle, or generate electricity to create ionic thrusters, or some variation of these concepts. There are

other concepts that up the ante to use nuclear explosions or pulsed nuclear events to directly capture explosive force. The use of nuclear fusion forces may be more adept to this more direct use force of coolants expelled directly from a nuclear reactor to achieve much more powerful propulsive force that could be used for launch of space rockets from Earth. NASA had concentrated most of its nuclear research in rocket propulsion into using nuclear reactor heating capabilities as noted above.¹⁰⁸

There are, however, other concepts that might be used for more direct use of nuclear energy in terms of nuclear fuel propulsion that is more direct. These concepts include Direct Nuclear Propulsion and Nuclear Pulse Propulsion.

Direct Nuclear Propulsion (Gaseous or Plasma)

This approach would use coolants for a nuclear reactor to create very high levels of thrust. This expelled coolant could be gaseous or plasma that would be created at very high thrust levels. These forces would be as high as 30 to 50 kilo-Newtons per second per 1 kg gram of expelled coolant gas or plasma.

Nuclear Pulse Propulsion (NPP) This approach to nuclear propulsion is also known as external **pulsed** plasma propulsion (PPE). The concept is based on the concept of contained or the focused force of nuclear blasts in pulses could create thrust for rocket propulsion for interplanetary travel. In the 1950s and 1960s both the British Interplanetary Society and DARPA examined this hypothetical method of spacecraft propulsion that use contained nuclear blasts for thrust. It was seriously studied

¹⁰⁸ Joseph N. Pelton, *Space 2.0: Revolutionary Advances in the Space Industry*, (2019) Praxis Publishing, Switzerland, Pp 148-150.

in DARPA's Project Orion. Newer designs using inertial confinement fusion as a propulsive force. The achievement of controlled nuclear fusion that could be contained by very powerful electromagnetic forces would likely be needed to make this a viable and safe form of nuclear propulsion and thus is a long way in the future launcher propulsion scheme.

Tether Lifting and Space Elevators and Funiculars

The idea of a geosynchronous orbit whereby a satellite or a space station might continuously travel around Earth and stay constantly positioned at the same location above Earth's equator was actually first conceived by a Slovene scientist engineer named Hermann Potocnik. His publishing name was the pseudonym Hermann Noordung. In his only book, published in 1929, *The Problem with Space Travel*, he wrote about the possibility of creating a space station that could be deployed in such an orbit. Later British scientist, engineer and science fiction writer Sir Arthur Clarke wrote about the potential of satellites for telecommunications services in an article published in 1945 suggested that three satellites appropriately positioned around the world about 120 degrees apart and deployed in a geostationary orbital location some 35,786 km above Earth's equator. 22,236 miles and following the path of the Earth's rotation could provide complete coverage of the world for telecommunication services. At the time there were no launch vehicles that could launch satellites and radio tubes tended to burn out so this would require a space station with a crew to replace the radio tubes.

Clarke, however, not only described the technical aspects of such a global communications system. He also indicated that this geostationary orbit could also be used as a place to create a space station where a tether system might be deployed to reach down to the equator to bring objects up

from the ground. He also explained that the tether would need to extend upward above geostationary orbit to create a sort of “antigravitational pull” to offset the huge mass of the tether below. The entire system would need to extend a total of 144,000 kilometers to make the physics and the equalized gravitation and rotational momentum forces offset. Clarke recognized the difficulty of accomplishing such a space elevator, or space funicular, that would have carriage systems both going up and others going down to offset each other, and he did not envision this might be accomplished in his lifetime. In 1979, however, he wrote the Science Fiction story “The Fountains of Paradise” that described such an engineering marvel and then later he wrote “3001: The Final Space Odyssey” in which humanity had moved to live in incredibly tall towers that were essentially space elevator constructs ... and planet Earth had become essentially a park for wildlife.

The idea of a feasible plan and appropriate materials of the needed tensile strength, and the problems of radiation in the Van Allen belts, and other scientific and engineering challenges have not led to any credible plans to build such a space elevator to lift cargo to space. Other scientists and engineers have suggested that tether lifting systems that do not require a tether of such tremendous length and such enormous technical difficulty. These tether concepts have thus been seriously examined.

A tether, when deployed from a spacecraft in Earth orbit, could conceivably be used as a means to lift mass to a higher altitude through what is known as momentum exchange between an orbiting facility with a tether that could attach to an intended payload and fling it to a higher elevation. This also takes advantage of the Earth’s velocity and rotational speed and is most advantageous from the equatorial location where the Earth’s rotation is the most rapid, and

the payload has the advantage of moving at about 1600km/hr or 1000 miles per hour.

To achieve this in practice, the orbiting facility's mass would need to be on the order of a 1000 to 2000 times greater than the prospective payload and the orbiting "Sky Hook" would also need to use something like ion thrusters to regain its original velocity and orbital elevation after such an orbital lift operation.

This type of orbital lifter is known as the Sky Hook concept. This has been proposed in various forms since it was first conceived and published by J.D. Isaacs and his colleague in 1966, some nine years after the Sputnik launch in 1957. The concept of a "Sky Hook" envisioned that the tether would rotate around the orbiting "Sky Hook" satellite's center of mass, but in a direction that was the direct opposite of the "lifting mass system's orbital motion. The tip of the rotating tether of great length could then reach enormous speeds.¹⁰⁹

This reversal of the tether rotation with respect to the satellite's orbital flight would allow the speed of the hook relative to the ground to be reduced at the point of its lowest descent. At this point, it could, in theory, capture the payload and then essentially yank it up into orbital speed and release it when it has maximum velocity. This design approach serves to reduce the required strength of the tether and makes coupling on the ground easier to achieve. (See **Fig. 9.3**)

109 J.D. Isaacs et al. (1966). "Satellite elongation into a true "sky-hook"". *Science*. 151 (3711): 682.3 Bibcode:1966Sci...151..682I. doi:10.1126/science.151.3711.682. PMID 17813792. S2CID 32226322



***Fig. 9.3: Conception of a Sky Hook in space
(Artistic impression)***

The proposed approach would require a tether of enormous tensile strength such as carbon fiber substance equivalent to diamond in its strength. To date, the longest tether that has been successfully lowered from a satellite is 31.7 kilometers or 19.4 miles, and this remains today as a Guinness World Record. Clearly this remains a largely theoretical concept today.

There was a study by Boeing of another approach that would involve the use of a hypersonic Scramjet aircraft that could reach an altitude of 100 km. This study suggested that the transfer might not be targeted to occur at ground level but rather at hypersonic speeds of up to Mach 10 (This would be equivalent to a velocity of 3.6 Km/ Sec) at 100 km altitude where it would allow a payload to connect from a Sky Hook's tip also rotating at a speed of 3.6 Km/ sec. This would be equivalent to a speed of 2.25 miles/second, and the exchange would take place at an altitude of 62.5 miles high. In order for this orbital lift apparatus to work, it would require the tip of a tether to travel some 600 km or 375 miles to reach an amazing speed of Mach 10, and for the hook of the rotating tip to exactly coincide with the speeding aircraft.¹¹⁰

The one clear advantage of this approach is the fact that the tether could be constructed of conventional and much more cost-effective materials, such as a very high molecular weight polyethylene construct rather than extremely expensive "Bucky balls." This study was known as the Hypersonic Airplane Space Tether Orbital Launch (HASTOL)

¹¹⁰ "Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Study, Final Report," Boeing Corporation/ Tethers Unlimited, Inc. 2000, https://www.niac.usra.edu/files/studies/final_report/391Grant.pdf

Other scientific writers, who also write science fiction has suggested. If one cannot create a viable space elevator/space funicular for Earth, perhaps it might be accomplished for Mars. Its lower gravitational field and lack of radiation zones might make this possible. The Moon is too close to Earth to make such a system work from the lunar surface, but examination of a serious engineering plan for Mars has yet to be done.

There is another way, however, to view the use of tethers and their ability to support a transport system. If a tether is designed as an efficient electric conductor, it can be used to generate electric power due to the Earth's magnetic field. There are scientists and engineers who have suggested that a sufficiently long tether, perhaps two kilometers long, could be deployed in Earth orbit, which might be able to generate enough electricity to heat ion thrusters to sustain their operation in Earth orbit for a significant period of time. One company, known as STAR Technologies, has proposed to design, build, launch, and deploy such a "tether-fueled" vehicle that would be able to operate for years in Earth orbit and undertake the deorbit of space debris as its mission. This tether propulsion system that STAR Technologies proposed to design and build was known as EDDE, which stands for "Electro-Dynamic Debris Eliminator". Technical viability and engineering efficiency are technical concepts that might most likely be achieved in the near term.

One feature which is common to all of the ways to launch mass into orbit discussed in this section is that they depend on the Earth's magnetic field and the Earth's rotational speeds to lift satellites into orbit or help to deorbit defunct materials. This eliminates or diminishes the need to use rocket fuels. Any future space transport systems that reduce the need to burn rocket fuels, create more greenhouse gases, and preserve the fragile upper atmosphere of our planet are

a plus. Several other future space transport systems discussed in this chapter would also present this advantage.¹¹¹

Rail Guns, Also Known as Mass Driver Systems, for Lunar or Mars Surface

The idea of a rail gun or mass driver system also relies on magnetic systems in the form of accelerator systems. The initial ideas in this area involved creating magnetic accelerators that could create the speed of payloads that are sufficient to send them to orbit from Earth. These ideas include the concept of creating such a system on a very high plateau since the higher the accelerator system, the less air and wind resistance there is, and also the less gravitational force to overcome. The further an object is away from the Earth's center, the smaller the gravitational attraction. At an elevation of say 8 kilometers (or 5 miles), this would be very small indeed, but a satellite in geosynchronous orbit has only 1/50th of its weight at the Earth's surface. The concept of a rail gun and the equivalent g forces of its launching things to orbit in this way would be only for cargo and not people. If one were to think of using such systems for launching craft from the surface of the Moon or Mars, the g-forces would be much less. The relative gravity of the Moon and Mars is 17% and 38%, respectively. On Earth, the g-force acceleration rate is 9.8 meters/s², but for the Moon it is only 1.62. meter/ s² and for Mars it is 3.711 meters/ss². This means two things. One thing would be a type of system that is much easier to devise, and the acceleration forces would not be as difficult for the human body to withstand.

¹¹¹ Jeremy Hsu, "Kilometer Long Space Tether Test Fuel-Free Propulsion" *Scientific American*, Nov 4, 2019, <https://www.scientificamerican.com/article/kilometer-long-space-tether-tests-fuel-free-propulsion/>

The idea of creating a rail gun or mass driver magnetic accelerator for both the Moon and even Mars has considerable merit. The acceleration goals for the Moon are only 17% of those needed for an Earth-based rail gun. Once built, this could be a cost-effective means of launching the solar system to virtually every location. This would be more cost-effective and safer than rocket launches. NASA has been studying the concept of rail guns for years. The technical concept of magnetic accelerators is very broad in scope. The concept could be applied to so-called “MagLev” (i.e., magnetic levitation) trains for transport on Earth, for launch of cargo to orbit, for launch from the surface of the Moon or Mars, or even designed to launch to deep space locations. This is a system that does not even need to be on a solid surface. A mass accelerator system could thus be operated from Earth orbit or other locations, such as in orbit around the Moon. NASA research should seriously explore all these options and give serious consideration to a lunar-based rail gun as advocated by Gerard O’Neill in *The High Frontier*. Below is a NASA artistic conception of a rail gun launch facility. (See **Fig. 9.4**)

Gravity Assist Concepts

The concept of gravity-assisted launches is certainly not new. The Voyager 2 spacecraft used gravity-assist several times to visit Jupiter, Saturn, and Uranus on its way out of the Solar System. The Parker Solar Probe used gravity-assist from orbiting Venus to fly within 4 million miles (or 6.4 km) of the Sun. The latest application of this technique by NASA is the multi-billion-dollar Europa Mission, which searches for possible life in the oceans of Jupiter's Moon. This 2025 launch will use both a Mars gravity-assist and a second

gravity-assist from Earth before it finally reaches Europa in April 2030.¹¹²



Fig. 9.4: Artist Impression of a Rail Gun Mass Accelerator
(Image courtesy of NASA)

This is an area that does not require scientific research but rather some development effort. The creation of an artificially intelligent modeling and computer simulation program could examine millions of gravity-assist alternatives that could be used for future missions to deep space. Most of these missions might be for unmanned scientific research, but if life were actually discovered on Europa, such a gravity-assist AI modeling capability might find a more efficient way to reach Europa with an astronaut research team. Any transportation system that uses solar

¹¹² “NASA’s Europa Clipper Uses Mars to Go the Distance” NASA release, Feb 25, 2025 <https://www.nasa.gov/missions/europa-clipper/nasas-europa-clipper-uses-mars-to-go-the-distance/>

energy, gravity-assist acceleration, magnetic field strength, or electricity generated from flying through magnetic fields is essentially free and zero-polluting propulsion. This is thus the safest, cheapest, and most sustainable way to travel in space. Thus, such propulsion systems should be prioritized in research efforts.

Solar Sail and Directed Energy Systems

This leads to another way to create space propulsion. This would involve using photons from the sun or directed energy systems to create propulsive power to provide for interplanetary travel. The solar sail concept would only be practical for very long trips that would allow the progressive increase in velocity over time, and if the solar sail vehicle were of very slight mass, thus for unmanned scientific voyages. Since a solar sail system needs to be made of very light materials with gossamer mylar sails, this is an unlikely transport system for astronauts. It is, however, possible that one of several forms of directed energy systems might be used for future astronaut transport. Such a mechanism might transmit lasers, microwaves, particle beams, or even sound beams. Most think of such systems as electromagnetic weapons, but such a mechanism could be employed to remove debris from orbit, correct a satellite or spacecraft orbit, or even support travel to a star.

There is one project of this kind. This was endowed by Russian billionaire Yuri Milner, and astrophysicist Stephan Hawking first embarked on it in April 2016. This effort recruited the former NASA Ames Research Center Director, Simon “Pete” Worden. The aim was to send a small craft to the nearest star by means of a tremendously large power source that could transmit gigawatts of energy. This would be used to power a laser transmission that could propel a very small spacecraft equipped with a video camera and

transmission system in order to eventually reach a velocity measured in a significant fraction of the speed of light. Such a craft might, in theory, take 20 years to reach the closest star system and then send back video images that would also take on the order of about four light years to return a signal with a close-up of Proxima Centauri.¹¹³

The difficult part of such an undertaking is not creating such a small spacecraft probe for exotic star travel. No, the truly difficult part would be to find out how to assemble sufficient power sources that might support the transmission of such powerful laser beams measured in gigawatts of power. And if this were eventually devised, then there would be the even greater challenge of ensuring its safe use. The accomplishment of actual star travel would be a huge scientific accomplishment in itself. There could also be some other major implications. Such a capability could be repurposed. This might be used to direct space debris to be safely de-orbit. It might even be used to perhaps save Earth's population by directing a killer asteroid, or perhaps a comet, from smashing into our planet and destroying the world's population and modern civilization.

Of course, it might also be refashioned to become a fearsome instrument of war. In light of world history to date, the more deadly and evil uses, perhaps, seem the more likely.

The key point here is that NASA scientists will closely monitor the use of beam energy to understand its potential utility to support transport systems and possible future uses that might be used for planetary defense, debris removal, or

113 Jason Daley, "Stephen Hawking and Billionaire Announce to Send Tiny Probes to Nearest Star System" *Smithsonian Magazine*, April 12, 2016 <https://www.smithsonianmag.com/smart-news/stephen-hawking-and-billionaire-announce-project-send-tiny-probes-nearest-star-system-180958745/>

orbital course corrections of importance. This brings us to another possible technical capability that also sounds today much like science fiction. Yet as Arthur C. Clarke has said, “Almost anything humans can imagine may someday become reality.”

Electro-Magnetic Field Systems

Early in this chapter, there was a discussion of how one could use high conductivity tethers to generate electricity in the Earth’s magnetic field, and that this might be sufficient to power a specialized craft to deploy deorbiting systems to ride low Earth orbit of space debris. There is, however, a much more profound technological concept that has been recently under study. The great unsolved question in particle physics is the so-called quest for GUT or a “Grand Unified Theory” of everything. This is the ultimate research goal: to understand the four primary forces of the natural world. This is an effort to try to understand how the four basic forces are interrelated. There is the concept that there is a fundamental relationship and that the force of gravity, the electromagnetic force, and the weak and strong atomic forces may have once been combined in some way prior to the occurrence of the “Big Bang.” Understanding these forces and their interrelationship drives the quest to understand why and how the “Big Bang” occurred. The answer to this basic question of astrophysics is thought to be a pathway to unlocking the mysteries of the universe. We now know, for instance, that a mass about one order of magnitude larger than that represented by Jupiter represents the threshold of gravitational force sufficient to create fusion and create a star.

Electromagnetic containment is sufficiently large and forceful so as to allow fusion to occur, thus requiring a containment force equivalent to the mass of ten times that

of Jupiter. If this is indeed the equivalence, then one supposition is that it can apparently achieve fusion. The potential thesis is that if sufficient electromagnetic force fields might be devised to offset gravitational force and then be used in a transport system. It is sometimes assumed that humanity and scientific researchers have truly come to discover most of the secrets of the universe, but there are still many scientific enigmas and unknowns. There are still many basic questions. We still do not know the nature of “dark matter” and “dark energy.” We do not know the cause and nature of the Universe, and what happened before the “Big Bang”, and what existed in this “pre-Universe” era. We do not even know if there may indeed be different universes and even more dimensions than the time-space continuum with its four dimensions.

Dr. Charles Buhler, the NASA engineer who once headed NASA’s Electrostatics and Surface Physics Laboratory at the Kennedy Space centre, is at this time the co-founder of the Exodus Propulsion Laboratory. He heads a scientific exploration team that includes scientists from NASA, the U.S. Air Force, Blue Origin, Exxon Mobile, and other investor interests. The focus of Exodus Propulsion Laboratory is on a process to directly translate electromagnetic energy into a propulsive force that does not require the consumption of a fuel. The surprising solution that is being sought by Dr. Buhler is whether such a feat might somehow be accomplished through electrostatics.

It is too soon to suggest that such a direct conversion of electromagnetic energy to propulsion would be possible, since this seems to run counter to our understanding of the four basic forces as we now understand them and how they interact. What we do know is that scientific discovery is an ongoing quest. It took Einstein to understand that Newtonian physics gave us only a partial understanding of the physics of the universe and that relativistic speed made

a difference in the laws of nature. Such breakthrough knowledge could provide a fundamental insight. This might reveal how to design spaceships of the future that are safer, faster, cleaner, and more sustainable for traveling into deep space. The key to the future is often about finding what is still unknown. The keys to the future may indeed rely on fundamental breakthroughs that lead us not only to clean, cheap, and sustainable propulsion but also a complete understanding of the four principal forces. Such a capability today sounds implausible, but such basic research has enormous potential and should thus be pursued.¹¹⁴

Conclusions

This chapter has covered a wide range of future NASA R&D activities. This agenda ranges from nearer term development to make known technologies more effective, efficient and safe—both for astronauts and for a future sustainable world. The latter would involve “greener fuels” that do not pollute the upper stratosphere.

The range of possible research and development spans many areas. The topics covered included:

- Perfecting reusable launcher systems, better chemical launch engines and electrical ion thrusters, to greener rocket fuel systems
- Developing and safety verification of nuclear propulsion systems with the emphasis on Nuclear Electric Propulsion, especially if systems such as the Pulsar Fusion Company new Sunbird Nuclear Fusion Vehicle could actually provide a reliance fusion reactor to make Nuclear Electric Propulsion technically possible, cost effective and safe.
- Tether-based Orbital Lifting and Space Elevators

¹¹⁴ Tim McMillan, “Scientists Have Solved this Anti-Gravity Mystery While Confirming a New Form of Levitation” *The Debrief*, Jan 8, 2025
<https://thedebrief.org/nasa->

- Rail Guns (or Mass Driver Accelerators) for Earth, the Moon, Mars, or free-flying in Outer Space
- Gravity Assist Optimization through improved AI modeling and simulation programming.
- Solar Sails and Directed Energy Systems for a broad range of applications and potential future uses
- Electromagnetic Field Systems are able to create anti-gravity lift systems that do not require the consumption of fuels to unlock the secrets of a Grand United Theory of everything and the potential of electrostatic systems.

As NASA is currently in a time of readjustment and shifting priorities during the new President Trump Administration, it will take time for new directions to take clear focus. There is merit in following the best and brightest research in all of these areas and emphasizing what today seems to be the way forward to more capable space launch systems that are able to produce higher efficient thrust at a lower cost, that is also safe and sustainable. Many of the technologies are for the longer term and may be a decade or so away from full feasibility. Yet others are more development work, and some, such as gravity assist optimization, might involve just some new programming and AI-based modeling costs. Each of these R&D areas has merit in terms of better technology that could be more efficient, potentially produce safer and more sustainable space transport, and reduce the cost of space travel.

The world of space and space launch systems is moving forward at an ever faster pace due to “New Space” industry innovation. Their leadership in developing reusable launch engines and astronaut capsules, precision landing of rockets on platforms, and mass production of highly reliable rocket motors has served to create the heady expectations. It has inspired bold researchers who are not afraid to ask new questions and challenge the norms of “accepted science.”

The key to space research by NASA on new transportation vehicles for deep space is to heed the inspiring challenge revealed to us in Arthur C. Clarke's First, Second, and Third Laws. His pithy, amusing, and incisive advice on pursuing the future is revealed in these three short statements. He urges innovators not to be afraid to seek new knowledge and insight. This means being willing to challenge the status quo and challenge conventional thought. His three laws are:

“Law 1: When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.”

“Law 2: The only way of discovering the limits of the possible is to venture a little way past them into the impossible.”

“Law 3: Any sufficiently advanced technology is indistinguishable from magic.”¹¹⁵

¹¹⁵ “Clarke’s Three Laws” *New Scientist*, (last accessed April 3, 2025)
<https://www.newscientist.com/definition/clarkes-three-laws/>

Chapter 10

Improved Crew Spacecraft for Deep Space

Introduction

The development of improved, safer and more sustainable launchers is an important goal, but it is only part of this study. There are many other key space transportation capabilities that are needed for astronaut exploration in the 21st century. These craft include capsules, spaceplanes, landers, and even space stations—both public and private. The previous book in this series on 21st century space stations has covered this topic sufficiently well, so this chapter will focus on capsules, spaceplanes and landers. These critical spacecraft must be super-reliable and geared to astronaut safety. The ongoing series of failed commercial moon landers that have crashed in the difficult task of landing equipment at the South Pole area has highlighted just how difficult this particular task is to accomplish. This chapter first addresses issues of more immediate concern for astronaut capsules, spaceplanes, and landers that are key to operations of the International Space Station and the Artemis Program. There are many issues of technical performance, cost, and safety that are urgent to be addressed here. These involve not only technical design, safety, and performance issues, but also fiscal policies and contractual issues.

The remainder of this chapter turns to planning for future deep space exploration concerns. This analysis addresses the R&D needed for the exploration of Mars and the need to make these programs safer and technically and operationally more viable.

Astronaut Capsules and Space Planes to Support International Space Station Operations

Currently, there are two types of launch systems that provide support to astronaut exploration missions at the International Space Station. There are the systems that take astronauts and materials to and from the ISS that are fully safety qualified for this purpose. There are also cargo transport missions that use capsules with a somewhat lower safety rated transport system.

The Space X Dragon Crew Capsule is launched by the Falcon 9 rocket launcher, and the Boeing Starliner Capsule was first launched by the Atlas Centaur and is now launched using the Vulcan Centaur rocket launcher. These astronaut crew vehicles were all developed under NASA funding to provide a new capability for astronaut launches to and from the ISS to replace the Space Shuttle. The Orion capsule was initially designed to accomplish this task using the Space Launch System (SLS). However, this launch arrangement proved in practice to be completely over-dimensioned and incredibly expensive. This launch option was abandoned when the Falcon 9 and Dragon Crew capsule were fully qualified. When the Boeing Starliner and Vulcan Centaur are fully safety qualified, these two commercial launch systems will compete for future missions under the terms of the NEXT Steps NASA Space Act Agreements that are now in place. In the case of the Boeing Starliner, there are continuing safety issues with the heat shield, the thrusters and the software. These will need to be addressed and fully resolved

before the Boeing vehicle is fully qualified for these ISS astronaut missions.

There are also three approved supply mission transportation systems approved by NASA for cargo resupply at this time. These involve the SpaceX Falcon 9 launcher with the Dragon Cargo capsule, and the Northrop Grumman Innovation Antares rocket that operates with the Cygnus capsule. Then, there is now the third option which is the Vulcan Centaur rocket that will launch the Sierra Space Dreamchaser spaceplane to the ISS.

There remain two key steps in completing the launch capabilities to resupply the ISS. First, there is the certification of the Boeing Starliner as being fully safety-qualified to transport astronauts to and from the ISS. The second is the full safety certification of the last cargo resupply to the ISS by the Dream Chaser. This overall transport launch system, when it is fully in place, will be able to support astronauts going to and from the ISS. These commercial capabilities should be sufficient to support all operations at the ISS up to its planned deorbit at the end of 2030.

When the ISS is deorbited, it is planned that there will be two private commercial space stations that will disengage from the ISS and function as independent free-flying space stations with NASA serving as “anchor clients.” Axiom Space, which also supplies the spacesuits for the Artemis lunar exploration program, is currently under contract with Thales Alenia to construct two habitats for the first of these private space stations. Blue Origin and its partners, Voyager Space Holdings/NanoRacks, are competing for the second private space station in partnership with Lockheed Martin and Northrop Grumman Innovation. Others, such as the Vast Corporation and SpaceX, also have advanced possible

designs for this second space station facility. The decisions on these other low Earth orbit space habitats are expected in the coming months.

Space Plane Safety and R&D Challenges

NASA has sought to develop spaceplane technologies for decades, and most of these developments were carried out on a cooperative basis with the U.S. Air Force. The X-1 was the first plane to break the sound barrier. This supersonic jet aircraft was piloted by Air Force Pilot Chuck Yeager. It was followed by the X-2, which was used for high-altitude spying missions. This was followed by X-3, X-4, and X-5, which sought a variety of objectives that included faster speeds and variable wing sweep adjustments that allowed increased performance at different speeds. The X-7 was an unmanned ramjet test vehicle, and the X-8 marked the transition to true rocketry. This was an atmospheric research rocket.¹¹⁶

The X-15 was developed in the late 1950s by NASA, the U.S. Air Force, and the U.S. Navy. It flew test flights from 1959 to 1968. It was one of the more well-known hypersonic rocket aircraft that reached record supersonic speeds of 6.7 Mach on October 3, 1967, when piloted by William “Pete” Knight.

The X-20 Dyna-Soar was the first effort to develop what could actually be called a Space Plane. The stated purpose of this new development was: “to serve as a reusable spaceplane capable of a variety of missions, including reconnaissance, bombing, satellite maintenance, and even potential manned space exploration”.

¹¹⁶ “The Complete Overview of American X-Planes X-1 to X-57” *The New Space Economy*, (Last Accessed April 2, 2025)

The X23A and X24 were unmanned “lifting bodies” that were jointly developed by NASA and the U.S. Air Force, while the X-30 National Space Plane (NASP) was an effort to create a hypersonic spaceplane that used ramjet technology to scoop air during high-altitude flights for combustion of its fuel. This led to NASA’s effort to create a single-stage to orbit (SSTO) X-33 Space Launch Vehicle. This project was ultimately cancelled due to technical problems. The X-34 that followed was an effort to create a low-cost and reusable spaceplane. These spaceplane development efforts represented a research pathway to future spaceplane development and to the Space Shuttle.

In a series of steps to develop an operational space plane, NASA started and stopped the X-33, X-34, X-37 (i.e., the Autonomous Reusable Space Plane and Orbital Test Vehicle, and X-38 (the Crew Return Vehicle) by cancelling these programs. Part of the reason was budgetary in nature, together with the cost of developing and operating the Space Shuttle and the cost of deploying and operating the International Space Station (ISS). Within one year, NASA went from stating that a reusable space plane was essential to abandoning it. The X-37a (also known as Orbital Test Vehicle) was a much smaller-scale single-stage to orbit (SSTO) vehicle. NASA once contended that its vehicle was very much needed to complement the Space Shuttle. The NASA X-37a development was a robotic, unmanned vehicle R&D effort. This project was developed by Boeing under contract with funding from NASA, DARPA, and the U.S. Department of Defense under the name X-37b. This spaceplane was known both as the unmanned Autonomous Re-usable Space Plane and the Orbital Test Vehicle. It was launched into orbit by a launch vehicle, where it has flown missions that have lasted up to over one year, and with one notable mission that lasted for 434 days. At one point, such a development of a manned and unmanned version of a

spaceplane was set as a top priority of NASA. Yet only a short period of time passed *before* NASA abandoned the X-37a and plans for a crewed spaceplane capability.¹¹⁷

The X-37b, which was the U.S. military version of this spacecraft, assumed complete control of this project, and thus completed the development and testing of this orbital test vehicle under this designation.

After the closure of the X-37A development, NASA has largely turned over the development of experimental space and hypersonic aerospace programs to the U.S. Air Force. NASA has concentrated instead on sustaining the safe operation of the Space Shuttle missions, despite the challenges represented by the Columbia re-entry failure in 2003. This tragedy occurred a full two years beyond the date of 2001 which the Presidential Commission that investigated the Challenger launch failure of 1986 had set for replacement of the Space Shuttle with a new heavy lift vehicle.

Indeed, in safety review reports, NASA did not manage to meet the recommendations of either of the Presidential Review Commissions that examined the Challenger accident of 1986 or Columbia Accident of 2003.¹¹⁸ (See **Fig. 10.1**)

117 (Brandon Spektor, "Top Secret X-37b Space Plane Returns to Earth in Dead of Night After Mysterious 434-Day Mission U.S. Military Reveals" *Live Science*, Mar 10, 2025 <https://www.livescience.com/space/space-exploration/top-secret-x-37b-space-plane-returns-to-earth-in-dead-of-night-after-mysterious-434-day-mission-us-military-reveals>)

118 Joseph N. Pelton, David Smith, Neil Helm, Peter MacDoran, Philip Caughran and John Logsdon, *Space Safety Report: Vulnerabilities, and Risk Reduction in U.S. Human Space Flight Programs*, (2005) George Washington University, Washington, D.C.)

Development of Space Planes and Hypersonic Aircraft by Space Agencies Around the World

NASA and the U.S. Department of Defense were not the only ones to seek development of spaceplane capabilities. The nature of these efforts has varied around the world.



Fig. 10.1: The X-37a Space Plane that NASA abandoned and turned over to the U.S. Department of Defense and DARPA
(Graphic courtesy of NASA)

The Soviet Union's Buran

The Soviet Union was the only effort to create a true spaceplane that could fly to outer space. This development of the Buran was also called the VKK Space Orbiter program and was initiated in 1974. This undertaking was clearly seen as a Soviet response to the U.S. NASA effort to design the Space Shuttle, or the so-called Space Transportation System. This effort was a long and drawn-out effort, and the initial test flight was an uncrewed autonomous flight which did not occur until 1988. Not a great number of details are known about the results of this flight. The program continued under a blanket of secrecy and apparently was

formally closed out in 2002 as a response to the American Space Transportation System, or Space Shuttle program, when its storage facilities collapsed.¹¹⁹

The Chinese Shenlong Spacecraft Development

China has undertaken a spaceplane development known as the “Shenlong Spacecraft”. This translates from Chinese into English as “divine dragon.” In Asian culture, dragons often fly or float on clouds. Little is known of this unmanned space vehicle since its development is not in the public domain. Its existence as a craft, 12 meters long with a wingspan of 8 meters and a mass of 9 metric tons, was released in photos from 2005 to 2007. The first flight drop tests were in December 2007, and a suborbital flight test of the spacecraft was in 2011.¹²⁰

There are thought to have been three actual operational deployment test flights as of mid-2025. These are thought to be a type of autonomous uncrewed spaceplane that could be launched by the Chinese CZ-2F launch vehicles or Type A launch vehicles. The CZ is the name now used for what used to be called “Long March” launch vehicles.

Japanese Space Agency (JAXA) Space Plane Development

JAXA has sought to develop a series of capabilities in this area. This included the effort known as HYFLEX

119 Buran Space Plane, (Last Accessed March 28, 2025)

<https://www.bing.com/search?q=UT&pq=Buran+space+plane&sk=CSYN1&sc=2->

[17&pqlt=297&q=buran+space+plane&cvid=ba9f60cdf4b84291ad65d2af8161509b&gs_lcrp=EgRlZGdlKgYlARAAGEAyBggAEEUYOTIGCAEQABhAogEJMTgoNzFqMGoxqAIIIsAIB&FORM=ANNTA1&PC=DCTS](https://www.bing.com/search?q=UT&pq=Buran+space+plane&cvid=ba9f60cdf4b84291ad65d2af8161509b&gs_lcrp=EgRlZGdlKgYlARAAGEAyBggAEEUYOTIGCAEQABhAogEJMTgoNzFqMGoxqAIIIsAIB&FORM=ANNTA1&PC=DCTS)

120 (“Shenlong (Spacecraft)” Wikipedia (last accessed on April 9, 2025)

[https://en.wikipedia.org/wiki/Shenlong_\(spacecraft\)](https://en.wikipedia.org/wiki/Shenlong_(spacecraft))

(Hypersonic Flight Experiment), which was an autonomous lifting body-type spaceplane. This project targeted a number of development goals. They included heat shielding needed for atmosphere re-entry and thermal insulation capabilities for hypersonic air transport. It also sought improved propulsion engine capabilities and a range of support technologies, such as aerodynamics and maneuverability, that might lead to a Japanese version of a Space Shuttle that was known as HOPE.¹²¹ (See **Fig. 10.2**)



Fig. 10.2: JAXA HYFLEX Lifting Body Uncrewed Hypersonic Re-entry Experimental Vehicle
(Image Courtesy of JAXA)

¹²¹ “Hypersonic Flight Experiment “HyFlex, Japanese Aerospace Exploration Agency, (JAXA) (Last accessed March 23, 2025)
<https://global.jaxa.jp/projects/rockets/hyflex/index.html>

European Space Agency Space Plane Development

The Europeans Space Agency (ESA), as well as several of the national space agencies such as German Space Agency (DLR), the French Space Agency (CNES), and Italy (Italian Space Agency), among others, have also invested in developing spaceplane technology. They have been joined by a number of European aerospace industries that have invested in the pursuit of this capability, with the backing of various space agencies as well as their own independent investment.

ESA issued a Future Launch Preparation Program (FLPP) call for proposals associated with a reusable spaceplane development to which the Italian Space Agency responded with what they called a PRIDE initiative. This Program for Reusable In-Orbit Demonstrator in Europe (PRIDE) led to what was known as the PRE-X, the prototype design for the follow-on, Intermediate Experimental Vehicle (IXV). This was the basis for a suborbital re-entry lifting body vehicle fabricated for testing for re-use and ongoing operations. This IXV was successfully launched in February 2015 and landed after launch without significant thermal issues from this test flight.

This mission with the newly developed Vega launcher set the stage for the subsequent development of the Space Rider System (SRS). The SRS System builds on the successful test of the IXV spaceplane lifting body, which now includes a service module that provides a solar panel and support capabilities that can allow the SRS to maintain longer-term operation in low Earth orbit as an autonomous and uncrewed research platform. As such, it is much cheaper than a crewed space station. It is designed to provide a complete system capability for governmental or commercial users and has been described as a flexible and expandable

concept. Thus, it could possibly be extended and adapted to be used as a platform for a variety of purposes. This might include being able to provide In-Orbit Services (IOS) and Close-Proximity Operations (CPO). Such a platform could therefore serve as more than just a purely commercial research utility. It could potentially be used to provide assistance to a crewed space station operation and perhaps provide for refueling or other support operations. (See **Fig. 10.3**)



Fig. 10.3: The Complete Overview of the ESA Space Rider System (SYS) and Its Architecture
(Graphic Courtesy of ESA)

This is not a complete inventory of all relevant spaceplane developments, but it does provide a useful view of the range of developments around the world. Although a few of these development efforts are geared to transport systems that could provide astronaut access to sub-orbital flights or low

Earth orbit access, the majority of them are focused on autonomous and uncrewed transport systems. These could, however, be used in support of astronaut operations on space agency or private commercial space station operations.

As far as NASA planning for the future with regard to spacecraft and/or space planes is concerned, there seems to be a growing willingness to look to commercial innovation and design engineering as a consequence of “NewSpace” Innovation.

NASA Looks to Commercial Spaceplane Development

In the earlier discussion, it is clear that NASA played a prominent and even commanding role in the earlier stages of the X-research programs as well as with the development of capsules that were used for the Mercury, Gemini, and Apollo programs. However, after the Space Shuttle, the development of a new capsule focused on the Orion Capsule, while the spaceplane developments that were undertaken frequently started and then stopped for several reasons noted earlier.

The bottom line here is that the only meaningful NASA development in all the X-series class vehicles since abandoning the X-37A program has been the X-43 Hyper X: the Hypersonic Scramjet Demonstrator that used scramjet propulsion to achieve speeds greater than Mach 5. The other key new development of note was the X-57 (The Maxwell: NASA’s First All-Electric Aircraft). This was just one development effort by NASA that sought to create a sustainable electric-powered aircraft. This NASA effort was actually a much lesser project in this field, in comparison to

the development of electric aircraft in Europe, which now outstrips the U.S. and other countries around the world.

In sum, for almost the last two decades, NASA has spent few resources and started fewer new spaceplane rocket system projects. The Orion capsule has led to significant delays, cost overruns, technical issues, and safety issues with its thermal protection design and performance. The X-57 has been its only electric aircraft vehicle development, despite its assigned role to be the lead U.S. agency for aircraft development as well as space systems. Meanwhile, European aerospace has taken the lead in this area, which some believe will be the future of safe and sustainable commercial air travel. These results and some critiques have led to recommendations in other studies, including those sponsored by the SSC Trust Fund, that the development of new aircraft should be transferred from NASA to the FAA and the Department of Transportation. This would allow NASA to focus more directly on new, better, and safer space transportation systems.

Commercial Development of Spaceplanes in the Age of “New Space”

For a number of reasons, including those noted above, the development work in the field of spaceplanes and innovative new space transportation systems, both for low Earth orbit and for deep space, has turned to commercial ventures and some of their very innovative concepts. The Dreamchaser, now designed and operated under the Sierra Nevada/Sierra Space Corporation, is currently one of the key commercial vehicles available to support supply missions to the ISS.

In addition to undertaking resupply missions to the International Space Station, it has a growing number of commercial launches now planned, including a flight

opportunity mission for developing countries that is operated by the U.N. Office of Outer Space Affairs. It may eventually be qualified for astronaut missions. It has the advantage of being able to land horizontally on a runway, rather than splashing down in the ocean for recovery.¹²² (See **Fig. 10.4**)



Fig. 10.4: The Dreamchaser spaceplane with solar array power system deployed
(Graphic Courtesy of Sierra Nevada)

¹²² “Dreamchaser Space Plane” <http://www.sierraspace.com/dream-space-plane/>

The other capability is the U.S. Air Force/Boeing X-43b that has flown up to speeds of Mach 9.6. It is such a craft that would be needed to attain the speeds required to complete missions such as the Sky Hook operation, as described earlier in Chapter 9.

Other meaningful efforts to create a commercial capability to undertake suborbital flights have included the Radian Aerospace development of a Single Stage to Orbit that could fly up to 5 day-long missions.

Jeff Gleanson's effort to develop sub-orbital space planes both at XCOR and Agile Aerospace focused on a piloted two-passenger commercial spaceplane vehicle. In the United Kingdom, Virgin Galactic's SpaceShip Company has been seeking to operate a commercial space adventure business to carry passengers into outer space and back on sub-orbital flights. The other British development is the Skylon Single Stage to Orbit vehicle, which is powered by the SABRE propulsion system. Blue Origin has also developed a vertical take-off and vertical landing rocket system known as the New Shepard.¹²³

This New Shepard sub-orbital flight operation has flown more passengers to outer space (i.e. above 100 kilometers or 62.5 miles) and back compared with all the other enterprises seeking to develop this service as a commercial market.¹²⁴

Virgin Galactic's Space Ship Company has developed a long list of potential customers to take such a flight, but its

¹²³Joseph N. Pelton and Peter Marshall. *Launching into Commercial Space* (AIAA, Reston, (Second edition as book and e-book issued in 2015

¹²⁴ Jeff Foust, "Blue Origin Launches Ninth Crewed Sub-Orbital Mission, *Space News*, November 22, 2024, <https://spacenews.com/blue-origin-launches-ninth-crewed-new-shepard-suborbital-mission/>

technical development of a reliable spaceplane to fly sub-orbital flights has faltered.

The latest effort, known as the Delta Space Plane, is currently in assembly to make test flights in the summer of 2026 and if successful there will be commercial flights after these test flights are complete.¹²⁵

Finally, and perhaps most significantly of all, NASA two decades ago turned to the concept of “partnering” with aerospace companies to develop new astronaut spacecraft under NASA Space Act Agreements. Instead of issuing detailed technical specifications, NASA solicited commercial companies to respond to performance specifications of new designs and to do so on the basis of fixed-priced bids and schedules. This also provided the ability to become a partner to provide transport services on a commercial basis once successfully developed. Under this approach, SpaceX developed the Dragon Cargo vehicle, and then the SpaceX Dragon Crew Vehicle was launched on the Falcon 9 launch vehicle to support the operation of the ISS. The Boeing Starliner development, which is now to be launched by the new Vulcan launcher, has not been as successful.

Of significance is that these two transport systems, i.e., the Dragon Crew capsule and the Boeing Starliner, are designed as reusable systems that are safer, cost-effective, and have technical performance superiority to the super-expensive and many ways outmoded Orion capsule that is a single-use and expendable spacecraft. On an overall unbiased assessment of technical and operational performance,

125 Leah March, “Virgin Galactic to start assembly of first Delta SpaceShip” Albuquerque Business, April 14, 2025, <https://www.bizjournals.com/albuquerque/news/2025/03/14/virgin-galactic-assembles-delta-spaceship.html>

schedule, cost, and safety, these newer commercial launchers, capsules, and/or space plane capabilities, on balance, seem well ahead of the older technologies. These are represented by the completely expendable launcher development of the Space Launch System (SLS) and the Orion capsule, which were procured under the older and, many think, outmoded means of developing new astronaut space transport capabilities.

Lunar and Mars Landers and R&D Challenges

One of the new NASA initiatives for the Artemis Program was the Commercial Lunar Payload Services (CLPS) initiative. This sought to create partnerships with commercial companies to develop robotic lunar landers that could take small to medium scientific payloads to the Moon. The objective was to create what was described as “rapid, frequent and affordable” access to the Moon for scientific equipment and also rover systems. Under this program that began in 2008, NASA formed partnerships with Astrobiotic Technology Inc., Deep Space Systems, Draper, Intuitive Machines, FireFly Aerospace, Masten Space Systems, Inc., Moon Express, and Orbit Beyond.

Larger companies such as Lockheed Martin, Blue Origin and SpaceX are also a part of this program with an overall \$2.5 billion budget. Lockheed Martin was tapped to create a larger lunar lander known as the McCandless Lunar Lander that was designed to deliver 400 kg payloads to the Moon. The McCandless Lunar Lander’s design was based on the designs of earlier Lockheed Martin Mars landers. At the smaller end of the spectrum, the Moon Express lunar lander was designed to carry only 30 kg payloads.¹²⁶

¹²⁶ Joseph Pelton and Peter Marshall, *Safety First: A Review of NASA Spacecraft for Astronaut missions*, (2024) 2nd edition, PM Associates, Washington, D.C. pp. 292-98

The commercial rocket launchers used under this program have generally been successful. However, the robotic landers to date have not been very successful. Intuitive Machines, of Houston, have had two missions where their Athena landers have landed in craters and tipped over to end their missions. In the tipped-over condition, the solar arrays cannot be used to generate power to operate. The first landing mission by Intuitive Machines occurred in 2024, and it was hailed as the first commercial lunar lander under this program to reach the surface. This lander, however, tipped over, and the lack of power quickly ended this mission. Unfortunately, the second landing in early March 2025 had the same unfortunate result. These two successive failures have unfortunately led to a sharp decline in this aerospace startup company.¹²⁷

The difficulties of the terrain and the limited communications capabilities to the South Pole regions of the Moon have shown that safe landings in this difficult-to-reach location are an even greater challenge than once thought to be the case. There are many more lunar launches to occur under this program, and it is hoped that additional planned lander missions will eventually prove to be successful. The positive side of this experience with Intuitive Machine Athena lunar landers is the recognition that landing sites at the extreme Southern location of the Moon require great care, good telecommunications, and navigational skills. A better understanding of the challenges with the lower cost and unmanned robotic landers is clearly better than this occurring with astronaut landing missions. Dozens of additional robotic lander missions are still to

¹²⁷ Passant Rabie, "Intuitive Machines Moon Lander Confirmed Dead after Toppling on Its Side," Gizmodo.com, March 7, 2025, <https://gizmodo.com/intuitive-machines-moon-lander-confirmed-dead-after-toppling-on-its-side-2000573314>

come under the Commercial Lunar Payload Service (CLPS), and so far, none of the lunar rover missions have been lost.

The only lunar landers chosen to carry astronauts to the lunar surface are those associated with the SpaceX Human Landing System, and later the Blue Origin Human Landing System. None of these capabilities are sufficiently developed for them to be operationally tested. The Starship development by SpaceX, which is then to be modified to become the first Human Landing System with a moon landing system and an externally deployed elevator system, is currently the pacing item for the Artemis III astronaut lunar landing. This is supposedly going to be in the later part of 2026.

Certainly, the successful completion of the Starship development as a reusable astronaut vehicle and the conversion of the Starship into the actual Human Landing System is a critical pathway in the safe occurrence of the first human landing on the moon in over half a century. There is a need for significant testing of such a vehicle. This would include safety certification of its extensive orbital refueling operations, once in low Earth orbit, and its proven ability to dock safely with the Orion capsule, both before and after the Moon landing. It was initially planned that the Lunar Gateway facility would also be available for the transfer of astronauts. To achieve this, both the Orion capsule and the Human Landing Systems would dock with the Gateway to add a layer of protection and alternative solutions if there were a docking issue.

Conclusions

At the current time, the direction of NASA astronaut exploration, scientific and applications programs are far from clear. The Artemis lunar exploration program has had

a stream of difficulties which has plagued this NASA initiative for years.

The Space Launch System (SLS), also known as the Artemis launcher, has had a string of delays, engine test firing difficulties, and questions, and has gone greatly over budget, which has been variously put at \$2 billion up to \$4 billion per launch. This is not only due to the launch vehicle itself, but also due to the overly large and expensive Orion Capsule that has been in development for some two decades, with a cost in excess of \$22 billion. The large size and mass of the Orion Capsule have led to a very expensive and complete launch abort system with special features not used before in a solid fuel rocket escape system.

The Commercial Lunar Payload Service, which seemed to be an innovative way to proceed and develop new ways to provide a great deal of scientific payload and lunar rovers to the Moon, has had a number of failed lander problems. These included the tipped-over landings that could not sustain their solar-powered electrical systems. The various commercial transportation systems developed by SpaceX, Sierra Space, and Northrop Grumman Innovation to provide transport to the Moon have been successful, but these systems have not been central to the planned architecture for the Artemis Program. The SpaceX Falcon Heavy has become very key to the program, but essentially, its positive role has been primarily due to the extreme cost and slow development of the Space Launch System.

On top of the problems with the SLS/Artemis Launcher, the Orion Capsule, the SLS Launch Abort System, and the CLPS, the Lunar Gateway deployment was delayed for its launch to support the Artemis III astronaut landing as an effort to speed this event up to be achieved by the end of 2024. In fact, the problems with the successful development of the

Human Landing System by SpaceX and the closely related Starship development and testing have now cast doubt on the Artemis III landing being accomplished by the late 2026 timetable that is slated.

President Trump and Presidential Senior Advisor Elon Musk, who is the head of the SpaceX Corporation, are advocates of going to Mars rather than the Artemis Program, which is exploring Mars. They have yet to make clear their decisions as to where NASA space programs should head next. One of the key indicators that has emerged is that President Donald Trump's budgetary planners have called for massive cuts in NASA's space scientific exploration program in the 2025-26 Fiscal Year Budget. Until the leadership of NASA and its budget for the coming year are approved and staffing changes are clear, the near-term space exploration program for NASA and the specifics of the Artemis Program, the Gateway lunar space station, and more remain in some doubt, with a wide range of questions.

What is clear from the review of transportation systems provided in Chapters 9, and now here in Chapter 10, is that the longer-range NASA R&D program should be addressing the need for what could be best described as a new set of space transport systems for deep space exploration and longer-term development.

This new type of space exploration architecture would most likely reorient the basic concepts of how this effort could be undertaken with the more effective, efficient and less costly way of proceeding. This should be a way that relies more heavily on reusable space transport systems and more direct connections to the Moon with astronauts beginning and ending their lunar exploration trips from low Earth orbit.

Ideally, it would also be refashioned around a concept where a fully refueled “Human Landing System”, such as the one conceived by SpaceX, might be able to fly from low Earth Orbit to land directly on the lunar surface. It would then serve as the temporary habitat while there, and then fly back to low Earth orbit. Such a revised architecture could eliminate the need for the Space Launch Vehicle, the Orion Vehicle, and the rendezvous with the Gateway lunar space station. This is provided as only one of various changes that might be explored for missions to the Moon.

There are also possible new space architectures that might be devised for going to Mars. A key in this respect would be whether it would be possible to develop a fusion-fueled electric propulsion launcher system that was effective, reliable, resilient and cost efficient to take astronauts to Mars.

The first priority would be to rethink the architecture to be used for deep space travel to both the Moon and Mars. The second step would be to develop the transport systems (i.e., launchers, spacecraft vehicles, and landing systems) plus the needed support infrastructure for telecommunications, tracking, command, monitoring, navigation, and other equipment such as space suits, logistical supply, food, water, shelter, and more. The Artemis Program started with the Space Launch System and the Orion capsule. NASA created a space exploration program around these two systems. Over time, they have both proven to be sub-optimal, exceedingly expensive, and with single-use equipment, ill-suited to the task. The recommendation here is to start over with a new space architecture that would eventually retire the SLS launcher and the Orion capsule.

Chapter 11

Design, Engineering, and Fabrication of Space Habitats

Introduction

The exact meaning and context of space habitat and how it might vary over time and place are not well defined. In the days of the Apollo Program and astronauts' travel to the Moon, the astronauts' living quarters were the Command Module and the Lunar Excursion Module.

In the time from the mid-1970s up to current times, astronaut habitats have all been in low Earth orbit and involved a variety of space stations or capsules. These included various versions of space stations such as Skylab, the Soyuz-Skylab project, the Salyut modules that led to the construction of the Mir, the various components of the International Space Station, and the Tiangong 1 and 2 that predated the Chinese Tiangong space station.

Most recently, there has been joint planning among the international partners for the deployment of the lunar Gateway space station in deep space. The first step is the launch of the Habitat and Logistical Outpost (HALO) and the Power and Propulsion Element (PPE), which have been joined together for a single launch of a specially modified Falcon Heavy launch vehicle. This will constitute the initial phase and will be able to accommodate an astronaut visit once deployed

and checked for both autonomous operation mode and for when astronauts are present on a periodic basis. Subsequent modules and additional capabilities will be provided by the Canadian Space Agency, the European Space Agency, the Japanese Space Agency (JAXA), and the United Arab Emirates. There may also be an additional lunar space station built and deployed by China and its international partners as part of the International Lunar Research Station, but the specific components, deployment plans, and participating countries are not yet firmly decided. The current indications are that there will be a lunar surface base camp in the Southern Polar Region of the Moon and a space station in lunar orbit.¹²⁸

Ever since Astronaut Alan Shepard made the United States' first sub-orbital flight on a Redstone Rocket NASA on May 5, 1961, nearly 65 years ago, up to the present time, space habitats have focused largely on space capsules, space stations, and a few vehicles that could carry crew and passengers into low Earth orbit.¹²⁹

Apollo 11, 12, 14, 15, 16, and 17 were the only missions to deep space. These astronaut landings on the Moon were made using the Lunar Excursion Module (LEM) (later shortened to just the Lunar Module). This relatively small vehicle was only designed for a brief stay and not a true off-world living system. The very modest habitation space on the LEM was not designed to sustain astronauts for any great length of time.

It has now been over 60 years since the last Apollo 17 mission, and a great deal has been learned about how to design, engineer, and build not only space stations, but also better space suits, improved environmental control and life support

¹²⁸ Joseph N. Pelton and Peter Marshall, *The Gateway Lunar Space Station* (2024) PM Associates, Washington, D.C. Chapters 3, 4 and 8.

¹²⁹ John Uri "60 Years Ago: Alan Shepard becomes the First American in Space" NASA Release, May 6, 1961, <https://www.nasa.gov/history/60-years-ago-alan-shepard-becomes-the-first-american-in-space/>

systems, as well as improved waste management systems. All of these topics are to be addressed in this chapter. There are other relevant aspects about space agriculture, aeroponics, and so on that relate to both environmental controls and waste management, but these will be addressed in Chapter 12.

Space Habitats

NASA, other space agencies, and commercial aerospace companies over the many decades have developed increasingly sophisticated capabilities to design, build, and operate space capsules, crewed spacecraft and vehicles, and a number of space stations. In the next few years, the lunar Gateway, with its HALO unit, which can accommodate up to four astronauts and is now integrated with the Power and Propulsion Element, will be deployed in a special orbit around the Moon. But its special design with a solar-powered electrical propulsion system requires a year-long deployment schedule. The original mission for this spacecraft had been to travel to an asteroid, capture it, and move it to a location with closer proximity to Earth. When this mission by NASA was cancelled, it was decided to repurpose this special capability and use it as a key element in the Lunar Gateway.

The special features that allow autonomous control of these first elements of the Gateway lunar space station will provide new and important information about how space stations can operate both with astronauts on board and in control of a space station, as well as a fully automated vehicle with no astronauts aboard.

In addition, perhaps two or more commercial private space stations are to be fabricated, launched and are to become operational before the ISS is de-orbited by year end 2030. China has deployed and successfully operated its Tiangong

Space Station and is also planning a possible crewed lunar space station as well.

This activity has allowed the successful development of key technologies to support astronauts living successfully in outer space. This has included the development of highly capable sensors for many health monitoring and environmental and risk monitoring tasks, such as fires, noxious gases, pressurized cabin leaks, and highly capable integrated environmental control and life support systems. Some of the key technical challenges that have been undertaken include: (i) finding ways to generate oxygen and exhaust or pressurize hydrogen gas from water in microgravity conditions through space electrolysis systems; (ii) enhanced use of AI and 'smart' robotic systems to support autonomous operation of the latest versions of space station designs in the future; (iii) the disposal, exhausting or recycling of waste materials; and (iv) finding ways to grow food and organic products in space. Other challenges have included successful end-of-life disposal or decommissioning of satellites, spacecraft, or space stations to avoid adding to space debris or abandoned systems blowing up due to electrical discharges or improper degassing of fuel tanks.

The development and operation of these crewed facilities has contributed a great deal of information that could be useful in moving to the next stage of space exploration. This would likely involve designing and fabricating a lunar habitat or a Mars habitat capable of long-term sustenance and livable conditions for astronauts and necessary infrastructural support capabilities.

Some of the more challenging issues to be faced by NASA are how to feed, provide water, and keep astronauts healthy have now been largely answered. The development of unisex toilets, fully integrated environmental control and life support

systems that automatically exhaust noxious or unneeded gases are just some of the many problems that NASA and other space agencies have largely addressed and solved.

Despite these successes, there are many challenges that remain with regard to planning for building crew habitats that operate on the Moon, Mars, or other deep space locations. Some of the key issues still be fully addressed with respect to crew safety include: (i) coping with the risks and difficulties associated with radiation sickness, solar flares, coronal mass ejections, micro-meteoroids, and cosmic rays; (ii) health related issues and concerns associated with micro-gravity and low gravitational impacts; (iii) telecommunications lag times associated with lunar and especially Mars habitats; and (iv) many aspects of deep space logistics and astronaut resupply when a settlement or deep space outpost is increasingly far from Earth.

The Gateway Lunar Space Station and The Habitat and Logistical Outpost (HALO)

The habitat unit for the lunar Gateway that will be deployed as a part of the Artemis Program is known as the Habitat and Logistical Outpost (HALO). This habitat that can accommodate four astronauts for up to a 30-day mission has now been mated with the Power and Propulsion Element (PPE) that provides a large solar power generation system designed and built by Maxar. This unit has been modified and augmented with the installation of several additional electric ion thrusters. This module also includes large-scale antennas for Ka-band communications that connect via the Deep Space Network (DSN) to mission control on Earth. There is also an additional antenna to provide the broadband telecommunications relay links to the South Pole base camp, where astronauts will explore for iced volatiles such as frozen water.

These first two modules of the Gateway Space station that are now joined together will be deployed to a special, highly elliptical cislunar orbit by means of a specially modified SpaceX Falcon Heavy launch vehicle. This launcher has an elongated fairing structure that was especially designed to accommodate both the HALO and PPE in their compact and stowed configuration. Once launched to orbit by the Falcon Heavy, the three large electric ion thrusters plus four smaller thrusters will provide the propulsion over a year-long excursion to reach the planned orbit. This special orbit allows visual and electronic telecommunications and space navigation contact with the entire visible side of the Moon as seen from Earth, as well as with the lunar North and South Poles. These two units, now firmly linked together, will allow docking port connection with the Orion capsule as well as logistical supply vehicles, the Human Landing Systems as built by SpaceX (i.e., the modified Starship) or Blue Origin and its National Team partners. This alternative lunar lander for astronauts is currently being fabricated, and it represents an entirely different design for the Human Landing System, astronaut habitation system, and cargo transporter.

The two, now integrated units of the Gateway will together provide for the command, tracking, control and navigational systems, telecommunications and data networking capabilities, large scale space antenna systems, solar power generation system, thrusters and attitude control systems, energy storage and power distribution capabilities, thermal control, and communications and tracing capabilities.¹³⁰

130 The Habitation and Lunar Outpost (HALO) and the Artemis Program, Northrop Grumman, (last accessed March 28, 2025)
https://www.northropgrumman.com/space/nasas-artemis-program?utm_source=bingpaid&utm_medium=search&utm_campaign=space-artemis&utm_audience=customerhill&utm_content=keywords&utm_format=cpc&code=APPLICANT_SOURCE-3-

Originally, the Lunar Gateway was planned to be in place to provide for the transfer of the astronauts from the Orion capsule to the Human Landing System and for the reverse transfer from the Human Landing System back to the Orion for the return to Earth. In an attempt to speed up the date of the Artemis III landing, the plan was reversed so that the Orion and the Human Landing System could simply dock and make a direct transfer operation. At this stage, final arrangements for the launch of the combined HALO and PPE modules and the landing schedule are not set.

The final decision on the details of the Artemis III Moon landing will not be decided until after three things have been decided or have actually occurred. One of the most important inputs will be the results of the Artemis II flight around the Moon. Another factor is the actual launch date of the two Lunar Gateway modules being sent into deep space to achieve their special cislunar Moon orbit. At this time, the final decision on the Artemis III launch and the Astronauts' landing will likely not be firmly decided until sometime in 2026. The original plan was for the Lunar Gateway to be available as a safe haven for the astronauts if needed, but currently the Lunar Gateway is not now scheduled to be a part of the transition process to move the Artemis astronauts from the Orion capsule to the Human Landing System prior to the Artemis III touchdown, nor to be a part of the transfer on the return trip. This particular decision has no impact on radiation exposure.

The fact is that neither the Human Landing System, which is to serve as the short-term habitation unit for the astronauts when on the surface, nor the Lunar Gateway space station offer a high level of radiation protection for the Astronauts against very strong solar flares should such a X-level or higher energy level solar flare occur during this mission. This is why critics of

the Lunar Gateway space station argued against the Lunar Gateway project and urged that a permanent base camp with a sub-lunar protective location should have been constructed or deployed on the Moon rather than creating the Gateway.

The desire to use the Gateway as a broadband telecommunications relay for broadband communications between the South Pole astronaut explorers and NASA mission control was a key part of the decision-making. The S-band antennas for communications between the Gateway and the lunar surface, as well as for communications to astronauts in the lunar rover, are mounted on the HALO unit. This lack of S-band broadband telecommunications links from the Gateway to the lunar surface at rates up to 25 Megabits/second is the major difference in performance and safety margin.

It could be argued that the Gateway space station should be in place and fully functional as a telecommunications relay system for optimum Artemis III astronaut safety. The sooner the Lunar Gateway space station is in place, checked out, and fully operational as a broadband telecommunications and navigational facility as well as a safe haven, the greater the flexibility and safety margin that could be provided to the Artemis astronaut explorers. This is for the reasons already provided, and also because of the realistic radiation exposure measurements that can be taken both inside and outside the Gateway facilities could also lead to better understanding of these risks.

The winning contract for the final design and fabrication of the HALO unit was awarded to Northrop Grumman Innovation with Thales Alenia as a key subcontractor. The structure was based on the Cygnus module that is used to resupply the ISS. This module's performance has been authenticated through a number of successful logistical resupply missions to the International Space Station for a period of over ten years. This

has proven the overall reliability, resilience, and safety of this design. The pressurized Cygnus structure, however, was extended by a little over two meters in its length to accommodate all of the telecommunications, tracking, data processing, sensors, scientific equipment, and the environmental control and life support system, thermal control system, and waste management systems. A key element of the design was to include multiple ports to link with the Orion Capsule, the Human Landing System, resupply vehicles, etc. Now that the HALO and PPE units are linked together, one of the possible flexible portal connections is eliminated. The permanent linkage removes only a small degree of flexibility for the future configuration of the overall Gateway's composition and the positioning and operation of the Canadarm 3 robotic device.

The extended volume of the HALO that is achieved by this expansion provides for not only for more interior space, but also for the mounting of scientific packages, sensing devices, as well as the key S band communications links to the lunar surface.

One of the strengths of the Northrop Grumman proposal was its partnership with Thales Alenia, which was designated as being responsible for the integrated environmental control and life support system for the HALO. Thales Alenia designed and built a similar system for the ISS and is under contract to Axiom Space to create two habitat units for the first of the private commercial space stations agreed to by NASA under a NASA Space Act Agreement partnership. Northrop Grumman is also one of the three finalists seeking a Space Act Agreement with NASA on a second proposed private commercial space station for Low Earth orbit. The plan is to deploy the Axiom Space commercial space station as well as a second one that has yet to be selected by NASA. The plan is for both to be

deployed in partnership with NASA within the next few years and prior to the deorbit of the ISS, as of year-end 2030.¹³¹ In addition to the HALO habitation unit and Power and Propulsion Element, which is the very first phase of the Lunar Gateway space station, there are to be other elements added over time by other countries. These plans include the addition of another habitation unit similar in size and design. This is known as the International Habitation unit (I-HAB). The design and fabrication of this unit are planned based on cooperative agreements between the European Space Agency and JAXA. It is their plan to design and deploy this unit, which is to become a key additional part of the overall design. The Japanese Space Agency is also working with Thales Alenia to support the communications and life support capabilities associated with the I-Hab unit.

The Base Camp Facilities for Astronauts on the Lunar Surface and Future Lunar Habitat Design

The current status of the Artemis Program, the landing date for Artemis III, and astronaut exploration, and specifics about the efforts to mine from water and volatiles from the South Pole area of the Moon are currently in some state of flux. The Trump administration has offered various thoughts about prioritizing a crewed mission to Mars, concerns about Artemis Program planning, the high costs of the Space Launch System and the Orion capsule, and has not yet set a firm date for the Artemis II flight around the Moon, or the Artemis III Moon Landing. The cancellation of the VIPER automated rover that was designed to mine frozen ice from the lunar surface is just one of the unsettling aspects of how current planning for the Artemis Program is to be undertaken.

¹³¹ Joseph Pelton and Peter Marshall. *The Gateway Lunar Space Station: A Review of its Status, Design and Safety* (2024), PM Associates, Washington, D.C. pp 225-38

The earlier book by the SSC Trust Fund on the Artemis Program about safety on the Moon indicated all 13 possible sites for the Artemis III moon landing and the criteria used to find the best location for the Moon Base Camp. The prime concerns were stated to include: (i) a broad and gently sloping area that did not have a slope incline that exceeded seven degrees and preferably less; (ii) suitable lighting for solar cell power generation; (iii) suitable location for direct communications, without a relay back to Earth, since the extreme Southern Polar lunar location make direct radio wave or laser communications from this location very difficult if not virtually impossible without a tower of some height to overcome the obstruction represented by the Moon's occluding mass, (iv) relatively close proximity to lunar craters that are permanently shadowed areas (PSAs) that are thought to contain frozen water deposits; and (v) broad enough open area to include safe distancing for human landing system (HLS) takeoffs and landings since there is a need for astronauts, scientific equipment, housing, vehicles, and buildings to be isolated from the dust storm issues associated with rocket engine disturbances; and (vi) area free from boulders or terrain irregularities that would endanger a safe landing and takeoff.

The complexity of the possible choices and the importance of this selection of a suitable and safe landing site currently continues. One of the greatest challenges is the complex lunar terrain that is found in this area, which makes this a difficult set of criteria to be fully met. Although as many as 13 possible sites were identified over two years ago, the selection of the Base Camp Site and Artemis III Landing Site remains pending.¹³² (See **Fig. 11.1**)

¹³² (Joseph Pelton with Peter Marshall, *Safety on the Moon: NASA's Artemis Lunar Exploration Program* (2023) PM Associates, Wash, D.C.)

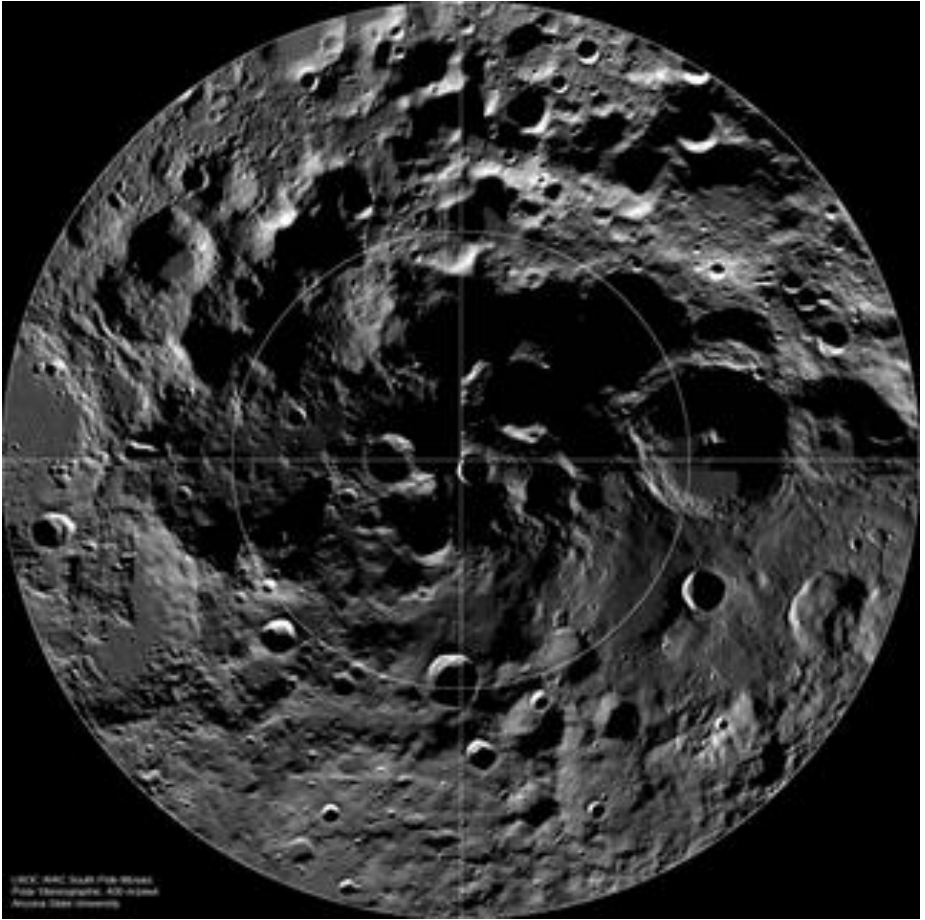


Fig. 11.1: Composite photo representation of the Southern Pole Area of the Moon, Showing Heavy Cratering of the Lunar Surface and Difficulty of Base Camp Site Selection
(Image courtesy of NASA)

The objective would be to choose a location that meets all of these requirements and could accommodate a wide range of functional requirements. These requirements would include the deployment of solar arrays for power generation, communications, networking, navigational, imaging, and search and rescue equipment and facilities. It will also include

the need for places for a so-called “lunar rover” and associated gear and equipment. In the future, there would also be the need to accommodate a larger pressurized vehicle that could accommodate three astronauts with sleeping arrangements, health and medical supplies, food and water, power, lighting, environmental controls, and life support systems.

Finally, there must be provision for as habitat facilities, storage of scientific equipment and a possible future laboratory facility. The final configuration and layout for such a lunar base camp facility will, of course, depend heavily on the final site selection.¹³³

One of the many unresolved issues would be choice of a landing site and a base camp site location for the Chinese International Lunar Research Station and its international partners. This requires coordination for the safety of lunar explorer astronauts associated with the Artemis Program and the ILRS mission. The provision for such coordination and agreements about the safety of the landing sites used by countries creating lunar bases is specifically referred to in the so-called “Moon Agreement.” One of the many unresolved issues would be the choice of a landing site and a base camp site location for the Chinese International Lunar Research Station and its international partners. This requires coordination for the safety of lunar explorer astronauts associated with the Artemis Program and the ILRS mission. The provision for such coordination and agreements about the safety of the landing sites used by countries creating lunar bases is specifically referred to in the so-called “Moon Agreement.”¹³⁴

¹³³ Leonard David, “Where Will NASA Set Up Its Moon Base?” *Space.com*, August 22, 2022 <https://www.space.com/nasa-artemis-moon-base-camp-location>

¹³⁴ UN Office of Outer Space Affairs, “Agreement Governing the Activities of States on the Moon and Other Celestial Bodies of 1979”,

The initial Artemis III landing will utilize the modified SpaceX Star Ship Human Landing System (HLS) as the habitat for astronauts on this initial astronaut landing. This is to be the first astronaut landing on the lunar surface after a pause that has lasted half a century.

The Artemis IV mission will likely include a non-pressurized lunar rover that will give astronauts greater mobility and flexibility to widen their mission and to support the creation of a base camp site that will be deployed over a much greater area. Another unresolved area is whether the VIPER robotic rover will eventually be activated and successfully mated with an appropriately-sized and proven lunar lander. Currently, this VIPER robotic rover has been canceled due to cost overruns.

This VIPER autonomous rover was initially thought to be a critical part of the Artemis undertaking, and its loss is seen as a key loss to the effort. This capability would have become a part of the overall base camp site infrastructural capabilities. **Fig. 11.2** is an artistic depiction of what a lunar base camp deployment might look like. It depicts what the VIPER rover might have looked like in the center of this image. (See **Fig. 11.2**)

The NASA lunar base camp concept is only related to the early stages of the Artemis Program space exploration. There are many studies and different visions of the architectural design of a permanent astronaut outpost that would likely represent a subsurface type design to afford astronaut protection. A subsurface arrangement would be able to offer protection from radiation sickness, solar storms, and cosmic dangers such as micrometeorites and cosmic rays. The main areas where architectural design and layout for the astronaut space camp diverge tend to focus on several key areas, such as location,

<https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intromoon-agreement.html>

safety, function, and available construction materials. Also, key to the design and operation of the base camp will be the construction tools that will be available. These will ultimately include important capabilities such as 3-D printing systems, material processing capabilities, and other construction support capabilities.



Fig. 11.2: NASA Artwork Representing a Possible Lunar Base Camp Site Configuration

(Image Courtesy of NASA)

The need for enhanced astronaut safety favors an underground or virtually underground location to provide radiation protection. It also favors a distributed layout to separate rocket landings and takeoffs from habitation areas. One of the key possible differences that impacts the consideration of landing site locations is where to carry out certain functions. This involves determining where these functions will take place. There will be a need to mine and then process regolith materials so they might be used in construction. There is a need to process mined materials before they can be employed in 3-D printing devices (also known as additive manufacturing). This processing is key to creating structures

on the Moon from local material resources. The alternative, of course, is to bring lightweight and durable pre-manufactured materials up from Earth. Experience has been gained in the use of very strong inflatables that have been proven to be durable in space onboard the International Space Station. The Bigelow Aerospace inflatable system currently deployed on the ISS has now been fully safety-certified by NASA for storage and other uses for many years. Indeed, separate concepts for private commercial space stations have embraced this approach for space habitation construction in their designs for low Earth orbit.

The proposed design for the private space station by the Nanoracks/Voyager Space Holdings effort envisions that the first stage of their space station could be launched by just one Falcon Heavy launch by virtue of using an inflatable structure that is being designed and built by Sierra Space. It is important to note that these materials for this inflatable are nothing like a “balloon” or easily penetrable material. It is actually a very heavily fortified elasticized material that is not easily penetrated by micrometeorites or space debris. No firm decision has yet been reached on which type of design, layout, building material, safety optimization strategy, or transportation system would be the best design in terms of health, safety, ease of deployment, structural effectiveness, cost, schedule, durability, and overall design effectiveness. (See **Fig. 11.3**)

Future Space Habitat Designs and Concepts

The future plans for space habitats that might be built on the Moon, Mars, or perhaps on the moons of Mars or other planets are actually quite diverse in their conception, design, sources of power, functional capabilities, and architecture. The human body is amazingly well-adapted to living in the Earth’s natural environment. This environment provides a one “g” gravity, a

reasonable range of temperatures to support life, an oxygen supply, access to food and potable water, protection from solar and cosmic radiation, and a range of supplies for building shelter and other devices to sustain life. The functioning of the human body in terms of its muscles, bone structure, respiratory, circulatory, sensory, and nervous systems is all attuned to conditions that are not found on other planets or their moons. The creation of human outposts in deep space thus presents a number of challenges. It turns out that the lack of a one-g gravitational system, radiation protection, and a ready supply of breathable air, water, and pleasant thermal conditions are not easy to replicate in deep space habitats.



Fig. 11.3: Distributed Inflatable Lunar Habitats for Two with Space Lab and Storage Facilities
(Image Courtesy of NASA)

Many of these conditions have been artificially created on space stations, or inside of space suits, but a truly livable off-

world existence for a large population of humanity is a very great challenge indeed. Essentially there are three strategies.

Strategy number one: This strategy is to create an environment that simulates human living conditions on Earth through technical infrastructure, equipment, and supply changes so that one can survive in the difficult environment of outer space. The International Space Station will have sustained a continuous human presence in deep space for three decades when it is finally deorbited. Despite this record, it is unlikely that any human could have survived living on the ISS for this length of time. A combination of radiation sickness, blindness due the reshaping of the skull that forcefully pinches the optic nerve, bone loss and weakness, muscle atrophy, impacts on the heart and circulatory system, and lack of exposure to sunlight and organically grown food stuff would have ultimately provided serious health impacts on the life-expectancy of astronauts. There is a good reason for cycling through astronaut teams and their stays in space.

Strategy number two: This strategy would involve what is sometimes known as “terra-forming” a planet so that it would replicate conditions similar to those of Earth by transforming the environmental conditions of another planet. Currently, the only planet where such a transformation might seem viable would be the planet Mars. The possibility of creating an artificial electromagnetic polarity for the Red Planet of sufficient strength could, in theory, deflect the solar wind from stripping away its naturally forming atmosphere. This possibility and other longer strategies, such as creating a propulsive system to move Earth further away from the Sun as its temperature increases over time, will be discussed in Chapter 14. These future possibilities involve not only very challenging technological and scientific challenges, but there are also philosophical and moral issues as to the risks and ethical aspects of transforming the basic nature and form of another part of the solar system or the universe that is

artificially conceived and engineered. The failure of the Biosphere II experiment that indicated that human-engineering efforts were inadequate to the task of creating a longer-term and sustainable ecosystem to sustain life should be a reminder that humans have a great deal more to learn, before seriously considering whether and how to undertake the “terraforming” of a planet for human habitation.

Strategy number three: This strategy would be to construct in space a free-flying artificial space colony that was designed, constructed, and operated so that it could come very close to meeting all of the necessary conditions needed for humans to live long, healthy, and sustainable lives. The first systematic effort to present such a concept in a comprehensive, scientifically and technically “how to do it” plan was undertaken by Princeton University, Dr. Gerard O’Neill. His award-winning book *The High Frontier: Human Colonies in Space* presented the what, when, why, and how arguments about such an undertaking.

The concept was to create a truly massive structure out of materials mined from the Moon and then flung into space by a “mass driver” accelerator and transport system. Since the gravity of the Moon is significantly less than that of Earth, at one-sixth “G” this would be a much easier mission to accomplish than transporting the materials to do this from the Earth.

O’Neill’s ground breaking — pun intended - proposal was first to build two large modified Bernal sphere structures that perfected the idea. Then proceed to construct a largely self-sustaining even larger giant cylinder many kilometers or miles in length with a rotating speed sufficient to simulate a one “g” artificial gravity. It would be built with ports for resupply, and sufficient shielding to protect against solar wind, solar storms

and radiation to protect the people, animal life, vegetation, and life forms that would live within this structure. (see **Fig. 11.4**)



Fig. 11.4: O'Neill's vision of an artificial human-engineered space colony with lakes, rivers, farmland, and cities
(One of many artistic conceptions)

Since this first conception, there have been many efforts to take this concept forward toward a possible practical conception and planning process that might be able to make such a deep space human colony possible. However, the economics, medical and health challenges, environmental concerns, scientific, engineering, technical, transportation, infrastructural and operational challenges are enormous. This leaves aside the additional ethical, moral, governance,

international relations, and safety concerns that would also need to be addressed.

Follow-on Efforts to Create Human Space Colonies Orbiting in Deep Space

NASA scientists in 1975 worked with a summer workshop at Stanford University, subsequent to O'Neill's conception. The object was to develop some simpler and less grand scientific and engineering concepts for such an undertaking. This was primarily aimed at creating a less demanding design that would require lifting less mass from the Moon to create such a human space colony.

This design, which is now known as the Stanford Torus design for a space colony, would be deployed in a Moon-Earth L₅ Lagrange Point, which is a roughly stable orbital location held in place by the gravitational forces of the Sun, the Earth, and the Moon. It would be essentially powered by sunlight with a main mirror to provide lighting. There would be a central hub and outer rotating torus that would provide artificial gravity equivalent to one “g”, a radiator system, a solar cell-based power and electrical system, and a so-called “solar furnace”, among other features.

The large donut-like torus-shaped facility was to be 1.1 miles in diameter (1.79 km), would revolve at a rate of once a minute, and create a living curved space measured in hundreds of meters rather than the great diameter of the O'Neill cylinder. Even at this scale, which envisioned the possibility of supporting a population of 10,000 people in towns with farmland, parks, countryside, lakes, rivers, and even farm animals, it would still be a quite massive and hugely expensive undertaking. It would involve a large number of components to support ongoing living and working accommodations and work facilities for astronauts and deep-space explorers. The

various parts of the design to address lighting, power supply, a solar furnace, a large-scale radiator, and a central hub where re-supply vehicles with cargo, as well as astronaut craft, are shown in the study diagram.¹³⁵ (See **Fig. 11.5**)

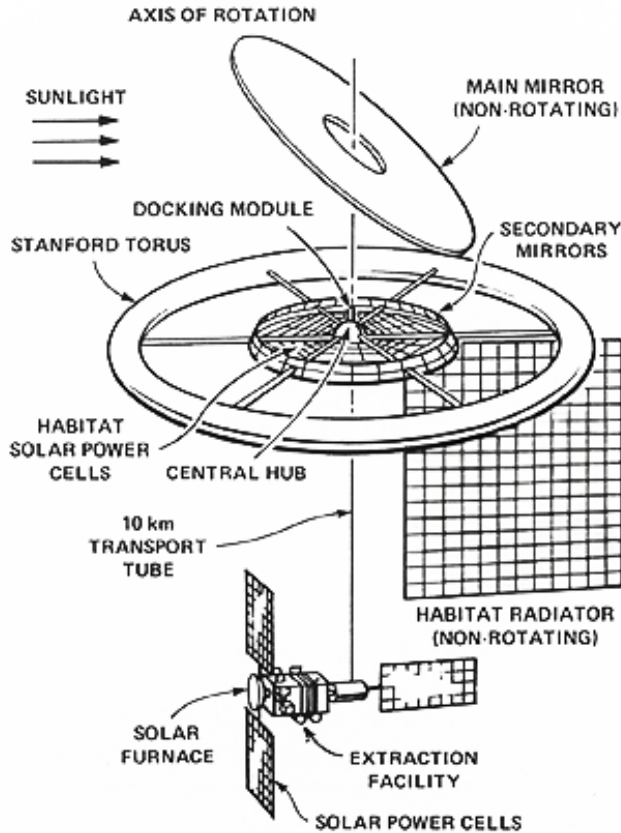


Fig. 11.5: A Proposed Functional Schematic of the Stanford Torus Project
(Diagram courtesy of NASA)

¹³⁵ Johnson, Richard D.; Holbrow, Charles (1977). "Space Settlements: A Design Study", National Aeronautics and Space Administration.

The detailed specification for this Stanford Torus Project was worked out during the course of the workshop in great detail. Only about a third of the torus (donut-like) circular structure would be used as living and practical use areas, such as housing (up to four levels with a vertical height of three meters per level). This architectural layout and design provided room for shops and industry, equipment, and entertainment, and other activities such as exercise and cultural activities.

There were even planned spaces that related to agriculture, farming, livestock, and even parks and countryside areas with lakes and rivers. This large and extensive space station with all of these additional features would have likely exceeded the budgetary appropriation limits that would likely have been approved through Congressional appropriation processes.¹³⁶ (See **Table 11.1** below with regard to the overall volumetric space that was to be assigned to many functions that were envisioned to be needed within this proposed massive, large-scale space habitat facility. The detailed allocation of space for specific functions is available at the referenced website.)

There have been ongoing efforts to perfect ideation exercises, such as the Lewis One study at the NASA Lewis Research Center and the National Space Society Kalpana One studies. The most recent version of the Kalpana One study has received the human population capacity of some 3000 people. There have been efforts to address the stability and “wobble” issues that use a re-orientation to the plane of the solar system and to use a weighting system as a “wobble-damping” capability. The

¹³⁶ “Stanford Torus”

https://en.wikipedia.org/wiki/Stanford_torus (Last accessed April 20, 2025)

Kalpana One Space Settlement design has a 325-meter radius and thus is still a quite massive structure.¹³⁷

<i>Table 11.1: The Volume and Usage of Space in the Stanford Torus Design</i>			
Used land area (m ²)	Total usable area (m ²)	Volume (m ³)	Notes
670,000	1,552,000	17,383,000	Only 670,000 m ² of the “land area” out of a total of 1,552,000 m ² of the torus interior, and only 17, 383,00 m ³ of the 69,000,000 m ³ of the volume available in the torus were planned to be used for habitation and astronaut living purposes.
For full details of space allocations and technical specifications, and specific indications of space allocated for various https: see: https://en.wikipedia.org/wiki/Stanford_torus			

Clearly, such conceptions for an orbital space colony are still very much at the conceptual and not the engineering design stage and development. The practical economic, technical, scientific, medical, health, and life support systems are also still to be developed.

Space Suits

The evolution of space suits began with the simple pressurized suits developed for pilots who were flying high altitude mission. These provided oxygen and pressure that simulated lower altitude conditions. For the Mercury Program, which

¹³⁷ “Kalpana One: Space Settlement ” National Space Society, <https://www.msn.com/?pc=DCTE>

was NASA's first crewed mission, a space suit of more complex design but still closely resembled a pilot's high altitude pressurized suit. **Fig 11.6** shows a picture of Astronaut John Glenn prior to his first mission that circled the globe, taken at the Kennedy Space Flight Center.



Fig. 11.6: Picture of John Glenn in Project Mercury Space Just Prior to his Test Launch
(Photo courtesy of NASA)

Since the early days of astronaut and cosmonaut flights, increasing capabilities have been added to space suit design. These additional capabilities added a very purified oxygen supply as well as the ability to vent carbon dioxide. The ability to support astronaut extra-vehicular activities (EVAs) requires these additional mobility and dexterity capabilities, as well as the ability to deal with the extreme vacuum and temperature extremes. These EVA suits provide astronauts with the ability to access drinking water, nourishment, and safety precautions.

These features are critical to astronaut safety. The closest call of an astronaut dying in space came from an undetected leak in his water supply system, which almost became a fatal accident. On July 16, 2013, Italian astronaut Luca Parmitano engaged in what seemed to be a routine “spacewalk” exercise with two other astronauts. He was undertaking some work to connect cables to sockets on the outside of the ISS, but ended up nearly drowning in space. He had undertaken an earlier EVA on July 9 and had detected some dampness on that occasion. However, it was attributed to sweat or a very minor water bag condensation or leak, and this problem was not properly reported through NASA’s chain of command to ISS mission leadership.

On this occasion, the water was more noticeable, and the problem began to become urgent. The ISS had just passed behind the Earth, creating a “sunset”, and he suddenly turned upside down. This motion brought water into his helmet and covered his eyes and nose so he could not see or hear. He managed to find the hand grips that got him to the airlock, but by then, he was almost unconscious. A fellow astronaut, Chris Cassidy, reportedly managed to reach the airlock and remove his helmet to address the emergency. She knew there were risks of damage to the lungs because of the depressurized nature of the air lock that was filling with oxygen at the time. Yet she could see his helmet was filled

with over a liter of water, and he was unconscious or nearly so. Although Luca Parmitano fully recovered from the accident there were clear mistakes made in the reporting of the July 9th problem up the chain of command, a broken protocol of not halting the EVA at the first sign of the water build up, and a very late public reporting of the safety emergency and safety review some four months after this nearly catastrophic event had occurred.¹³⁸

The initial development of space suits involved governmental researchers at space agencies and some national military research centers, as well as research universities that specialized in space-related research. NASA had initially opted to develop space suits in-house for the Artemis Program and were seeking to develop space suits for this moon exploration effort as well as the next generation of space suits to be used for EVA related to maintenance and repairs for the International Space Station and also presumably for missions to the Lunar Gateway space station. Between 2007 and 2021, NASA spent over \$400 million on a new NASA space suit development. Despite this development effort and significant cost, no actual space suit prototype was identified for production. NASA decided to reverse away from in-house development of these new Artemis space suits and instead seek proposals from private contractors to develop the new suit design. NASA sought and received approval of a \$3.5 billion budget to support the development and obtain it through this commercial process for the period through 2034.¹³⁹

As a result of this process, which was another procurement under the “Next Steps” program for commercial partnerships

¹³⁸ Astronaut Nearly Drowned in Space Due to NASA’s Poor Communications, Report Says” ABC News, Feb. 26, 2014

<https://abcnews.go.com/US/astronaut-drowned-space-due-nasas-poor-communication-report/story?id=22687977>

¹³⁹ Jonathan O’Callaghan, “Astronauts will wear these spacesuits on the Moon—and maybe MARS, too” *Scientific American*, July 14, 2024

and NASA Space Act Agreements, two suppliers were selected. These suppliers were Collins Aerospace and the Axiom Space Corporation. Axiom had already been selected as a partner with NASA for developing and deploying a habitat unit to attach to the ISS and then operate it with additional modules as a free-flying private space station after the ISS was deorbited at the end of 2030. Axiom, under the terms of this contract, was committed to developing a new space suit design and fabricating it, but contingent on NASA undertaking the safety qualification. Once accepted by NASA, it would use these suits to support private astronaut space adventure flights to the Axiom space station and, in effect, “lease” the use of these new suits to NASA for its astronaut research, development, and operation. Axiom entered into the R&D effort on a joint development fixed cost contractual arrangement basis and a commercial arrangement to provide their developed and designed space suits to support the Artemis moon landing for NASA and international astronauts participating in Artemis missions. The Collins Aerospace agreement was similar, but the costs of the development grew to a very high level, so that this other contractual partner withdrew from the development. They concluded that this undertaking represented too high a financial risk for them to take on.¹⁴⁰

Currently, the Axiom Space-developed space suits, known as AxEMU (Axiom ExtraMobility Units), are being tested by NASA. This new suit design offers greater mobility and other new capabilities. These AxEMU suits are being tested by NASA in its Neutral Buoyancy Laboratory, in thermal vacuum chambers for vacuum seals as well as for the extreme cold temperatures registered at the lunar South Pole for a period of at least two hours. The ultimate completion of these tests will also eventually be tested on EVA missions on the ISS. The

¹⁴⁰ Collins Aerospace Pulls Back from NASA Spacesuit Contract, *Space News*, June 24, 2024 <https://spacenews.com/collins-aerospace-pulls-back-from-nasa-spacesuit-contract/>

current critical path for the Artemis III lunar landing is the successful development and verification of the SpaceX Human Landing System, which is a major present concern. Nevertheless, the successful acceptance of the AxEMU is also key. The cancellation of the alternative design by Collins Aerospace also serves to raise this level of concern.¹⁴¹

The successful acceptance testing of the Axiom new space suits is thus of most urgent concern. Nevertheless, NASA must continue to conduct longer-term research on a variety of space suit systems and capabilities. New types of capabilities related to radiation protection, more compact and dexterous systems that also include smart computers, navigational, and AI capabilities, and longer-term functionality over longer periods of time.

11.3: Environmental Control & Life Support Systems & Waste Management Systems

Closely associated with the space suit R&D effort noted above is the associated effort to develop smarter, more efficient, and more mobile environmental control and life support systems. These might be used within space stations or space habitats whether on the Moon, Mars or free flying space stations such as those discussed earlier in this chapter.

This R&D effort should also extend to improved recycling, reuse, or repurposing of waste systems, whether these are gaseous, liquid, or solid forms. NASA currently has launched a new initiative known as Luna Recycle. This \$3 million effort includes various strategies that include a challenge competition with prizes, and use of crowd-sourced initiatives to start new efforts in this challenging area of coping with

¹⁴¹ Joseph Pelton and Peter Marshall, *The Gateway Lunar Space Station: A Review of its Status, Design, and Safety*, (2024) PM Associates, Washington, D.C. pp. 270-274.

waste re-use, recycling or disposal on the Moon or in the future on Mars.¹⁴²

11.4: Remote Medical and Health Care

Yet another key challenge that becomes increasingly more difficult the further deep space exploration, research, or human activities are removed from the Earth, is that of medical care, access to medicines, or sophisticated medical equipment such as X-rays, MRI, etc. A similar effort to the Luna Recycle Challenge might well be considered to seek new answers on how to provide telemedicine services, remote medical testing, and consultation, as well as develop new AI medical applications. These are based on the Watson project to develop AI-based medical diagnostic systems and other similar capabilities to cope with the provision of remote deep space medical care and the remote creation of and disposition of medicines. This is in the context of creating habitats and living quarters for astronauts at deep space locations that may ultimately be millions of miles or kilometers away from Earth.

Findings and Conclusions

This chapter has examined efforts to develop future deep space habitats and astronaut living accommodations, as well as essential elemental technologies and vital services needed to support such future capabilities. There are many health, medical, environmental controls, and life support systems that are required to support deep space living conditions. As astronaut exploration expeditions moves from low Earth orbit to the Moon and then to Mars, the

¹⁴² “NASA Luna Recycled Challenge: Innovating Waste Management and Recycling Systems for Long-Duration Space Travel” (Last Accessed April 3, 2025) <https://www.nasa.gov/prizes-challenges-and-crowdsourcing/centennial-challenges/lunarecycle/>

challenge of creating remote habitats ever more difficult since resupply operations become much more expensive to operate, take a great deal of time for the transport operations to reach their designations and return with waste materials, returning astronauts, etc.

The prime challenge is seeking ways to make all deep space facilities as self-sustaining and independent of an Earth-supplied operation, which is essentially what the International Space Station and the Chinese Tiangong Space Station currently represent. The Lunar Gateway Space Station is largely the same, although it is designed for autonomous and uncrewed operations so that it does not have to be constantly resupplied. Efforts by NASA planners for the Artemis lunar exploration missions are seeking ways to reclaim frozen water from the South Polar areas of the Moon to process and purify it to ultimately provide for both water and oxygen supplies to support these operations in the longer term. Developing these capabilities before attempting viable astronaut exploration operations and habitats on Mars is a logical way to proceed.

The necessary R&D to support creating possible future human habitats thus indicates a wide range of new technological innovations. Prime objectives to pursue include:

New Architectures and Capabilities for Future Deep Space Habitats and Space Colonies

There is a need to develop comprehensive architectural concepts for habitats and space colonies that can be, as far as possible, self-sustaining to the maximum extent possible and thus increasingly self-sufficient. This means a way to produce and recycle water and oxygen, food, produce food, provide acceptable temperature and atmospheric

conditions to support human and animal life, and vegetation. It would also require protection from solar and cosmic radiation, coronal mass ejections, and solar wind, removal of noxious gaseous and pollutants, and some reasonable approximation of one g gravitational conditions. Beyond these survival needs, there are also the more complex needs for such remote future “colonies” to be able to become economically viable and able to carry on trade exchanges of goods or services as well as a viable legal, regulatory, and governance system to protect the peace and prosperity of such remote human living spaces in deep space.

Advanced Space Suit Design

The architecture and physical conditions of such deep space habitats will create different needs and capabilities for space suits. The basic research goal would be to allow people as much self-sufficiency, freedom of movement, dexterity, and provide for all bodily functions as possible, while also ensuring maximum safety and freedom of movement. The other constraints, of course, are those of reliability, resilience, and the lowest possible costs. This will ultimately require achieving designs that can be mass-manufactured and supplied locally. Thus, research must seek to develop optimum designs, as well as the processing of materials and manufacturing and fabrication systems that are capable of sophisticated devices and systems, as well as maintenance and repair capabilities.

Sustainable New Environmental Control and Life Support Systems

What is true of space suit research, design, development, manufacturing, maintenance, and repair is also true of the best new capabilities that provide for the environmental

control and life support systems. The capabilities need to be fully integrated within future space habitats and colonies since they are essentially completely interdependent systems that back up each other in being able to support and sustain healthy and happy human life. The development of future space suits, environmental control, and life support systems should be a very closely coordinated and interactive R&D program.

Advanced Waste Recycling and Disposal

The NASA Luna Recycle initiative is an innovative way to probe for new ideas on how to recycle waste materials efficiently. The objective is to create a “circular economy” based on reusing materials over and over again rather than continuing with a “one-use and trash disposal” manufacturing cycle born of the industrial revolution. This type of incentivized thinking should be encouraged and motivated in every one of these efforts to create sustainable space colony designs and architecture, space suits, environmental control, and life support systems. There is an organic whole to each of these concepts of creating a holistic idea of a sustainable, deep space human environment. The Biosphere II experiment has shown that self-sufficient human bio-systems are extremely difficult to conceive and operate on a long-term basis. Clearly, getting all of the needed component parts to work in a unified and sustainable way is the greatest part of this challenge.

Remote Medical and Health Care

The other aspects of this challenge to create a viable deep space human habitat, and eventually even human colonies as addressed above, are largely focused on creating systems, hardware, devices, and machinery to achieve a sustainable environment for future astronaut exploration and research.

There is, however, a parallel need for supporting expert services that may be most challenged by what might be called remote medical services and health care. This includes access not only to doctors and nurses but also to needed medication, treatment systems, operating rooms, MRIs, CT scanning equipment, and more. This means not only the development of many improved versions of teleservices, but also AI and robotically optimized medical treatment centers, remote pharmaceutical production plants, and more.

What is important to focus on in all these research areas is that there is also an important application for a deep space habitat in everyday life and human health safety right here on Earth. All of these capabilities and new technologies are very much applicable to remote villages and hazardous locations with limited access, such as mines or nuclear power plants. Further, such capabilities are important to strategies for coping with climate change, rising medical and educational costs, and more. All of these research areas need to be pursued, not just for future space exploration, but also for addressing human economic, environmental, and societal needs for a better life on Earth.

Great strides have been made in the design of life-sustaining space habitats for many decades, and there are important new research and development programs. These are processing results for not only space applications, but also key developments that can be used immediately here on Earth. The results in areas such as improved remote health care, life support systems, pure oxygen supply systems, and dozens of other areas of R&D for deep space colonies can also aid health and medical research for terrestrial applications. It has been demonstrated for many years that NASA-sponsored research can and indeed has been used in many dozens of areas involving home insulation, building

construction, industrial robotic manufacturing, medical and health services and equipment, to even simple household products and need types of materials that can be used to build key products, make products lighter, more durable, or more easily tooled or manufactured. The design of future space colonies may seem a lot like Buck Rogers science fiction, but the practical applications and uses of such research by NASA can and have been consistently used to aid health and medical services and practices in manufacturing, construction, service industries, health care, and clinical and hospital practices. These spin-off applications have now appeared in millions of products and services that originally stemmed from NASA research and have been demonstrated to be an important source of new technology development.

Chapter 12

Promising New Technology for Long-term Sustained Space Operations

Introduction

The previous chapter focused on key new systems and technologies that would be integral to the development of sustainable and viable future space habitats and even possible space colonies from the perspective of their architectural nature, safe design, and operation, and ultimate viability in terms of sustaining human life over the longer term. This is really only the start of a thought process and the development of a research and development program to achieve such a future objective. This chapter continues this analysis and expands the consideration to include additional vital capabilities that will be needed to bring such a future to a realistic level of development that could more clearly establish R&D goals and objectives that could, in time, be much more refined. Then, perhaps, these developmental needs might even be converted into specific, quantifiable, and qualitative goals and objectives. This might be specifically for NASA, or perhaps for NASA to work jointly with other space agencies, aerospace industries, leading space research universities, think tanks, and research foundations. The goal in every instance, however, would be to formulate specific targeted goals and objectives, complete with expected performance dates wherever possible.

The specific areas to be address in this chapter are: (i) advanced and sustainable transportation systems, especially for deep space travel; (ii) advanced AI enabled robotic systems and “telepresence” systems; (iii) remote mining, material processing, and space-based manufacturing and construction; and (iv) space-based agriculture, genetic and organic optimization for deep space environments and human habitats.

The most sophisticated plan for a deep space habitat or even a full-scale space colony on Mars would be impossible without a sophisticated space transportation capability as well as many additional infrastructure capabilities and support systems. These needs will be discussed not only in this chapter, but will be returned to again in chapter 14. This is where specific recommendations are made with respect to NASA proceeding to develop more targeted objectives for its strategic planning processes.

Let’s start with advanced transportation needs and continue on to other key future needs to sustain astronauts and space travelers’ ability to survive in space. This discussion addresses the future needs in terms of goals related to technology, performance capabilities, sustainability, resilience, reliability and safety.

Advanced and Sustainable Transportation Systems

There are really only a few known concepts that are technically plausible for rapid missions for human crews to reach truly deep space locations, such as to Mars or beyond. Concepts such as solar sail systems, mass drivers or mass accelerators, generation of electrical energy with space tethers, sky hooks or tether lifting transport systems might some day prove to be both possible and cost-effective means of space transport for cargo to deep space locations. For

practical and performance reasons, they are unlikely approaches to be used for astronaut deep space transportation systems as the basic propulsive force. These techniques, as well as gravity-assist, might supplement other transport systems, but none are likely to provide astronaut transportation capabilities to far deep space, although they might provide supplementary assist capabilities or support cargo transport missions. This is due to a combination of factors such as too long a time duration for voyages through deep space, excessive acceleration factors, or for health, medical, or safety reasons.

Instead, one should examine the alternatives that seem to have the greatest potential for astronaut interplanetary space travel. First of all, chemical, electrical ion thrusters, and electrical thrusters with either fission or, more likely, fusion power generators supplying the heat energy source are all possibilities. Chemical rockets, whether liquid or solid fueled, are actually too slow to be safe transport for astronauts due to thrust-to-fuel ratios and radiation sickness dangers. As discussed earlier, fusion-fueled electric thruster rocket systems, although slower at first, would ultimately reach much faster velocities and cut the travel time to Mars in half. Direct nuclear thrust propulsion represents safety dangers and unproven technology at this time.

The idea of space elevators or funiculars that could provide reliable transport to geosynchronous orbit, or conceivably even from the Earth to the Moon, is perhaps ultimately achievable in another three decades. As a practical matter, such a capability as this would only provide access to the Moon or geosynchronous orbit. Further, if achievable, such a capability is still many years, indeed decades, away. Such a development depends on the production of so-called nanotube “Bucky ball super graphite materials for the ultra-high tensile strength cables and climber robot technology powered by solar or other

energy sources. Further, there are serious concerns about the harmful effects of Van Allen belt radiation. There are durability considerations about the longer-term effects of Van Allen Belt radiation on the duration and resident strength of the space elevator cabling. Also, this would only provide access to the Moon or geosynchronous orbit and would not provide a transportation capability from Earth to other deep space locations.

In a nutshell, the earlier conclusion still stands. NASA's primary focus is on a crewed mission transportation system to take astronauts to Mars for truly deep space locations should focus to create. Such a launch system can produce superheated fuels to generate a continuous electronic ion drive that can continuously accelerate to incredible speeds. This would allow the completion of transport missions to Mars with four-month duration flights or perhaps shorter travel times. Most of the crew could perhaps be located in suspended animation beds inside a radiation shelter with water supply tank walls to provide radiation protection. This would still allow one or more, likely two, crew members who remain conscious and active and who are able to receive messages, react to problems, and provide needed updates. One of the prime unanswered questions is whether such a transport system could also be designed to provide artificial gravity through a rotating system of habitable pods moving at a suitable speed to achieve at least a half "g" or more level of simulated gravitational effects. Such a craft might consist of rotating pods that would be linked together to allow connectivity, perhaps via the connecting central hub. This would likely be where the propulsion system, steering thrusters, and telecommunications antenna would be mounted. These antennas would have to be engineered to achieve constant and continuous pointing accuracy.

Research needs to focus on the development of such an advanced transportation capability for deep space travel. An

optimal configuration would not only provide for habitable crew pods that offer a reasonable level of artificial gravitation through rotation. This should be able to simulate at least the equivalent of the gravity of Mars.

Such a rocket transport system, or steerable transport habitat, would seem to represent a basis for a deep space launch and crew vehicle that would be able to travel to Mars, asteroids, or the moons of Mars and Jupiter. Research at some level should be continued on all areas discussed in Chapter 13. Nevertheless, priority should be given to the most promising options. These would offer the greatest potential for rapid interplanetary transport capabilities. The performance specification would thus seek the most technically and operationally creditable design. The goal should be to design the healthiest, safest, and technically viable system that could be achieved within a twenty-year time horizon and within a reasonable cost budget, and include reusable propulsion systems to the fullest extent possible. What is absolutely clear at this point is that the Orion space capsule and the Space Launch Systems represent obsolete technology and fail to meet such performance specifications in almost every dimension.

This is the type of competitive design research effort that the NASA Innovative Advanced Concepts (NIAC) Program should be assigned to initiate with special priority. It is proposed that NIAC should solicit proposals from leading research universities, think tanks, and particularly relevant “new space” industries. This might start with a \$250,000 competitive study challenge. This might offer something like \$50,000 in grants to the top five proposals, with follow-on workshops to develop the best technological and design approach that emerges from such competitive challenge studies. This might be divided into two parts, with one \$250,000 challenge grant being for the transport and propulsion system and another \$250,000 for the astronaut habitat transport and landing system. These

transport systems would be designed not as what might be called an Earth-to-Mars transportation system, but rather as an “Earth Orbit to the Orbit of the Destination Location Crew Re-Usable Tug.” The access to the Earth's orbit starting location and the lander capability are the least demanding parts of the challenge, and they would be the last element of the transportation system that would depend on the gravity well of the intended destination.¹⁴³

The fundamental error made in the planning for the Space Transportation System and the Orion capsule was the starting architectural concept to create a surface-to-surface Earth-origin and destination round-trip transportation system that would go to the surface of some deep space location. The architecture of a re-usable deep space transportation system that would travel between Earth orbit and another orbital location that could be a re-usable tug system has a much greater range of service, which could be more cost-effective and versatile. It could also use other capabilities to get astronauts from the ground to Earth orbit, which would need to be customized to the orbital characteristics of the destination location. Basic architectural concepts and their utility and versatility should be the key starting point for innovative thoughts on space transportation systems in the future.

It is important for NASA to have both shorter-term development strategies and longer-term research and scientific objectives in its strategic planning process. Ongoing experience has shown that NASA's efforts to develop transportation systems, such as launchers and crewed vehicles, that were advertised as systems that would provide

¹⁴³ NIAC: *NASA Innovative Advanced Concepts Program*, <https://ntrs.nasa.gov/citations/20190032347> (Last Accessed April 7, 2025)

lasting service capabilities over many decades, failed to achieve such a goal. These systems have consistently proven to become technologically and economically obsolete. The “New Space” companies in the age of Space 2.0 have consistently been able to find new innovations that have made older transportation options obsolete.

This means that NASA must continue research into technological areas that are at the edges of scientific knowledge and examine such unlikely innovations. This includes research into anti-gravity capabilities or the other advanced concepts as positron drive transport systems or practical application of a grand united theory of the four known forces of gravity, electro-magnetism, and the weak and strong nuclear forces.

There is power in the Arthur C. Clarke concept of almost unlimited human imagination and innovation. He believed that anything that humans can conceive of such as time travel, anti-gravity systems, or the possibility of there being more than the four dimensions of the space-time continuum, might be achieved in practice sometime in the future.

It is imperative that NASA seeks to continue to be a cutting-edge institution that explores beyond the scope of the known, into the unknown that today may seem magic. Only a few centuries ago, transportation capabilities such as winged aircraft, helicopters, launch vehicles, space planes, or automotive vehicles or robots would have been seen as impossible achievements. For NASA’s future vision, it is imperative that the area of deep space transportation capabilities and human travel into space at unprecedented speeds and to more remote locations continue to be pursued. Such an effort to unlock new scientific knowledge is key. Advanced scientific breakthroughs in space transportation must continue to be the heart of its mission.

A review of NASA's currently published strategic planning goals, which are so vague and amorphous, suggested a new, far-ranging effort to state future objectives in this and other areas.

Advanced AI-Enabled Robotic Systems

Another key R&D initiative must focus on the growing importance and significance of advanced AI-enabled robotic systems and the ever-increasing capabilities that they can add to future space exploration, applications, and sciences. The key to cost-effective, efficient, and safe space exploration for the future will involve smart planning and phased preparations for space exploration activities. This would include pre-crew mission activities to prepare for astronauts to travel to targeted deep space locations. These pre-crew missions could include the creation of deep space habitats, key support infrastructure, and transportation systems. A great deal of these pre-astronaut visit preparations could thus include the deployment of telecommunications, navigation, search and rescue, habitat facilities, life support systems, power generators, re-fueling stations for lander systems, and/or even reusable launcher systems. This could even conceivably include such efforts as the creation of agricultural growth areas for food production, robotic mining, material processing and refining, or even manufacturing or fabrication capabilities based on 3-D printing or additive manufacturing.

The rapid advances in AI-enabled robotic systems with manual dexterity and an increasingly capable set of sensors are now possible. They may, over time, develop even greater tactile, depth-perception, hearing, smelling, or other capabilities and be equipped with pneumatic and other strengths. Such advanced robotic systems could be deployed to carry out a range of key tasks before actual astronaut landings. If automated systems could be deployed on Mars to find and

extract ice to produce water, oxygen, and even liquid oxygen fuels, these capabilities could greatly accelerate the ability to create permanent settlements on Mars and provide fuel for return missions back to Earth or to other deep space locations. Much of this might be accomplished with limited human presence on Mars prior to a viable human habitat that is operational and largely self-sustaining on the Martian surface.

Since the start of NASA, three basic activities have been undertaken. These were space applications, science and exploration. Space exploration basically involved astronaut related activities as represented by the Mercury, Gemini and Apollo Program, that was followed by the Space Shuttle and International Space Station construction. This also included astronaut-related scientific and exploration missions, and most recently the Artemis Program, the Artemis Space Station and planning efforts to explore Mars and possible other deep space locations. These activities have typically involved the largest share of NASA's budget. Space Applications and Sciences for the most part involved automated space systems and unmanned missions, although astronauts may have been involved in some of these scientific or space applications activity.

In the years ahead, the industry might seek a significant growth in the nature of its overall mode of operation to make much greater use of AI systems and "smart" AI systems as well as robotic capabilities to achieve much greater efficiency. The aim would be to achieve major cost reductions with regard to its staffing size, the number and nature of its various research Centers and specialized facilities, and also potential changes that this might make to the number of employees that would be required at its many thousands of contractors.

The idea would be to consider the future possibilities for changes that might be made. NASA might start with some experimentation. It might consider that instead of a two-way division of its various projects and labor required, now largely divided between activities involving crewed missions with astronauts aboard, which accounts for the bulk of its expenditures, or non-crewed activities, such as space applications and science, which is the lesser of its expenditures. There is also a number of smaller programs that are a small part of the overall outlay. Instead, it might well consider a modest experiment with what might be called a three-way division of its activities. One area would be astronaut missions with crew. Another would be missions that are focused around the use of astronauts supported by AI-enabled robots or even pre-astronaut activities conducted by AI-enabled robotic systems and telepresence enabled mobile platforms. The third area that would remain focused on is essentially fully automated and non-manned space research, development, scientific studies, and unmanned probes, tests and experiments. This too could also be supported by accelerated use of AI and ever more powerfully equipped algorithms that could also bring new efficiency and productivity to these space science and application areas as well.

The crux of this experimental effort started in chosen areas where the most impact might be envisioned, and given a year or two to see what such leveraged use of AI-enhanced and “smart robotic” activities could be employed to accomplish much more with far fewer scientists and engineers. They would be working with ever-smarter software, AI-enhanced software, and increasing use of smart robotics to aid astronaut-related activities and the possibility of what might be called remote deep space “pre-astronaut” mission developmental work to pave the way for actual astronaut activities in deep space. This would not

only seek new efficiency, reduced resupply costs, and other benefits, but it would also reduce astronaut risk. The idea would not be to eliminate astronaut activities, but to leverage their capabilities and safety with robotic systems that were increasingly more capable.

Paul Allen has argued that Ray Kurzweil is wrong and that the proposition that the Law of Accelerated Returns (LOAR) with exponentially evolving algorithm capabilities is essentially a myth. NASA programs seem a very logical place to see if practical experimentation with this concept can be proven one way or another with a practical test of these competing theses.

The object here would be not only to increase productivity or decrease cost. The prime objective would be the increase in astronaut safety. If in the Artemis program, the first astronaut loss or fatality were to be a “smart robot” seeking to mine ice from the Moon rather than a live astronaut, this is an event that NASA would survive much better than losing an astronaut because an unforeseen risk had been overlooked or minimized.¹⁴⁴

There is no really convincing argument as to why such a testing of the LOAR proposition as presented by Ray Kurzweil and others should not be conducted. This would be to create a new, more cost-efficient and more productive NASA - one that seems to embrace the power of what AI experts and innovator Ray Kurzweil have championed as the Law of Accelerated Returns. It is not only Kurzweil, who was the creator of “SIRI” and other chatbot AI capabilities, but also other key U.S. AI experts who have suggested that improving AI-based algorithms have the potential of geometric and exponential rates of acceleration. This is in

¹⁴⁴ Mark Buchanan, *Law of Accelerating Returns*, *Nature Physics*, <https://www.nature.com/articles/nphys1010> (Last Accessed April 21, 2025)

contrast to the way human ideas and traditional thought processes have essentially always followed. This has been what might be called “linear patterns” of innovation, with occasional breakthrough ideas such as Galileo or Einstein providing human insight and knowledge.¹⁴⁵

The following is a quote from the U.S. Council of Advisors on Science and Technology that reported to the President and Congress some 15 years ago.

“.....performance gains due to improvements in algorithms have easily exceeded even the performance gains due to processor speed.”

In this report, a number of examples were provided by the Council of Science and Technology. These examples are impressive examples of exponential gains. Thus, the report cites how improved algorithms for solving a benchmark production model problem using linear programming, with ever-improving algorithms and available processing power at the start of this process, would have taken 82 years by conventional computing processes. Yet only 15 years later, as a result of improved algorithms and faster processing speeds, this problem could be completed in one minute's time. This is an efficiency increase factor of 43 million times. The processing speeds increased exponentially during the time period in accordance with Moore's law, which represented a significant increase that was measured hundreds of times faster. However, the overwhelming reason for the astonishingly large increase was the

¹⁴⁵ Ray Kurzweil, *How to Create a Mind* (2012) Viking, N.Y. p 269-70 and p. 126-28

completely new software and the reformulated algorithms that increased efficiencies by many orders of magnitude.¹⁴⁶

Kurzweil argues that the key to creating the equivalent of a human brain involves more than just the challenge of creating the equivalent of processing speeds and memory. This has been quantified by Professor Henry Markham in his “Blue Brain” project as 10^{18} Flops of digital processing speed and 10^{17} of bytes of memory storage capabilities.

Kurzweil argues quite persuasively that it is the capabilities to create software that can “evolve” at an exponential rate of improvement and suggests that there is increasing evidence that this is now occurring at a very impressive and accelerating rate.

The objective of such a new way forward for NASA would be not only to find ways to be more productive, or to cut costs. A prime reason would be to save astronaut lives. Further, if a “smart” robot is lost mining ice from the South Pole of the Moon this would be a most unfortunate result and loss by NASA. Yet, if it were the first U.S. astronaut fatality it would be a much, much worse result indeed.

It is not as if NASA is not already involved in R&D in many of these areas. It is actively involved in such activities as testing a smart robot system to undertake mining operations in Australia. It is also sponsoring possible robotic mining machinery in the challenge contests it is sponsoring. (See **Fig. 12.1**)

The idea is for smart robotic systems to concentrate on developing a range of advanced algorithms to undertake a

¹⁴⁶ U.S. Council of Advisors of Science and Technology (2010)
<https://www.federalregister.gov/documents/2010/04/27/2010-9796/presidents-council-of-advisors-on-science-and-technology>

wider range of tasks. In light of current progress being made in the AI domain to advance the capabilities and skills of smart robots there appears to be an opportunity for wider operational implementation on a more pervasive and rapid schedule. Mining operations on the Moon, of course, is just one of dozens of opportunities to make astronaut exploration not only safer, but also more effective, cost-efficient, and with faster results achieved.

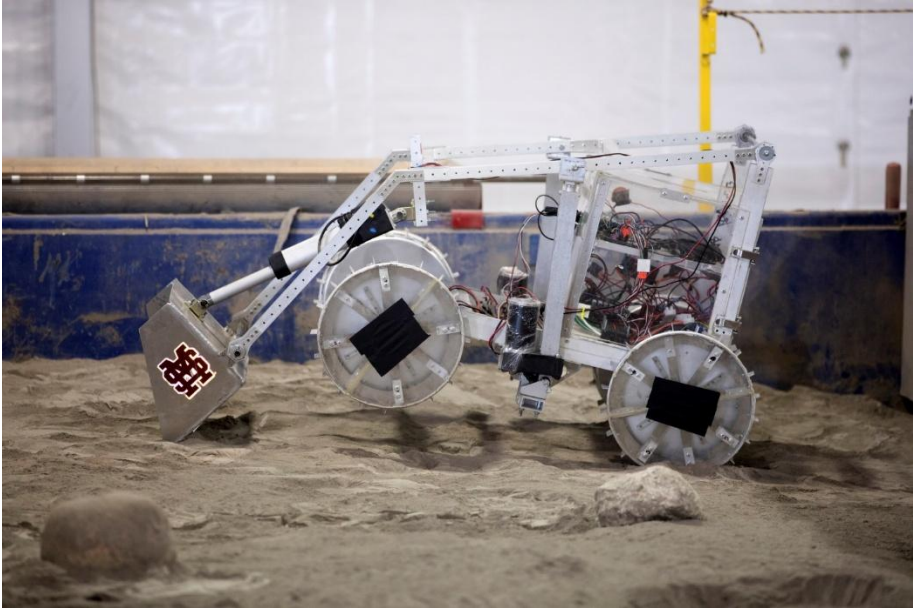


Fig. 12.1: Image of a Robotic Lunar Mining System in Testing at a NASA Challenge Competition (Image courtesy of NASA)

Telepresence Systems

There is a parallel capability that should work in close parallel with regard to advanced planning for more extended use of smart robotic systems to accomplish an expanded range of deep space operations. These increasingly capable robots might be used in building habitats, mining for volatiles in ice

form, transporting supplies, or even undertaking scientific experiments, tending to agricultural plants, or many other tasks. This support capability would involve creating a highly functional telepresence capability that could function in a local context but also relay broadband updates and improved software and AI capabilities to and from Earth from various deep space locations. In view of the time delays associated with interplanetary distances, it is important that these telepresence capabilities have a local dimension and another deep space relay capability as well.

Smart humanoid mobile robots designed to serve as astronaut exploration and building systems should be built to serve a wide range of functions. These walking and “talking” robots would not only be able to communicate, store terabytes of useful data and information, but also be equipped with a wide range of apps. These would include programs to build things, control 3-D printing systems, undertake mining and surveying operations, lift and transport things, and more. One of these important capabilities might be that they could also provide what might be described as a tele-presence capability. These human-like mechanical aids would be able to hold and manipulate items and perform a wide range of tasks requiring strength and dexterity. They should also be equipped with at least three, if not more, high-resolution video cameras installed so that they are aimed at different angles to create a “multi-raster digital imaging system” in order to achieve depth perception. They should also be a sort of mobile Wi-Fi hub that allows streaming of the activities being accomplished and relayed to a central transmission link at the base camp location for broadband transmission to NASA’s deep space network on Earth. There, the information could be stored and retrieved on demand. Not all this information would be transmitted back to Earth, but it would be stored for on-demand access as needed by keyword or time and date.

This would be received on a delayed basis back at NASA's facilities on Earth. Nevertheless, it would also allow a review of difficulties and accidents that might occur, even if this review analysis would be on a delayed basis. This type of tele-presence capability would be a way to continuously monitor progress and keep everyone informed and aware of what was occurring throughout the base camp operation. This type of integrated design would allow a "shared awareness" among the NASA ground control staff, astronauts, "smart" robots, various sensors, environmental controls, and life-support systems. Many of the smart equipment in use in the Mars exploration habitat and work sites would include various electrical and optical devices with some level of "smart" Internet of Things (IoTs) capabilities.

This approach thus envisions a deep space habitat as a sort of fully equipped tele-city facility with the 'smart' robotic systems being the key to a continuing capability to provide assistance in a number of important ways. These would include physical, transport, and mechanical skill capabilities, imaging and recording of activities and work, and access to data and information for safety or accident reviews. Its sensors, video cameras, computer facilities, smart algorithms and apps, and continuous communication with the base camp communications center via Wi-Fi capability would be automatically relayed to NASA ground control. These smart hominoid robots would be much more than "assistants" but rather vital infrastructures to keep the mission operating at maximum efficiency, reliability, productivity, and sharing of information, with many capabilities to keep astronauts safe, healthy, informed, and free from danger and injury.

For years, vital infrastructure has been seen in terms of physical assets to provide power and fuel, water, heat, transportation, cooling, and life support systems. In the 21st century, intellectual infrastructure with regard to

communications, computer applications and processing, networking, data storage, digital records, operational and safety standards, and more, must be every bit as important, fault-free, and widely available as possible. In short, an integrated team should design the “Smart” mobile robotic systems, the telepresence systems integrated with the mobile robots, and the overall architecture of deep space habitats or eventual deep space human settlements. NASA has been working with research universities and relevant industry for years to develop increasingly capable robotic systems. This R&D has made significant progress.

Now is the time, however, to transition from simply creating smart robots to the next stage of development. This new effort should integrate smart robots and telepresence technologies within the overall architectural design of deep space habitats and future base camps. This effort would benefit from the formation of interdisciplinary teams that would work together. The challenge would be to develop highly interactive smart robots equipped with sophisticated sensing, networking, and telecommunications systems as well as intelligent and AI-enabled processing capabilities. The goal would be to include all of these “smart infrastructure capabilities” with a holistic architectural design optimized to create an interactive base camp design for future deep space exploration. Such results might, in time, prove to be not only optimal for future deep space colonies, but also the design for safer, better-conceived, and more productive towns and cities here on Earth as well. (See **Fig. 12.2**)

Astrobiotics, Inc., that was selected to design and build the lander in collaboration with NASA Artemis officials has come up with a replacement payload for the scheduled SpaceX Falcon Heavy launch and the Griffen lander system. This replacement rover is being designed and fabricated by Venturi Astrolab and is known as the Flexible Logistics and

Exploration (FLEX). This is a larger version of the Lunar Innovation Platform (FLIP) that Venturi Astrolab also developed.



Fig. 12.2: SpaceX Smart Robot Concept
(Image courtesy of NASA)

This mission is slated to land in the Nobile region at the lunar South Pole, perhaps at the end of 2025 or early 2026. The lack of success with commercial lunar landers to date is a concern because of the rugged terrain and difficulty of navigation in this region of the Moon's surface.

The final status of the VIPER remains somewhat undecided. Currently, however, there is no proven and appropriate lander system or launch vehicle designated by NASA to support the delivery to the lunar surface.¹⁴⁷

The problem with failed lunar landers not completing their deliveries to the lunar surface is, in some ways, a useful indicator of inefficiencies in the current Artemis Program. The great complexity, costs, and difficulties of the VIPER autonomous rover, in some ways, seem to be symptomatic of a NASA holdover from using the U.S. DOD approach to working with traditional aerospace corporations. This was to undertake major new massive technological development programs, such as a new aircraft system. This automatically assumes that such a development will be a multi-billion-dollar undertaking with years of R&D and a massive procurement of the new system once developed. This process thus almost always led to the selection of one or more of a very few major U.S. aerospace companies with experience of this type. Each of these large aerospace enterprises had a national presence with a very wide stable of subcontractors, and a large workforce of scientists and engineers suitably trained for both the R&D and subsequent production. This approach, that evolved from World War II military defense needs, has continued for the U.S. Department of Defense for many decades. NASA, when first created in the late 1950s, tended, for many years, to closely follow this model. This was a system that was designed to invent new generations of tanks, automatic weapons, rockets and missiles, bombers and fighter jets. It also served to produce rocket launchers, spacecraft, and satellites for NASA.

In the age of commercial space services and with the development of “NewSpace” industries, however, NASA was

¹⁴⁷David Dickinson, “New Rover Will Head to the Moon in VIPER’s Place”, Sky and Telescope, Feb 11, 2025, <https://skyandtelescope.org/astronomy-news/new-rover-will-head-to-the-moon-in-vipers-place/>

increasingly forced to look at new models of procurement. This includes examining new methods of procurement. This examination of new ways forward showed new models that could be used to undertake the research, design, and development, and production of new space systems. NASA became aware, in some detail, of the methods used by commercial space organizations to provide satellite telecommunications and other services. This included such organizations as Intelsat, Inmarsat, or Eutelsat, and fully also commercial organizations such as SES, Boeing, and hybrids such as Telepazio, and Telesat.. These space service providers which operated on a commercial basis, offered new models that could be more efficient as to cost, delivery schedules, and productivity. These organizations almost always developed commercial “performance specifications” and required commercial aerospace companies to submit their technical designs and fixed cost quotes in accord with specified delivery dates.,

There are also now the “NewSpace” aerospace companies which are much more geared to the practices and business models of the computer industry and Silicon Valley than the traditional aerospace companies that arose with the so-called WWII military industrial complex. They utilized innovative design processes that are created and tested new systems designed on computer systems, simulators, and digital modelling systems. The use of computer power, modeling algorithms, and new “smart” automated production facilities have revolutionized the way that new reusable rocket launchers and spacecraft are now designed. They also tended to be vertically integrated to the largest extent possible, offered new types of pay and stock option incentives to employees, and had exacting strategic planning and goal setting methods that inspired hard work and many challenges to its highly motivated and largely younger workforce. These “NewSpace” industries offer new opportunity for NASA.

These motivated “NewSpace” industries, along with a number of “re-invigorated” traditional aerospace companies that have responded to the challenges presented by their new competitors, offer NASA new opportunities as well. These are the commercial resources that NASA will need for the future. They can provide both the needed scientific and engineering workforce, which is motivated to take on new and demanding assignments to create new and innovative space systems.

They will also be able to provide the latest digital processing, networking, telecommunications and navigational systems. Likewise, they will be able to maximize robotic production machinery and use ever-higher performance software and adaptive software. The type of approach that was taken in the development of VIPER autonomous rover, where great complexity and many requirements were put together in one huge expensive system, is emblematic of the traditional “military industrial complex” model, rather than the “NewSpace” way of developing new space products, services, and space exploration capabilities in a more agile way of finding innovation and new ways forward.

The difference in approach to developing entirely new system capabilities that NASA might traditionally take to space exploration and “NewSpace” innovators can be shown by the example that emerged from the Google “Lunar X-Prize Competition”. This was sponsored by Google to stimulate new commercial and low-cost transportation systems that were capable of flying to the Moon and producing video coverage of the lunar surface. There was also a bonus if this video coverage could provide images of the Apollo 11 historic landing site.

The Grand Prize was set at \$20 million, and the second prize was \$5 million. If this had been a NASA project, its budget would have likely been in the billions of dollars and not tens of

millions of dollars for the undertaking of a lunar exploration program.

Some of the proposed mission designs would have never made it through a NASA mission design process. One design was for a small lunar rover with a miniature video camera and a modest battery-powered drive system. The unique factor in this design was that the entire payload was the size of a roller skate. Other innovative designs included a snake-like slithering motion type of locomotion. These “NewSpace” innovators were able to focus on the minimum size and cost capability that might be able to realize the stated mission objective. They were not seeking to develop a multi-billion-dollar aircraft, but something that might be achieved within an exacting and small budget with quick design and production schedules wherever possible.¹⁴⁸

NASA needs to re-examine its approach to new space systems manufacturing and focus its development efforts for the Artemis Program, seeking to identify and mine volatiles from the lunar surface with a simpler approach. This would be closer to what might be called an “Occam’s Razor” mentality. This approach would seek to emphasize the simplicity of design and execution. This applies when it comes to designing systems to find and extract lunar resources, build lunar habitats, process lunar materials, and undertake the manufacture of various types of products on the Moon. Certainly, low-cost challenge competitions with innovative people and workshops might be a better way to start than the VIPER autonomous rover, which has seemed to have become the “Edsel Ford” type failure of the Artemis Program, at least at this stage. (See **Fig. 12.3**)

¹⁴⁸ “The New Space Race” The X-Prize Foundation
<https://www.xprize.org/prizes/google-lunar> (Last accessed April 4, 2025)



Fig. 12.3: The Now-Canceled and Perhaps Over-Engineered VIPER Rover: Is it the Edsel of the Artemis Program?
(Image courtesy of NASA)

Another dimension of this new way of thinking is to see what technologies are already developed for U.S. commercial markets. These include additive manufacturing, 3-D printing of various products, and chemical assaying and analysis that could be adapted or qualified for use on the Moon or Mars. Part of NASA R&D should be to develop new capabilities and technologies for space that might be useful products or capabilities here on Earth.

The other side of the equation is one that the “NewSpace” companies have been using for years. This is simply adapting industrial products and systems and integrating them into the space systems they develop. Companies such as Planet Labs

and many of the entrants into the Google Lunar X-Prize competition have shown that this is quite possible.

Nevertheless, care must be taken. Electrical wiring produced for use in homes and buildings will, for instance, turn into fire hazards in space. The people who try to make such adaptations must know what they are doing and how the space environment is quite different in many ways from what we experience in microgravity, thermal shifts, and radiation dangers of outer space. So-called “common sense” approaches that are still seeking innovative designs and inspiration, however, have their limits. Those seeking simpler solutions must have their judgments and decisions tempered and verified by scientific knowledge.

Ralph Waldo Emerson once famously said, “The mind, once stretched by a new idea, never reverts to its original dimensions.” The time has come for NASA to recognize new and better ways to design, research, develop, engineer, and manage its efforts going forward. NASA leadership should create new knowledge and programs for the future of space science, engineering, exploration, and application that build on the new strengths born of the age of “NewSpace” companies. These companies embrace more innovative ways to create new space systems and capabilities. Jeff Bezos, in a much shorter way, has expressed ideas for innovative ways to move boldly forward with a willingness to abandon the past for better ways. This led to him adopting this motto for his company: “Gradatim Ferociter: Step by Step Ferociously.”

Space-based Agriculture, Genetic, and Organic Optimization for Deep Space Environments and Human Habitats

Perhaps the biggest challenge for NASA with regard to successful exploration of deep space will be in creating

successful agricultural production in space that is also symbiotically compatible with human existence within an integrated biospheric living environment. In chapter 5, it was noted that NASA faced a much greater challenge than simply getting plants to grow effectively. This required being able to go through multiple cycles of seed to plants, from plants to edible food, and viable seeds to plant through to a sustainable way to provide food for astronauts and space travelers of the future. This step beyond developing space specific scientific knowledge to undertake farming is to create an organically viable and sustainable space habit environments - a sort of holistic biosystem where humans, animals, plants, and recycled waste materials could be truly viable on a longer basis without reliance on outside help or rescue from self-generating destructive practices, debilitating decisions, or a lack of food, water, oxygen, or other life sustaining capabilities.

The ultimate goal for future space habitats would be an environment in which a natural balance would be achieved so that humans and animals would be able to live in atmospheric harmony. This is in terms of balanced levels of oxygen, carbon dioxide, and other gases needed for both flora and fauna, where life could exist on a continuous, longer-term basis. As noted earlier, this would represent what has been defined as a “Bio-regenerative Life Support System” (BLSS). The achievement of a true biosphere system that would be self-sustaining should become a key longer-term goal to be attacked by NASA--“ferociously, step by step.” Such a breakthrough capability would represent a crucial step for life sustenance on a long-term MARS habitat. If this could be designed and proven for a larger scale and holistically designed system for MARS, research should also continue to seek to do so on an even smaller scale. This type of smaller biosystem development would, of course, be quite valuable for a Mars space transport vehicle that would ideally include artificial

gravity, radiation protection, food, water, and air, as well as effective resource and waste system recycling. The NASA-developed “Environmental Control and Life Support Systems” (ECLSS) has shown continuous program improvements over several decades, but clearly, these truly self-sustaining goals still lie well ahead. Challenge competitions, workshops, and other incentivized activities to create “mind-stretching” ideas toward such objectives should be areas for priority focus.

Sustainable Electrical and Other Energy Supply Systems for Space Exploration

The difficulty of having sufficient clean and sustainable energy sources for deep space habitats and living centers has already been noted. The use of solar energy is clearly an option for space exploration. The further away one gets from the sun, the less effective it becomes. This limitation, however, might conceivably be overcome by the creation of solar radiation concentrators or a mirror system such as that depicted in the Stanford Torus Habitat conceptual design shown in **Fig. 11.5**. The future achievement of effective and lower cost nuclear fusion is certainly a possibility that might support a future MARS habitat, as discussed earlier. Battery and similar storage capabilities for electrical energy systems are also evolving rapidly based on the expanded use of electric vehicles, which is now quickly driving innovation in this area.

Clean, abundant, and easily accessible energy supplies will be critical to the future needs of deep space habitation. The ability to support fuel supplies such as xenon for electric ion thrusters and even to produce liquid hydrogen, liquid oxygen, or other fuels must be a further area of study. One of the areas for NASA to consider is whether it is best to simply monitor the research efforts of others, or whether there is a particular future energy development and

research objective that is uniquely tied to the needs of future space travel, space science R&D, or deep space exploration that requires a dedicated advanced research effort in this area as well.

It is imperative that NASA also continues to consider and explore the best energy systems of the future that will support space programs on a thirty-year agenda. Improvements in the “smart and sustainable energy sector” could be vital to the success of future space habitats and living areas. Breakthroughs in this area could potentially also become vital to a cleaner and more viable design for “smart energy” systems right here on planet Earth.

Conclusions

This chapter has addressed the need for NASA to reshape and enhance its research agenda in new and dynamic ways that build on the innovations that have come to the modern world. These new ideas have come from Silicon Valley, from “new space” companies, from thought leaders who gave birth to the X-Prize. Inspiration has also come from other challenge-based competitive design exercises, as well as from more efficient contractual agreements, and complementary research and development initiatives between NASA and its various research partners. In the past two decades, in the era of “NewSpace,” companies have seen innovation everywhere. This has produced reusable launch systems and spaceplanes that fly to orbit and commercial transportation to the ISS. These “NewSpace” companies, with a much more vertically integrated and efficient operation at a consolidated location, have transformed the aerospace industry. They have instituted new management systems, higher levels of automation, more use of computer simulation and modeling, and employee compensation and incentive packages. These new ways of doing business and

designing new space systems, with goal-driven innovation, have all lead to amazing new breakthroughs for the aerospace industry, and NASA has moved to embrace many of these changes as well. The Space Launch System and the Orion capsule, however, remain a part of the Artemis Program as a reminder of the old way of doing business in the aerospace world.

Reforms and innovations discussed in this and earlier chapters point to new ways to develop new space technologies and capabilities in a more rapid, self-sustaining, cost-effective, and yes, even safer way forward.

Advanced and Safer Space Transportation:

A top priority is in the development of more efficient, clean, sustainable, effective and safety transportation systems with even higher performance capabilities. Clearly electric ion propulsion systems with nuclear fusion thermal capabilities are a high priority. There are also other capabilities to research. These include: (i) more effective use of AI modeling, simulation, and computer-based analytics to increase the design and engineering of new space propulsion engines; (ii) enhanced abilities and algorithms to increase gravity assist programming; (iii) targeted R&D in such space transport-related areas as natural electromagnetic propulsion, tether-based or space elevator space transport systems, and other nuclear-based propulsive systems; and especially (iv) new architectural concepts for reusable and integrated space transportation vehicles that would include original circular and reusable vehicles and tug systems to maximize both safety, performance, and multiple reuse of launchers, spacecraft and tug systems

AI-Assisted “Smart Robotic Systems:

In this area as well, there is a need for new and improved technology, but also a new conception of how to optimize the effectiveness, efficiency and safety of space exploration in the 21st century. This includes not only the development of new, “smarter” and efficient robotics and increased capabilities in terms of agility, dexterity, sensor and perception capabilities, communications, data storage, and specialized applications and capabilities, but also the degree to which such increased capabilities offer new opportunities to increase the safety and efficiency of astronaut deep space exploration missions. This suggests that more advanced use of “smart robots” to set up remote space base camps, habitats, and deep space facilities before astronauts arrive at deep space locations and supplementing astronaut exploration missions with more robotic system support. The Star Wars movies were just scripted fantasy, but deep space capabilities of truly capable robots could, in fact, reprise the role of an ARTOO or an 3CPO in future space missions to provide key new capabilities, greater efficiency, cost savings, less costly resupply missions, and most of all increased safety.

Advanced Telepresence Systems:

A part of the plan to develop what might be called new hominoid robotic systems would integrate these new systems into the support system and deep space infrastructure for deep space habitats and base camp planning. This should include in the design of such robotic assistance increased capability to provide such capabilities as physical tasking and transport. It should also include assistance with seeing, hearing, video recording, sensing problems, providing telecommunication and navigational services, and providing vital information or protective

actions on demand. The object would be not to create new and better robotic devices, but a smart, integrated and support team that constitutes a “smart” walking, talking, constantly available resource available to help astronauts and to keep them safe.

Remote Mining, Material Processing, and Space-Based Manufacturing:

The Artemis Program is seeking to transform lunar exploration from just a visit to a remote place of scientific discovery into an opportunity to make practical use of this now barren and remote location. This would include support for future human endeavors, commercial trade and industry, and perhaps serve as a base for future remote mining, material processing, and even space-based manufacturing of a variety of products and services. It is even envisioned that the Moon may become a place to manufacture satellites that could be lowered to Earth orbit, or other now well-understood possibilities. Even Gerard O'Neill's concept of lunar-based mass drivers, mining operations, and support services to eventually create a free-flying space colony might someday become possible.

Advanced Energy Systems and Capabilities

All of the above advanced space vehicles, robotic systems, telepresence capabilities, remote mining, processing, and manufacturing systems will require an ever-increasing supply of power. This might be provided by a variety of different sources. Reliance on solar may prove inadequate. Nuclear power presents safety problems, waste materials, and environmental concerns. Clearly, this is an area that NASA researchers must pursue to find new solutions and clean and safe answers for future deep space power supplies.

The Bottom Line

Research and development by NASA is of true importance not only to support the advancement of the core capabilities needed for deep space exploration. It is essential to also note that advances in these areas are likewise key to human needs and progress right here on Earth.

Chapter 13

Advanced Longer-Term Space Research and Outside-the-Box Initiatives

Introduction

In the previous chapters, the focus has been on areas for advancement in space safety and NASA strategic planning for essentially the next decade, but also on the importance of seeking to establish thirty-year-long-term goals as well. We have sought to identify areas that could be improved in terms of new technology development and innovation, improved concepts and methods in space safety, and even new space system architectural concepts. This chapter seeks to explore, in much greater detail, the longer-term future. It examines what might be called a thirty-year perspective on what NASA might accomplish in the longer-term future of deep space initiatives. This should include the pursuit of truly breakthrough accomplishments. There is a great deal that can be done in scientific and uncrewed spacecraft that is truly groundbreaking and worthy of NASA's longer-term support, and is also touched on in this book in various ways. Nevertheless, our focus is primarily on astronaut and human safety, travel, and exploration. Thus, this chapter primarily focuses on how NASA should strategically plan to develop new technologies, systems, and capabilities to save both astronaut and human life as space exploration continues to include more and more people. This is also important because new and breakthrough space systems and technology can be used to protect humanity

against cosmic hazards. This longer-term NASA research agenda thus includes the pursuit of new and improved ways for astronauts and even space exploration citizen-astronauts to fly and then perhaps ultimately to live safely in deep space.

There are indeed innovative ways forward that could change the course of human events and truly allow humans to alter the nature of their existence and their longer term sustainability. These prospective new areas for research and development are described in some detail in the pages that follow. These recommendations include suggested new areas for NASA to pursue. Thus, in this chapter, we seek for NASA to undertake truly new pathways to the future in space research and exploration.

The first key step would be for NASA to undertake the development of a new and revised strategic plan in two stages. One would be for the near-to-medium term, and the other would represent a thirty-year plan. Only with a sense of purpose, clear goals and objectives, and consistent focus can many of these forward-looking goals actually be reached. For the last 20 years, there have been many erratic changes in the nature of NASA's strategic mission. There have been abrupt changes due to presidential elections, new NASA Administrators, and shifts in Congressional appropriations. There have also been political interventions and dramatic changes as a result of the Space Shuttle accident. In some cases, shifts occur slowly as vaguely defined goals and objectives are abandoned, or sometimes past aims are simply forgotten.

There is an old but very true axiom. This is to remind leadership that if one does not know where one wants to go, one will never get there. Top goals need be: (a) better defined and qualifiable goals and research timetables for both the shorter-term and longer term in NASA's strategic planning

process; (b) a willingness to think more unconventionally and accept the pursuit of “outside the box” breakthroughs; (c) accept concept that far-reaching space research goals and objectives are critical to the longer term future of human survival and well-being; and (d) accept the wisdom contained in both Arthur C. Clarke’s vision of the future as contained in his Three Laws, plus Ralph Waldo Emerson’s admonition about “the need to stretch the human brain.” This is to say that NASA must be willing to set truly bold and demanding goals that are indeed difficult to achieve and might take even three decades or longer to achieve some goals that are true breakthrough accomplishments.¹⁴⁹

NASA's thirty-year goals must thus seek new insights and extend the length of humanity’s scientific reach. This means exploring viable ways for people to live and survive in deep space in new and unexpected ways. This will require new knowledge and accomplishments once thought unattainable. In short, it is time for NASA to create a dynamic and truly longer-term set of strategic goals to take on key and truly challenging development goals, even if they require decades of dedicated effort. It is time for NASA to take on challenging problems that today seem almost too difficult to achieve. These future goals may even seem impossible without longer-term and very expensive effort, but these are the key objectives that NASA must be incentivized to pursue. Clarke’s Second Law clearly states: “The only way of discovering the limits of the possible is to venture a little way past them into the impossible.”

If one reviews NASA’s currently published strategic vision and its specifically stated plans for the future, a task that is federally

¹⁴⁹ Ralph Waldo Emerson quote,

<https://www.bing.com/search?q=Ralph+waldo+Emerson%27s+quote+about+need+to+stretch+the+human+brain&form=MSNSB1&refid=5b82511c109d4493a2a222a516df59b&mkt=en-us&ocid=>

mandated, the results are disappointing. What appears on NASA's website is quite vague, and frankly, it seems almost deliberately intended to be soft and amorphous. It says very little about what the space agency is really striving to achieve and very little about longer-term aims. The very vagueness of the goals allows NASA to proceed with almost any program that Congress is willing to fund and send to the President to sign.

The actual NASA strategic plan is simply divided into four verbs. These are Discover, Explore, Innovate and Advance. These are perfectly good verbs, but they reveal very little about the goals NASA is actually striving to achieve. Not having a clear roadmap is safe, but it is the opposite of challenging.¹⁵⁰ (See **Fig. 13.1**)

The analysis that follows suggests that NASA leadership should chart a new way forward to create strategic plans for a thirty-year period with clear objectives, targeted aims, and timetables. There should be clarity about seeking breakthrough results, rather than routine spending of its annual appropriations. Here are some thoughts—not for the near term and for projects that have gone through White House and Congressional approvals, but longer-term, “outside-the-box” goals that could truly make a difference for NASA, the world's future, and meaningful deep space exploration. The ideas and recommendations that follow seek to offer examples of what such a longer-term strategic planning process might entail.

¹⁵⁰ NASA Strategic Plan for 2025, Feb 13, 2024,
<https://www.nasa.gov/ocfo/strategic-plan/>

Vision: Exploring secrets of the universe for the benefit of all

Mission: NASA explores the unknown in air and space, innovates for the benefit of humanity, and inspires the world through discovery

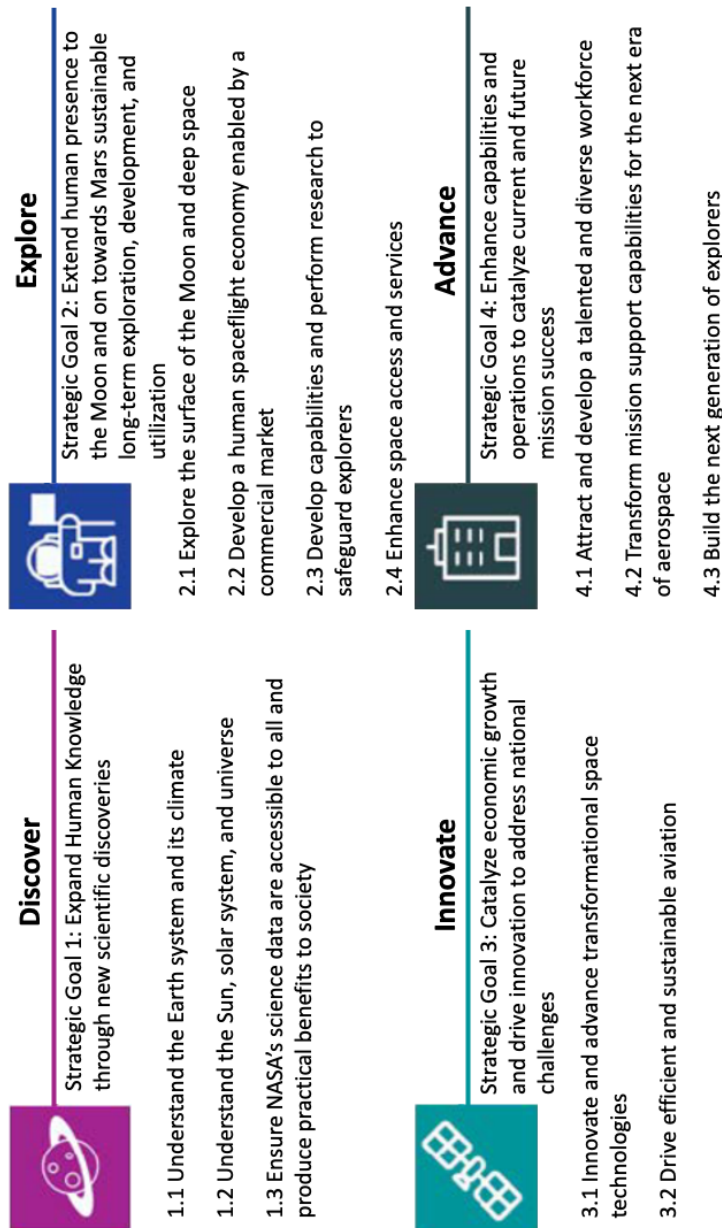


Fig. 13.1 : The NASA Strategic Plan reveals little of its plans and even less of its vision for future research objectives
(Graphic courtesy of NASA)

Use of Suspended Animation and Artificial Gravity Capabilities for Astronaut Travel and Advanced Space Station Design

Today, the ability of astronauts to travel safely into deep space is indeed limited. The human physical constitution is closely adapted to living on spaceship Earth. Here, in a stable one-g world, humans largely live in a steady gravity environment except for occasional roller coaster rides or a weightless experience on the “Vomit Comet” parabolic loop on a jet aircraft reaching high altitude. We also breathe air from an open atmosphere that usually provides a ready supply of oxygen, while natural atmospheric and magnetic forces serve to protect us from solar and cosmic radiation through the ozone layer. Our atmosphere generally provides a viable range of temperatures for survival. We do indeed live on a Goldilocks planet, whose bodies were excellently adapted over many years of evolution.

It is possible for astronauts to safely spend a relatively short period of time on space stations such as the International Space Station, but there are dangers to human health and a variety of diseases in cases of a truly longer-term stay. Dangers include such maladies as radiation sickness, heart disease, bone and muscle tissue loss, and even potential loss of sight if one stays too long in outer space conditions. This is because longer-term exposure to a microgravity environment can cause calcium loss in the bone structure. This can, over time, lead to the reshaping of the human skull so as to pinch the optic nerve and ultimately lead to loss of sight.

All of these challenges and more means that it is very difficult to design and build a space station or deep space-based platform that could actually sustain a constant human population for a long time if the passengers were not rotated in and out. What would be needed would be a sustainable

environment or biosystem that would closely resemble a very Earth-like environment. To achieve this, we would need to create space habitats that meet dozens of exacting specifications that included air to breathe, food to eat, the recycling of human waste, stability of oxygen, water vapor, carbon dioxide and other gases in the atmosphere, and a well-maintained balance among all of the living organisms within the biosystem. And this is only the start of the key specification for this long-term goal.

It would take years to develop the details of the dynamic balance to be achieved, the hundreds of specific levels to monitor and maintain, mix of interactive components and more. Then one would have to create testing and modelling capabilities followed by actual fabrication of a biosystem to detect its flaws and deficiencies. Such a remarkable achievement would take a long time, but it could be accomplished in a thirty-year window of time.

One key element would be to create, through centripetal force, an artificial gravity that comes close to simulating one g force. The rotating Stanford Torus (or donut-shaped) ring about one mile (or about 1.6 km) in diameter, as shown in Fig. 12.5, is one possible design. One approach would be to launch a number of radiating modules that could be joined together at a rotating hub. The Vast company has proposed such a design. Its concept is an incremental design with modules that can be added over time. The idea is to create a self-sustaining and fully functional capability to sustain astronauts' health with an increasing ability to offer artificial gravity capabilities that can increase as modules are extended from a rotating hub. Such a rotating structure could help to meet artificial gravity requirements to support long-term human health in outer space. This modular rotating space station undertaking might take decades to ultimately achieve, but it is a very interesting and thought-provoking approach. NASA has considered

various designs for a long time, with the most complex and advanced system being the so-called Stanford Torus. There have subsequently been various offshoot versions of rotating torus designs. What is needed as a first step is a viable and cost-effective prototype design. **Fig 13.2** shows one such NASA design.

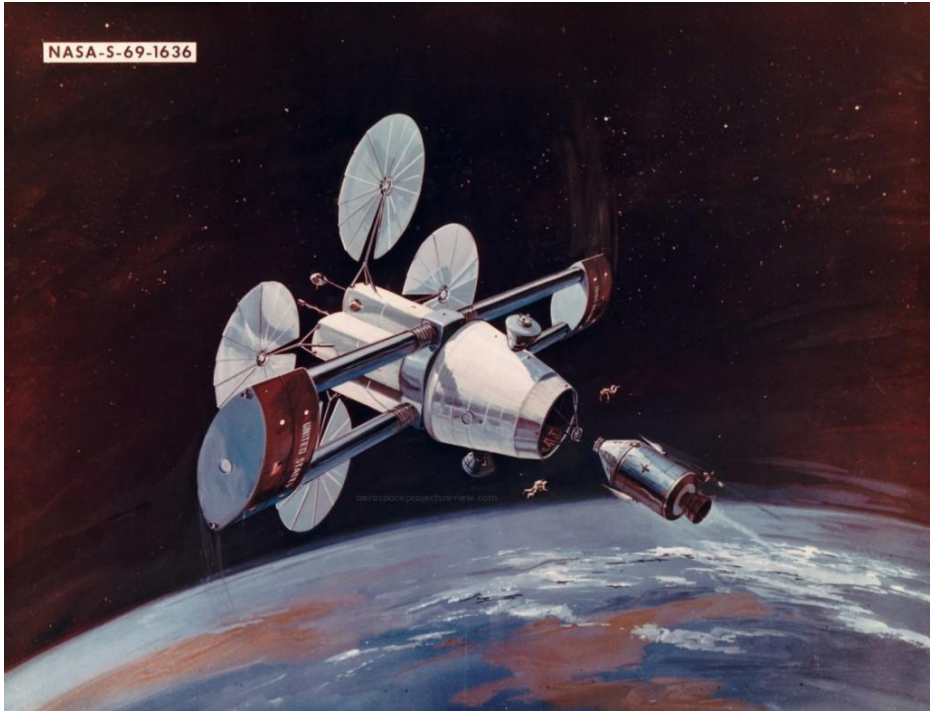


Fig. 13.2: Prototype design for a rotating space station with artificial gravity
(Graphic courtesy of NASA)

The achievement of a one-g environment on a space station is clearly easier to accomplish than one on the surface of the Moon, where the gravitational force (1.52 meters/sec²) is only 17% of what we experience on Earth. We have not undertaken the necessary medical research to find out if the gravitational force of Mars is sufficient for longer-term human health. Its

gravitational pull is at 3.7 meter/sec^2 , is only 38% of Earth's 9.8 meter/sec^2 accelerative force. This may well be a much better and healthier condition, but research on the health and medical impacts on humans living on Mars remains a key area of future research.

There are many other challenges to creating an artificial simulation of living conditions here on Planet Earth. The design of a system to provide protection against solar and cosmic radiation has many possible solutions that are different if the location is the surface of the Moon, or Mars, in low Earth orbit, or orbiting in deep space.

The other challenges to the creation of an environment so that humans have sufficient oxygen to breathe, water to drink and use, and sufficient healthy food to eat are enormous. The ultimate goal of bio-regenerative stability among and between humans, animals, vegetation, and micro-organisms is likely to be one of the greatest challenges of all. This should thus become a top candidate for a thirty-year NASA research goal.

The experiences, failings, and scientific and biological findings that came with the Biosphere II experiment conducted in Arizona in the U.S. from September 1991 to 1993 were a useful reminder that this is no easy task. Replicating such a homeostatic balance that was largely reached on Earth after billions of years of evolutionary progress is no easy goal. It is unlikely to be achieved without a lot of trial and error and many decades of research, development, and failed experiments. This only means that the sooner clear goals are set to seek such an ecological and environmentally balanced capability, the better. The goal of creating a viable biosystem within what is essentially a closed or nearly closed system with limited inputs and outputs is difficult indeed. In short, can NASA scientists and engineers design a bio-regenerative life support system that can sustain astronauts, flora and fauna,

and necessary micro-organisms, and everything else that is hosted within a nearly closed biosystem that can sustain itself through hundreds and even thousands of life cycles if NASA was successful in creating and achieving such a goal the better the chance of finding the answers that humans actually may need to know how to survive. This seems to be the case whether we are talking about sustaining life in outer space or the longer-term survival of humanity right here on Earth. I believe that few people understand that human survival in outer space and human survival with respect to climate change or other planetary cosmic threats are basically one and the same problem. This could be an opportunity for NASA, and perhaps the National Science Foundation (NSF), to establish such a long-term goal and work together to realize this life-sustaining objective.

This leads us to another possible goal area. There have been attempts in the past by the National Science Foundation and other scientific research organizations to define “Grand Challenges.” The focus of these challenges has been to pursue and perfect the next generation of technologies to meet humanity’s future needs. These have ranged from mastery of nuclear fusion to the cure of cancer and Alzheimer’s’ disease.

There is even a specifically devised term for such types of societal goals that impede the future of humanity. It was environmental scientist Tim Morton who invented such a term. The focus of his concern was the threat to life and survival due to climate change, but there are, of course, others that face humanity as well. Several of these involve problems associated with living not just on Earth but in the cosmic universe as well.

Here is a quote about Tim Morton and his invention of the concept that he calls “Hyper-Objects.”

“Tim Morton thus coined the term “Hyper Object.” He invented the term to refer to “Climate Change” and its long-term threat to human survival. According to Morton, a “Hyper Object” is something so gigantic in its longer-term impact, so long-lasting over a substantial period of time, and so complex and difficult to address that most people simply dismiss it. A threat like climate change is something clearly above their pay grade. Thus, things like climate change, asteroid or comet strikes, or pandemics can simply be dismissed. These are mega-dangers that they feel are beyond their personal ability to address. Certainly, they are too big and formidable for anyone individually to personally address or resolve in a favorable way.”¹⁵¹

The issue of creating a sustainable and bio-regenerative environmental system must not only be able to support human life, but also all of the living systems and capabilities on which human life depends. The ability to create such a scientifically engineered bio system that could be used for a deep space human space colony or right here on Earth should be a prime NASA development goal. This should be supported by a detailed and interdependent set of research goals that could lead to the development, testing, and ultimate verification of such a proven capability. This should be central to a new set of NASA strategic plans and a detailed plan to achieve this goal, as well as a blueprint for a viable deep space colony as a lifeboat for humanity if needed. There must be a “Planet B” option.

Electro-Magnetic Solar Storm Shield Systems to Terraform Mars and Protect Earth

A second element of a longer-term strategy plan for NASA and the safety of astronauts and humanity involves another challenge that could also be deemed to be a “Hyper-Object”

¹⁵¹ Joseph N. Pelton, *Space Systems for Sustainable World*, (2021) Springer Books, Switzerland. Chapter 1.

challenge. This objective would be to develop the range of technologies and space transportation capabilities to design, build, deploy, test, verify, and operate over the longer term a new system that could achieve some key protections for life on Earth and for life in deep space. This would be the development of what might be called electro-magnetic shielding systems to protect Earth from solar storms, and which could also be deployed to protect Mars from both solar wind and massive solar storms.

Not all axioms or old sayings are true. One of them is actually particularly stupid. The saying is that: “What you don’t know can’t hurt you.” Massive solar storms in the form of radiation flares, powerful solar wind, and coronal mass ejections (CMEs) of quintillions of destructive ions that can travel at millions of miles (or kilometers) per hour are largely unknown to most people on planet Earth. Yet these deadly “unknowns” can have deadly consequences for people, the vital infrastructure on which their lives depend, or astronauts on their future space travels once they leave the safety of life on our home planet.

Space travel and exploration represent a great part of what NASA has done for over half a century. It is now time, however, for NASA to play a greater and more ambitious role in humanity’s planetary future. That role is to make the solar system safer for the long-term existence of humanity. The second great future developmental challenge would be to develop a way to create a geomagnetic shield that could be deployed for Mars to start a process to create a viable and sustainable atmosphere for the Red planet. This magnetic shielding system would need to be constantly powered, strong enough, and well designed and constituted so that the solar wind would no longer strip away the atmosphere that is naturally formed from melting ice at the Martian polar areas. Earth has a metallic core that creates a natural magnetic shielding system that allows a protective atmosphere and

magnetosphere to form. Mars is a planet without this natural protection. NASA scientists such as Dr. James Green, former NASA Chief Scientist, has worked with other U.S. national laboratory scientists to explore how such a magnetic protective system could be created. This might be accomplished by generating magnetic fields from the polar areas of the Mars surface, or generated from systems located on the two small moons of Mars, Deimos and Phobos, or perhaps from orbiting spacecraft.

We know that such a protective shielding system is theoretically possible, but the best, most enduring, and sustainable design for such a capability would very well require decades of effort. This would involve experimental testing and development work to create a planetary evolution system for Mars and its future potential to regain a viable atmosphere that could sustain life. The key first steps would be to devise practical models for testing what might be the best solution and to create some sort of plan that might be both technically credible and not unduly expensive. The question is whether an alternative livable planet is something whose value would be stated in billions or perhaps trillions of dollars? U.S. taxpayers spent over \$100 billion on the International Space Station. We could create the possibility of a future livable planet for human settlement for less.

The questions to be addressed and goals to be set for research and development are numerous. The basic question would start with the probing of a possible design for a Martian magnetic shielding system that would be strong enough and appropriately positioned so as to be able to divert the solar wind and coronal mass ejections (CMEs). It would need to be designed to limit the adverse effects of solar radiation, as well as CMEs and the solar wind. This would need to be a design that would ensure that humans and other life forms could live within such a biosystem and that eventually crops and animal

life could grow and thrive in such an environment. It would also require a system that had a perimeter great enough so that the incoming ions and radiation would not only be blocked as they are streaming out from the sun, but are also blocked from simply flowing around the shield and reforming again to provide a destructive blast that would still reach the surface of Mars. Conceptual frameworks are one thing. However, a viable magnetic shielding system that could work technically and economically and then be sustained for years, decades, centuries, and millennia is a much more challenging question.

And, of course, the ultimate challenge of such a great NASA undertaking would only be the first phase of an even greater challenge. This proposition is whether Earth could also be protected from Solar Storms and an increasingly hot level of solar heat. It is thought that it might be possible to design and build an augmented geo-magnetosphere shielding system that could serve to protect humans and vital infrastructure. Even if the Earth's metallic core offers protective magnetic shielding against powerful ionic solar storms, this shielding system is far from perfect. (See **Fig. 13.2**)

Fig. 13.2, which is not on an exact scale, shows the nature of a CME that is an ionic solar storm. In the figure, the distance between the Sun and Earth is compressed, but the ratio of the Sun to the Earth's size is still fairly accurate. The Earth is represented by the very small blue dot, and the blue lines around Earth reflect its magnetic shielding system. It demonstrates how the charged ions, traveling at millions of miles an hour, are smashing the geo-magnetic shield that helps to protect the world's electronic and electronically controlled infrastructure.

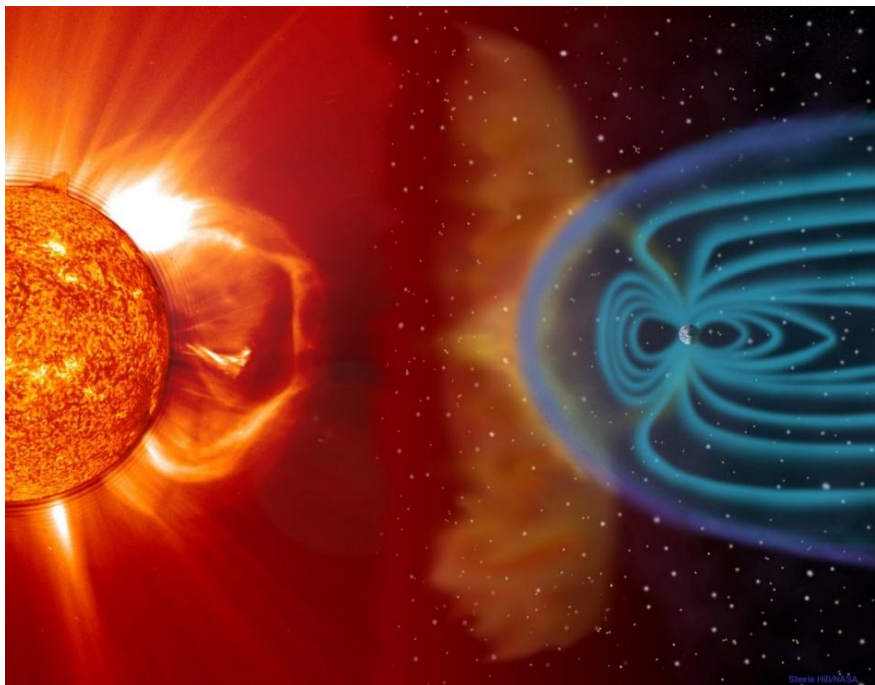


Fig 13.2: Image of Coronal Mass Ejection Smashing into the Earth's Magnetosphere
(Image courtesy of NASA)

The extent to which our world is also vulnerable to massive solar storms is not well understood by the general public. U.S. intelligence analysts at Homeland Security and the CIA, who consider and assess the degree of possible dangers of “black swan” events, however, do understand just how vulnerable modern infrastructure is with regard to major solar storms. They know that such resources as global pipelines, electric power grids, the Internet, satellites, and a host of other electrical systems are very vulnerable to a massive Carrington Event-like solar storm. Within each of the 11-year Solar Max/Solar Min cycle there is the possibility of a “killer” CME that could devastate the world economy, upend employment in service jobs (now about 70% of all world employment) and

provide a sea change to the conveniences of modern life as we know them today.

The creation of an electromagnetic shield for Earth is, of course, an even greater challenge than seeking to do so for Mars, which is smaller in size but also much further away from the sun than Earth. This means that the effective size of a shielding system for Mars can be much smaller in its dimensions. Further, the Martian moons are in orbits that might prove well situated to generate the required protective magnetic field. The Earth is one Astronomical Unit (AU) away from the sun, while the distance of Mars from the sun is a little over 1.5 Astronomical Units (AUs) away. This means that both the radiation from the sun (moving at the speed of light) and Coronal Mass Ejections (CMEs) are spreading out in a conic fashion. This means that a CME that intersects with Mars in its orbit would be diminished in mass intensity by a factor of 2.3 times. The amount of mass to be diverted would be 2.3 times less in its overall dimensions. Further, what might be called the “target size” of the planetary cross-section of Mars is only 28% of that of Earth’s cross-section.

In quantitative terms, Mars is, on average, about 1.52 AUs further away from the sun, and its cross-section is therefore much less of a target. When one considers the size of the impacted planet and the intensity of the “hit” due to the spreading effect of the solar storm, the effective performance requirements for the shielding system would be on the order of 10 times less than that which would be required for protecting Earth. Further, the Moon, because it is too far away from Earth and is only a unitary body, is not a logical part of the design architecture for such a magnetic shielding system.

In sum, a second grand challenge is for NASA. Indeed, this might also be a goal to be pursued in partnership with research universities, national research laboratories, and perhaps other

government agencies such as the National Science Foundation, or even Homeland Security or the U.S. Department of Defense. The first step, however, would be study a viable concept that could lead to engineering specifications for a magnetic shielding system that could allow Mars to evolve a natural atmosphere that could accommodate life on the Red Planet.

If this research finds a viable way forward, this could reshape Mars into a livable biosphere for the future evolution of life on Mars. Further, this could lead to an even more revolutionary Step two. This would mean the pursuit of a yet much more ambitious plan to create a protective shielding system for Earth.

Many are led to believe that Earth is naturally protected by its own magnetic shielding system that forms the protective shielding from massive radiation zones that surround Earth and are now known as the Van Allen belts. If this provides protective shielding to our “Goldilocks Planet” why would this be needed at all?

The answer is that this “natural shielding” that comes from Earth’s core is not a perfect shielding system at all. There is a switching of the Earth’s magnetic poles that occurs over time, and this is occurring all the time, greatly weakening the protection it affords to the Earth’s modern infrastructure. This vulnerability extends to various types of satellites, to the world’s electrical power grid systems, pipeline control systems, communications and networking systems, including the Internet, and automatic control systems. When the Carrington Event occurred in 1859, the only impact was that telegraph offices caught on fire. Today, the equivalent event would have a catastrophic impact on the entire globe. One study undertaken by Lloyds of London by qualified scientists and engineers indicated that the impact on just the North

American electric power grid would require much more than \$3 trillion in 2025 dollars. Recovery from such a catastrophic event would require many years for such a recovery to take place. Tens of thousands of transformers would need replacement around the world, and there would be no stockpile of supplies.¹⁵²

This would be a global “Black Swan” event of the greatest magnitude. The residual consequences and collateral damage might include loss of electrical power lines and vital pipeline control systems, the Internet and telecommunication and navigational services. This could also potentially lead to the loss of billions of jobs in the service industries. This would only be one of the consequences.

These and other dire consequences mean that we as a modern civilization are not prepared for a coronal mass ejection like the Carrington Event of September 1859. Such powerful solar eruptions can perhaps be expected to recur every 150 years or so. Neither the sun’s physics nor the universe has changed in the last century and a half, but the infrastructure on which we rely every day of our lives is now hugely different. The world had less than a billion people then, and now there are over 8 billion people who rely on support systems that did not even exist then. They are greatly at risk, and the likelihood of a destructive solar storm is much higher than a huge asteroid or comet strike. This means NASA must seriously consider, along with the National Space Foundation and Homeland Security, a new, more focused, and prioritized R&D effort in this area.

¹⁵² Joseph N. Pelton, *“Space Systems and Sustainability: From Asteroids and Solar Storms to Pandemics and Climate Changes”* (2021) Springer Press, Switzerland, Chapter 8 (p. 137-50)

Longer Term Space Development Goals for NASA's 30-Year Strategic Planning Effort

Grand challenge research efforts take time and scientific and engineering resources, and those that are the largest in scope also take even more time. The speed of modern innovation and scientific discovery is, however, evolving at an ever-increasing pace. Some ambitious projects require not only significant scientific and engineering R&D but also a very long implementation process. Undertaking activities such as restoring the health of oceans and wetland or reforestation can take decades or even centuries.

Let's then consider other longer-term space development initiatives that NASA might investigate for evaluation. One key area might be an investigation of the sun's evolutionary changes and how new capabilities might be developed to protect Earth against the more destructive aspects of those changes and threats to life on Earth. Such investigations could even consider changes that might evolve over an eon. Solar studies are indeed a very long undertaking.

Scientific and science fiction writer Kim Stanley Robinson has proposed in a well-research article in the *Room's Space Journal* a few years ago about the possibility of gradually relocating Earth farther away from the Sun. This would be a very big undertaking that would take a very long time.

First of all, one should consider what is clearly known. We know, with some precision, the size, mass, and enormous difficulty of raising its orbit. Robinson concedes that such a plan has huge challenges and many shortcomings. It is, however, a useful thought experiment, because we know that a gradual heating up of the sun is an issue beyond the subject of climate change and the increase of greenhouse gases.

In some instances, investigating a seemingly impossible task reveals another way forward that is achievable. Such a strategic review by NASA should start not with whether there are easy or obvious answers, but rather with systematically identifying potential threats that could become central to the very survival of the human race. The fact of the matter is that it is quite clear that when the Sun goes to its nova stage, this process will burn up Earth and all its inhabitants. Fortunately, this is billions of years away based on current scientific research, even though there is much we still do not know about the sun's internal operation, its magnetic instability, and its 11-year Solar Max/Solar Minimum intensity cycles. A process whereby NASA pursues possible planetary threats of a cosmic nature is a fertile area for research, along with potential solutions and defensive actions.

What is known about Earth is that it has a mass of about a six-sextillion metric tons. Thus, accelerating this very big rock and applying thrust to move it outward from the Sun will require a very large amount of thrust for a very sustained period of time to move it even slightly outward from its present orbit. We also know that the mass is not entirely fixed. Scientific studies have indicated that two sources of change are occurring. One change is that about 40,000 metric tons of solid stuff, such as space debris, meteoric materials such as so-called star dust, meteoroids, and bolides, are coming down to Earth as a result of its large gravitational well. This would make the task ever so slightly more difficult if it were not also true that the Earth is losing, on a gradual basis, its atmosphere at a rate of about 95,000 metric tons a year.¹⁵³

¹⁵³ "Earth Loses 50,000 Tonnes of Mass Every Year,
<https://scitechdaily.com/earth-loses-50000-tonnes-of-mass-every-year/>
(Last accessed April 30, 2025)

If these measurements are correct, the Earth will become about 55,000 metric tons less massive in a year's time. In a hundred years, this would presumably add up to a loss of mass of 5,500,000 metric tons in a century's time or 55,000,000 metric tons in a millennia. In terms of a delta mass decrease for an engineer to consider in devising a propulsion system to start moving the Earth into a higher orbit, there is only one thing to know. It really doesn't make any significant difference when you recognize that the Earth's mass is actually very, very large. The actual detailed amount is about 5,900,000,000,000,000,000,000 metric tons, although it is constantly changing. A net gain of about 55 billion tons is actually in the infinitesimal noise level of planetary mass change.

We might wish to lose more hydrocarbons and use up and disperse less hydrogen and helium from our atmosphere, but that has nothing to do with the possible task of considering raising the Earth's orbit. Tens of billions of tons of lost mass for Planet Earth will not make it much easier to move it away from the sun. The answer would require a massive propulsion system.¹⁵⁴

The creation of a propulsion system such as a nuclear fusion system that could raise Earth's orbit has been proposed by people such as space scientist and SF writer Kim Stanley Robinson in the *Room Space Journal* a few years back. Although he accurately notes this would be too slow of a solution to cope with humanity's current climate change crisis, he does note that it could provide some relief from the sun's heating up and eventually creating major temperature increases for the world's oceans and our atmosphere a billion

154 *How Much Additional Mass Does Earth Acquire in A Year?*"

<https://www.bing.com/search?q=how+much+additional+mass+does+Earth+acquire+in+a+year%27s+time+from+stardust%2C+meteorites+and+bolid es%3F&pc=GD01&form=GDAVST&ptag=3449>

years from now. He has also suggested that raising Earth's orbit over a very long time period would give us sufficient time that we could then proceed to terraform other parts of the solar system or perhaps even "borrow" a suitably sized planet within a range of 10 to 40 light years of Earth that could serve as a suitable "Planet B" for human existence.

The idea here is not to devise the design and engineering of a powerful nuclear propulsion engine (or more likely engines) to extend Earth's orbit away from the sun. Nor is it to map out how to find a so-called "exoplanet" that could sustain humanity an eon from now in another part of the galaxy. No, the challenge would be for NASA to create a far-ranging set of goals for research, development, and innovation that would create truly thoughtful, longer-term strategic goals for NASA's future efforts that could stretch the minds of what is meant by longer-term space research and for the "Future of Living in Space."

Another concern, for instance, would be how to cope with potential planetary threats from killer asteroids or comets that could bring another form of cosmic threat to humanity. The so-called Tunguska asteroid strike that smashed into Siberia on June 30, 1908, was only 35 to 40 meters in diameter. Yet this relatively small space rock managed to destroy a forested area the size of San Francisco and key areas of Silicon Valley. Such a heavy bolide rock traveling at tens of thousands of miles or kilometers an hour could kill a massive number of people. If such a potentially harmful asteroid were to make a direct hit on Beijing, Mexico City, Cairo, Lagos, Sao Paulo, Moscow, London, or New York City, it could instantly kill tens of millions of people.

Currently, there is a funded research project to create a directed energy system that would create a ultrahigh laser energy system that might be able to accelerate a very small

interstellar spacecraft equipped with a video camera and space telecommunications system that might be able to travel at speeds at a significant fraction of the speed of light that might be able to reach the Proxima Alpha Centauri star system and might be able to send back information of significant scientific value.

This could be, of course, useful to know about other stars in a close-up and useful way, but it is not why the development is mentioned here. What is of even greater possible significance is that the directed energy system that is powered by a collective power of many gigawatts in size in order to accelerate a small starship so it might travel light years away, could potentially be repurposed for other uses.

Indeed, such a capability might be used to defend against a “killer asteroid” that could collide with Earth with catastrophic consequences. The worrisome asteroid Apophis (which is nicknamed the “God of Chaos”) has whizzed by Earth several times before. It is currently calculated to make a very close approach on April 13, 2029. Current estimates are that this city-killer-sized and quite hazardous asteroid could come within 19,000 miles (or 31,000 km) of striking Earth. The diameter of Apophis is 10 times greater than that of the Tunguska asteroid and thus potentially some 1000 times more destructive. In short, another civilization protecting activity for NASA’s 30-year agenda would be to defend Earth from asteroids and comets. Currently, planetary defense against cosmic hazards is not overtly part of NASA’s strategic planning agenda.¹⁵⁵ (See **Fig. 13.3**)

¹⁵⁵ Vicky Stein *Apophis: The Infamous Asteroid Which Might Hit Us*” *Space.Com*, Dec. 14, 2022, <https://www.space.com/apophis>



Fig. 13.3: Artist Image Created by the European Space Agency of a Potentially Hazardous Asteroid that Might Hit Earth

(Image courtesy of P. Carril of ESA)

The concept for NASA's longer-term strategic planning would develop a short list of significant cosmic threats to humanity, or ground-breaking deep space research objectives such as a Bio-regenerative Life Support System (BLSS) or a viable deep space station design that could sustain deep space astronauts and explorers to survive a full lifetime or even on a multi-generational basis. These types of outside-the-box goals and true breakthrough developments, such as finding other intelligent life in the universe, must seek to stretch the human imagination of what is possible and perhaps also create entirely new system capabilities to protect human civilization.

The place to start is creating a process to develop some longer-term but specific goals and objectives for NASA, with a more innovative and well-thought-out research agenda. These must not be mundane initiatives but bold and visionary. They should

also consider planetary defense as a priority. The various propositions discussed in this chapter are not the specific proposed list, but rather a call to action. This is a clarion call for NASA to begin a thought process as to what these 30-year visionary goals might actually be. Goals that include public and astronaut safety should command priority attention and resources.

This list of objectives for 30-year goals might seek to develop and test actual space habitats or colonies that could artificially simulate all human needs for survival. This would include the development of a Bio-regenerative Life Support System (BLSS) capability. This could include meeting all the health and medical conditions and sustainability needs we have in order to survive and flourish here on Earth and in a deep space habitat. This might include a way to provide for the sustainable provision of food, water, energy, artificial gravity, recycling of waste materials, bio-regenerative flora and fauna biosystems, protection from radiation, and provision of various types of infrastructure and living facilities. These might include specific new space-related capabilities that range from housing, offices, and key utilities, to hospitals, health services, athletic and sports facilities, provision for culture, arts, and entertainment, educational, training, and research facilities, and more.

It would also set specific goals and objectives for creating magnetic space shielding systems for Mars and Earth, as well as other planetary defense systems. These would address other planetary defense systems, such as asteroid and comet defense systems, as well. Thus, there might also be goals for addressing threats from cosmic radiation, and the development of space systems and technologies to support future human evolution and the sustainable existence of the species over time on a rejuvenated and terraformed Mars or on one of the moons of Jupiter. There could even be an exploration of Arthur C. Clarke's possible vision of transforming Jupiter into a star that

could power a new deep space civilization. The prospects are almost boundless.

In short, there could be even more speculative and far-reaching strategic planning efforts such as those envisioned by speculative thinkers such as Sir Arthur Clarke, Ursula Le Guin, Isaac Asimov, Freeman Dyson, or Kim Stanley Robinson. One of the areas that NASA might encourage in this process is a challenge for students, scientists, engineers, and universities to provide their own thoughts or mine the writings and speculations of science fiction writers or other visionaries to propose ideas for the thirty-year agenda for NASA's future-oriented undertakings. These could, of course, go well beyond a thirty-year time horizon. It might undertake careful examination of such mind-expanding and stretching thoughts, such as seeking to discover the presence of so-called "Dyson Spheres." Other investigations might explore his idea of designing "compact and miniaturized human colonies consisting of fertilized ova or astronauts traveling in suspended animation. Such space travelers could then be reactivated or even born from embryos on arrival at locations even light years away. As Freeman Dyson has proposed, this remote space colony might emerge from designer vegetative seeds, animal ova, and other incipient life forms. These might be designed to be transported in refrigerated, frozen, or suspended animated forms to other locations that represent years of travel distances away from Earth.

As noted earlier, Arthur Clarke's Laws Two and Three suggested that to discover the limits of the possible, one must extend one's thoughts beyond the limits of the possible. He then went on to challenge those who wished to seek meaningful new insights to venture beyond the realm of the

possible into the areas that might seem to be magic or outright impossible.¹⁵⁶

Thus, it is that we call on NASA to develop new, ambitious, and innovative strategic plans to guide its future path forward. This needs to begin with a well-conceived strategic plan for the next ten years with precisely defined objectives that are clear and measurable. This should be followed by a medium-term strategic plan for the next ten years after. Finally, this requires a truly longer-term and far-reaching strategic plan that expands NASA's vision of the possible and leads NASA research areas into truly transformative technologies and future capabilities only dreamed of today.

Regulatory and Institutional Issues for the Longer-Term Future

The expansive and truly “outside the box” speculative nature of this longer-range vision of NASA's future potential in this chapter has essentially focused on scientific discovery and breakthroughs, technological innovation, and setting new and ambitious goals. It explores possible and perhaps achievable goals that give NASA not only more vision but also dares to go beyond conventional space exploration goals for astronaut explorers, and even for longer term human existence in off-world environments.

Absent from the discussion has been the consideration of the legal, ethical, moral, regulatory and institutional framework for this longer-term research agenda for NASA. This covers not only what it should do, but also what maybe it should not do for legal, peace-keeping or moral considerations.

¹⁵⁶ “Arthur C. Clarke’s 3 Laws about Technology and the Future”
<https://psychologyfor.com/clarkes-3-laws-about-technology-and-the-future/> (Last accessed April 30, 2025)

This type of exercise, however, must also be a part of the undertaking. It is not just a matter of exploring what totally new scientific, engineering, and technical breakthroughs are possible in the realm of space exploration and astronaut safety. It is also a matter of assessing whether there is a reasonable, safe, productive, and cost-effective pathway forward to make significant and valuable breakthroughs against a thirty-year research window. Further, there must also be an assessment of the ethical, moral, legal, regulatory, and safety implications of such a longer-term vision.

It is possible for humans to explore and develop new capabilities in space. This could include the extraction, material processing, purification, application, and use of deep space resources to create new habitats for astronauts and explorers, and perhaps expand new infrastructure that could expand human capabilities to live in deep space on a scale once not thought possible. The point is that this is not just a technical or engineering decision. It also must consider moral and ethical as well as legal, regulatory, and safety issues and concerns that are involved.

There are a host of issues that need to be considered, evaluated, and resolved. The list is actually long and complicated. There are key unresolved issues about whether space mining and resource extraction are consistent with the provisions of the Outer Space Treaty and the so-called Moon Agreement (which actually includes not only the Moon but also “Other Celestial Bodies”). There are also unresolved issues as to the legal, regulatory, and even practical economic and safety concerns about how these activities can proceed without international conflict and dispute. There is also a need for agreement to be reached on necessary safety and health regulations. The processes and regulatory provisions that will be critical to the future, as contained in the Outer Space Treaty and its four subsidiary international agreements, were developed within

the U.N. General Assembly and the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS). Most of these agreements were negotiated and agreed upon a half-century ago, when the world and the world of space research and development were much simpler, and agreements were much easier to reach when the number of nations involved in space-related activities was much smaller.

In theory, the nations of the world will also be required to develop new and additional provisions and international agreements and technical and safety standards as to the who, what, where, when and how of what comes next in the world of space.

These will be the rules, regulations, standards, and safety processes that will govern not only space exploration in deep space and on the Moon and Mars, but also other key issues such as the ethics to engage in terraforming or pursuing off-world human space colonies, or priorities for planetary threats against cosmic hazards. There is also a need to address the regulation of rising and dangerous space debris, the need for international agreement on space traffic management for space safety, and various types of actions to prevent space-related accidents. Certainly, there are many issues to address concerning the long-term sustainability of space. This means seeking international agreement on a way forward with regard to potentially hazardous asteroids, comets, cosmic radiation, solar storms, coronal mass ejections, and safe space transportation, navigation, communications, networking, applications, and commerce. And certainly, these are all highly technical and challenging issues that involve a host of scientific and engineering questions. Yet they also involve questions of ethics, morality, safety standards, legal, regulatory, economic, equity, and peace-keeping issues.

The U.N. Committee on the Peaceful Uses of Outer Space has grown from a small number of countries with a very targeted interest in outer space science, applications, and exploration to a global organization with over one hundred countries. It operates on the basis of consensus agreement and getting consensus among so many countries with great diversity of economic, political, cultural, religious, scientific, technological, and geographical interests. It may be that new ways forward will be needed to find agreement and voting procedures to reach agreement on a new way forward to global agreement on what are becoming urgent questions on these key space issues that cloud the future of an expanding range of space-related research, exploration, and application issues. Some of these issues may find their way forward to judicial review and adjudication with potential rulings from World Courts, where battle lines are now formed. Winners and losers can produce harmful clashes and lasting problems. A clear pathway to political agreement and negotiated agreements within a U.N. COPUOS-based agreement would be a more desirable outcome. Unfortunately, under current political circumstances and current unanimous agreement processes, and no enforcement powers behind agreements that it reaches, this end result remains in serious doubt.

Final Conclusions and Findings

The NASA Strategic Plan, as depicted in **Fig. 13.1**, is an exercise that has little actual meaning and sets no ambitious goals for achievement and certainly no breakthrough results, meaningful new knowledge, and vital information, or even clear targets for future achievement. The difference between extrapolation and progress forward, based on past results and strategic planning, is that new goals and objectives that one strives to achieve are set to strive for, rather than letting nature and happenstance take their course.

This often requires altered actions. It might require reversal action in one area, yet redoubled effort in others. What is needed most of all is to be able to move toward clear goals. This is often hard to achieve in the context of governmental programs. This is because there are often so many vested interests involved. There are always competing and special interests in political processes. These interests include the preservation of jobs and NASA centers at particular locations. There is the constant seeking of benefits for favored contractors and lobbying on behalf of special interests of legislators or cuts to promising programs because of mismanagement, faulty planning, or distributed systems that are not well coordinated. NASA, in its formative years, produced rapid results with a 'can-do' workforce and a drive to conquer the challenges of exploring space and creating entirely new technology from scratch. NASA, in its first two decades, was a source of key innovation. It needs to return to this innovative mandate and renew within itself a commitment to rapid progress and clearly defined goals.

Here are the top recommendations from this chapter.

First and foremost, NASA needs to resurrect its commitment to bold planning, rapid innovation, and the ability to achieve results and strive for truly breakthrough results. This can best be achieved through committed leadership that is willing to create challenging goals with clear aims and deadlines that everyone clearly has a motivation to achieve. It is recommended that there be a progression of ten-year plans that would combine to cover a thirty-year period. This would consist of: (i) the current ten-year plan that is the most specific in terms of goals, objectives and target dates; (ii) the twenty-year plan that combines the initial ten-year plan with the plan for the following decade; and (iii) the entire thirty- years vision

that would consist of three “ten-year plans” that ultimately find an overall unity of purpose.

What is important about this concept is that the goals for the third decade of the plan’s goals and objectives would fuel the effort for the first and second-decade plans. Further, it should be clear that none of these plans should be discarded and thrown away, but kept and diligently reviewed each year as a critical part of the strategic planning process. The most important aspect of this review would be to see not only where goals were met or surpassed, but also to understand when there was underperformance and aims not achieved. The key is to have the thirty-year plan to lead the way. The motivational part of the process would be to let the longer-term goals and objectives, which would be the most demanding and first ones to be developed, examined, critiqued, and added to, set the most ambitious goals at the start of the process, and not the last. To get to where one is going, it is important to see and visualize one’s goal. Today, NASA operates on the basis of executing programs such as the Artemis Program, the operation of the International Space Station, and developing, testing, and operating its launch vehicles and spacecraft. What it does not have is a hierarchy of objectives and a clear understanding of critical path barriers to achieving success. A new and more vibrant strategic planning process could help to cure what some would see as almost a malaise and a highly decentralized structure that is hard to unite toward commonly agreed goals. It is more a collection of activities operating under a very wide umbrella.

Second, there would be a strong and challenging process to create new, demanding, and longer-term goals for NASA. As outlined in this discussion, these might include such aspects as:

(i) Greatly enhanced astronaut space traveler safety. This could include such aspects as research on suspended animation, supplementary use of “smart robotic systems” to aid astronaut performance and safety, expanded use of AI capabilities, and development and use of artificial gravity-equipped spacecraft.

(ii) a new and improved safety concept for deep space astronaut exploration, such as for space station or space colony designs and planning, that could lead to an engineering model that fully duplicates or simulates a fully healthy and sustainable life support system for astronauts in space. The goal should be to achieve the same living conditions and even level of safety that residents now enjoy here on Earth.

(iii) A plan for a magnetic shielding system that could be deployed for Mars that would allow the evolution of a life-giving atmosphere for Mars and a follow-on plan for a magnetic shielding system for Earth to protect it from solar Coronal Mass Ejections (CMEs);

(iv) Outside-the-box concepts such as extending or changing Earth’s orbit over time, new advanced transport systems for star travel, or exploring ways to overcome gravity, or the completion of the Grand United Theory of everything. This would include the seeking of an integrated understanding of the four basis forces of the natural world: (a) electromagnetism, (b) gravity; (c) weak nuclear force; and (d) strong nuclear force, plus a deeper understanding of the nature of dark matter, dark energy, and the possibility of additional dimensions beyond those now known as the space-time continuum; and

(v) A systematic review of the legal, institutional, regulatory, ethical, global cooperation, and practical concerns, issues, and constraints that will limit and help refine NASA’s strategic

planning process to decide the best path forward for the next thirty years.

The idea is not to define the specific goals for a thirty-year strategic plan for NASA here. Instead, it is a call for NASA to undertake this task with new vigor and imagination. The above discussion is intended, however, to widen the horizon of NASA's current limited view of space technology and exploration goals and aims. The potential is much greater than is currently being sought. There is a need to stretch the goals, ambitions, and the current mindset of NASA's strategic planning. Setting more imaginative goals is the place to start. Shifting aeronautical R&D efforts from NASA to the Department of Transportation. This would be done so that NASA could then focus more fully on its goals and objectives on breakthroughs in space technology and exploration. Other complementary measures might be to centralize NASA activities with fewer centers and clearer management goals. This would start by making a more clearly defined definition of the goals and specific functions of various NASA Centers, as well as a better overall NASA plan that clearly defines how it envisions the future. The status quo is no longer an option.

Chapter 14

New Ways Forward for NASA

Introduction

In the previous chapter, the focus was on how NASA might seek to revitalize its strategic planning effort. The specific proposal was for NASA to create a proactive and aggressive vision of what it might be able to achieve within the next thirty years. This would be driven forward by three successive ten-year plans that established quite challenging technical and scientific goals of almost “impossible objectives.” This would envision an epic amount of new space technology that could only be achieved through a series of breakthrough achievements. This would require envisioning bold new plans for space exploration and the creation of innovative life support capabilities for remote space colonies. This would also lead to the development of new types of deep space vehicles that could bring new levels of safety to astronaut exploration. It would embrace the expanded use of AI and smart robotic capabilities to work in partnership with astronauts in space exploration in deep space. The idea was to shoot for truly remarkable long-range goals. Then, once these goals and aims were “imagined,” a three-decade-long strategic planning process would connect the present with thirty years from now. This would, in effect, be a reverse engineering process to design a process to connect with an amazing future. This would connect the goals for the 2065 time period with the technical and scientific knowledge that exists today in the mid-2020s.

The focus of the last chapter was to define where NASA should be striving to achieve in the course of the next thirty years. It was a call for new technical, scientific, and space-related goals and objectives for space exploration and space safety for NASA's longer-term future. It was urging a new sense of purpose to move deep space exploration forward at a faster pace, with a new sense of mission, with breakthrough goals, and a new sense of exceptional effort.

This chapter, however, is much more about how NASA might be able to accomplish such new and demanding goals. It is about creating new processes, management techniques, organizational work culture change, reforms in contracting processes, and a shift to a more entrepreneurial type of operation. Such a shift in "how" NASA works and is managed is required if it were to seek to achieve such new and breakthrough aims. Instead of NASA making perhaps just one percent or two percent annual gains and slow but steady growth, its expectations would become much higher. The objective would be not just to set new goals, but also to revitalize and motivate the NASA workforce. Such a reinvigorated NASA would seek to achieve a surge in productivity and rapid gains through a goal-oriented strategic planning process.

In short, if NASA can set new goals as to the **"What"** it wants to accomplish, then it must also answer the question as to **"How"** it must work, organize, incentivize, manage, and structure its workforce in order to accomplish new and more ambitious goals. NASA must not only have a clear and challenging set of technical and scientific goals, but also a good game plan for achieving its goals. What follows are recommendations as to how NASA might strengthen and enhance its programs, methods, and practices to achieve more rapid progress toward achieving future success.

Advanced Concepts Competitions, Workshops, and Challenges

Step one for NASA should be to advance and “trigger” innovation through more effective incentive programs. Here, NASA has already learned from the “NewSpace” revolution that challenging a wide audience of bright people outside of NASA to come forward with new and truly innovative ideas is a great way to discover new ideas. These are key ways that new ideas can be encouraged and breakthrough systems actually developed. There are even proven ways that some of these advances can be achieved at minimal cost.

Peter Diamandis, who spearheaded the X-Prize initiative that led to the breakthrough development of “SpaceShipOne”, has shown ways in which this can be accomplished. The first X-Prize competition proved that what was essentially a million-dollar investment from the Ansari Family could lead to perhaps well over a hundred million investment in R&D to develop new spaceplane systems. This occurred well over a decade ago. And breakthrough capabilities emerged in a remarkably short period of time, using a modest incentive fund to challenge new innovations.

NASA had invested billions of dollars seeking to develop space planes. This effort involved almost a half dozen development efforts over many years, and with minimal results in its own R&D efforts. In the time period from the late 1980s to the 2000s, various initiatives were started and stopped to develop space planes and lifting bodies. Some were to be piloted, and others were designed as automated and autonomous vehicles. Although each development was different in concept and design, each ended up being cancelled. Key reasons for some of these cancellations were the excessively high costs of the International Space Station (ISS) and the cost of operating the

Space Shuttle and related expenses associated with recovering from the Space Shuttle Columbia accident.

Diamandis, who also played a key role in the launch of the International Space University with colleagues Todd Hawley and Robert Richards, and also authored the best-selling book Abundance, has long championed the idea of competitions and prizes. He has written frequently that throughout the history of aviation and now space travel, this has led to powerful breakthrough innovations and broken records.

This use of prize money to spur innovation in the aerospace world has been true since the case of the Collier's prize, which was started by Robert J. Collier, publisher of Collier's Magazine. He was an aviation enthusiast and also headed the Aero Club of America. When he created the Collier Trophy in 2010, the first of these annual awards went to Glenn H. Curtiss in 2011. This award was for developing the world's first hydroplane that could land and take off on water.

Many years earlier, Charles Lindburg won the \$25,000 Orteig Prize on May 20, 1927, and more recently the Collier Prize, the X-Prize, and now a number of space agency prizes, competitions, workshop activities that cost relatively modest amount of money have been a source in innovation and new ideas. Among them, the Google Lunar X Prize in the most recent contest gave birth to a number of new aerospace companies, of which several have been selected by NASA for the Commercial Lunar Payload Service to transport cargo to the Moon as part of the Artemis Program. These "NewSpace" companies that had their initial impetus from this competitive contest include Moon Express, Fire Fly Aerospace, Inc., and Deep Space Systems.¹⁵⁷

¹⁵⁷ Joseph Pelton with Peter Marshall, *Safety First: A Review of NASA Spacecraft for Astronaut Missions (2024)* PM Associates, Washington, D.C. pp 192-196

The X-Prize Foundation initiative, NASA competitions and other new initiatives and incentive programs have been a true shot in the arm to space-related research, and increasingly other space agencies are embracing such contests and competitive design activities. For example, defense agencies are likewise using this process to create breakthroughs in the design for everything from robots to new types of vehicle systems.

The European Space Agency is not only sponsoring a number of awards and competitions for new developments in the space systems field, but also linking up with other organizations. This broadened effort is designed to widen the number of people and student groups that participate. Currently, this is the tenth year for the Student Aerospace Challenge. It is now co-sponsored by The Astronaut Club Européen (ACE), the Ariane Group, Dassault Aviation, the Le Bourget Air and Space Museum, and the European Space Agency.

The design specifications for this two-part competition are quite specific. The first challenge is for “A suborbital vehicle for high-speed long-range transport”. The design specification in terms of performance is to create a spaceplane system that is equipped with liquid hydrogen and oxygen rocket engines. It must be capable of transporting cargo plus 10-20 regular passengers. It must also be able to travel a distance up to a limit of 10,000 km, such as transport from Rome to Los Angeles, and to achieve this route within a limit of one hour.

The second challenge is the design for an orbital vehicle servicing low Earth orbit. This servicing vehicle must be able to accommodate up to seven people. It must be reusable and also able to be launched into space by an existing launch vehicle or one under active development. It must also be flexible in that it could provide for just a few days in autonomous flight, among other mission capabilities. This

would include the possibility of serving for several months in a secure docked position connected to a space station.¹⁵⁸ (See **Fig. 14.1**)



Fig. 14.1: The Student Aerospace Challenge represents a new level of specific and stringent design competition in new space systems
(Graphic courtesy of ESA)

¹⁵⁸ The European Space Agency, “Student Aerospace Challenge 2024-2025”

(last accessed April 16, 2025)

https://www.esa.int/Education/Engagement/Student_Aerospace_Challenge_2024-2025

Currently, the idea of competitions, design workshops, and challenges are now being widely used not only by NASA and other space agencies, and the idea of expanding the range of partner organizations has caught on to extend the range of participating students, researchers, and amateur engineers and scientists.

Initially, programs that were first designed for activities such as “cube sat” designs were more focused on encouraging students to become interested in space or science and technology. However, as can be seen in the above example, very specific and precise technical performance requirements are being set to generate very demanding and realistic specifications that would be applied to actual space agency or commercial space operations.

Over the past two decades, the idea of space competitions and challenges has emerged. Design workshops and similar undertakings have moved from a possible tool to motivate students and amateurs. It has also created an interest in space-related activities to become a new mainstream means of achieving innovative new technical, design, engineering, and even scientific innovation in the creation of improved and indeed viable and operational space systems.

Greater Organizational Efficiency and Productivity Through Better Focus

In earlier research efforts for the SSC Trust Fund with regard to space safety and NASA’s historical efforts to develop, implement, and operate new space systems and vehicles safely and efficiently, there have been consistent findings that NASA has consistently faced a number of challenges in this area. These past findings have noted the following issues of concern that require reform and new, more modern and forward-looking operational and management practices. These

concerns fall into several categories that include: (i) excessive geographic decentralization and too many Centers, Offices, and activities that are designed to respond to problems rather than proactive achievement;(ii) need for disintermediation and thus fewer tiers of organization management; (iii) modernization of contracting processing, design specification practices, and developmental and management practices; (iv) better optimization of staffing and organization for diverse roles that include research and development; (iv) operational and financial management of space systems, launch vehicles and space craft and real estate; (v) safety standards development and oversight; and (vi) safety as an independent verification and validation role and not as a design requirement.

Many of these concerns and issues actually have overlapping and interrelated causes and effects, but these all deserve a review as a cause for concern and the need for reform and improvement in all of these areas. It is not an organization designed for success or breakthrough innovation. A great strategic plan that is developed for an organization that is highly distributed and saddled with many layers of bureaucracy does not optimize staffing to the requirements of specific tasks and duties. Also, it does not have demanding incentives for productivity or disincentives for sub-par performance, and will have problems achieving rapid progress or encouraging entrepreneurial innovation. A review of safety-related accidents and performance issues, as well as concerns with regard to programmatic management, communications, and goal development, all have common concerns. It reveals an organization that lacks a clear sense of cohesive purpose and a tightly coordinated institution working together for a clearly understood purpose and focused effort to achieve common goals. Let's briefly review all of the above-cited concerns with specific examples of the observed deficiencies.

Excessive Geographic Decentralization:

This is an issue that largely stems from the historical development of NASA that was essentially thrust on the organization as one of the consequences of the Apollo Program and the urgent response by the U.S. to the Soviet Union launch of Sputnik and the so-called “missile gap” that was key to the U.S. Presidential election of 1960. When NASA was formed, it took over the duties of the National Advisory Committee on Aviation (NACA) which had been established to undertake the development of advanced aeronautical development as well as the role of developing space systems and rocket launcher systems. Thus, the NACA facilities in Cleveland, Ohio, instantly became a NASA facility. NACA had been created to undertake and coordinate aeronautical development and safety, but it was subsumed by the NASA Act of 1958. These facilities today constitute the NASA Glenn Research Center.

Also, there was the Ames Aeronautical Labs that constituted NACA’s second research laboratory. This was located in the heart of Silicon Valley that was likewise turned over to the newly created NASA as a second facility. This involved carving out a part of the large Moffet Airfield to support this activity.

The Werner Von Braun team that had been spirited away from Nazi Germany were tasked to support the new civilian rocket development program. Thus, the Von Braun team at the Redstone Arsenal in Huntsville, Alabama, was able to support NASA efforts to create a U.S. launch capability that could lift crew to orbit and eventually go to the Moon. Von Braun was the designer of the Saturn 1 and Saturn V rockets that took the first crew to the Moon with the Apollo 11 mission. Thus, this led to setting up the NASA Marshall Spaceflight Center as a carve-out from the Redstone facility to create this NASA Center in Huntsville, Alabama.

Then there was the concentrated effort to get a U.S. launch system able to place a satellite into orbit. This effort initially centered on the U.S. Navy Vanguard launch vehicle while President Eisenhower was still in office. The Beltsville Space Center was first established in Maryland near Washington, D.C., as another consequence of the NASA Act of 1958. Construction of laboratory facilities began to support this Vanguard development effort in support of the NASA mission. Engineers, scientists, and technicians actually began work in Washington, D.C., as the first facilities in Maryland were being built. As of May 1, 1959, however, it was decided to rename this center after the American rocket designer Robert Goddard, and thus it was designated the Goddard Space Flight Center. The new NASA organization thereby began with a very swift start and four far-flung research centers in Cleveland, Ohio, at the Ames Lab in Mountain View, California, the Marshall Spaceflight Center in Huntsville, Alabama, and the Goddard Spaceflight Center in Beltsville, Maryland.

NASA headquarters were also set up in Washington, D.C., with very modest initial facilities, but this, too, began to grow and expand in size and staffing over time. The newly created NASA organization, created by the NASA Act of 1958, was born with four research centers to support its mission, with facilities in Ohio, Alabama, California, and Maryland.

The Jet Propulsion Center, which developed solid rocket propulsion systems for the U.S., and was a Cal Tech University operation, also became a part of the growing NASA facilities as this rapid build-up zoomed ahead. Testing facilities and runways at Andrews Air Force Base were also made available to NASA and this has now become the Armstrong Flight Research Center in Edwards, California.

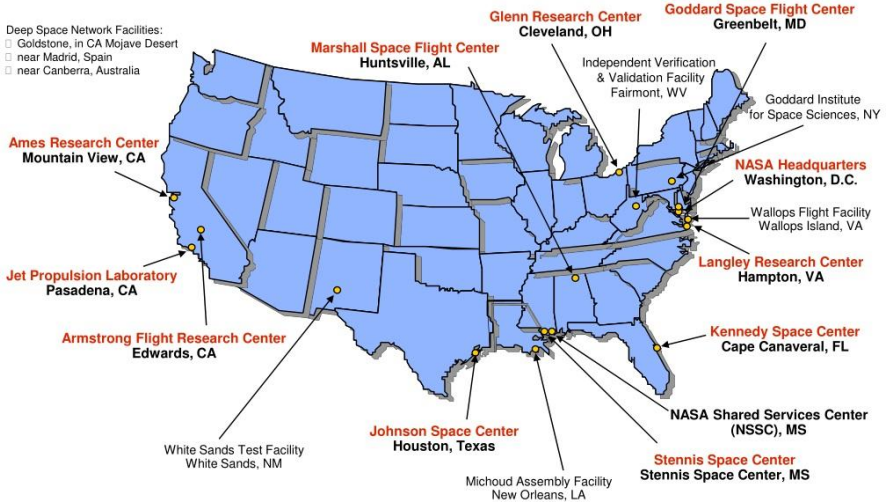
NASA officials, with the command to launch astronauts to the Moon, realized that they needed to create a launch pad

complex to support their launches. This led to the creation of the Kennedy Space Flight Center in Florida. This then led to the building of the giant vehicle assembly building for the accommodation of the massive Saturn I. followed by the towering Saturn V launch vehicle of even greater size and height. This vast and costly building even has its own internal atmosphere. Rain clouds can form within its walls. In sum, NASA erected a vast and costly infrastructure, and many of these facilities were the result of the Apollo Program era expenditures.

There was also the perceived need for a training center for astronauts and the creation of a Mission Control Facility for astronaut missions. Vice President Lyndon B. Johnson, as Vice President of the U.S. under President Kennedy, assumed a key role in space matters as the Apollo Program was undertaken in an amazingly swift fashion. The vice president played a powerful role in selecting the site for this facility in Houston, Texas, which is now named the Johnson Space Center.

In a matter of a few years, NASA developed a wide range of facilities, Centers, laboratories, and capabilities spread across the country. Political influence and pressure certainly had a role in the process, as the site selection for each new facility emerged in the well-funded and high-profile Apollo Program. As can be seen in **Fig. 14.2**, NASA now has Centers, test facilities, offices, and activities in ten of the U.S. states, including California, Florida, Louisiana, Mississippi, New Mexico, New York, Ohio, Texas, Virginia, and West Virginia, plus Washington, D.C.

NASA Centers and Installations



5

Fig. 14.2: The many locations of NASA Centers and other facilities
(Graphic courtesy of NASA)

Studies to examine the much greater rate of innovation, productivity, and cost-efficiency of so-called “NewSpace” companies often cite the advantages of vertical integration and consolidation of their workforce in a few very centralized facilities. Such corporate practices reduce transportation costs, enable efficiency of communications and coordination, allow re-allocation of workforce capabilities, and eliminate the need for additional support staff overheads at multiple locations. There have been many NASA Administrators who have sought to reduce the number of facilities and the geographic spread of its many facilities and centers, but political support in Congress has served to block such attempts to close various NASA sites. This geographic spread has consequences that involve increased economic costs, communications,

transportation, coordination issues, overlapping functions, and duplications.

Too Many Tiers of Management

In addition to geographic decentralization and related issues and concerns, there are organizational and structural issues as well. As NASA was first brought into being, it had a close link to the U.S. military and Department of Defense facilities and resources. The Marshall Space Flight Center in Alabama, the Ames Research Center at Moffet Field in California, and the Goddard Spaceflight Center were linked to the U.S. Navy-led Vanguard launcher development, and JPL was also linked to missile development. The military system for doing business was based on distributed bases, an administrative and management system that had a large number of ranks for officers and non-commissioned officers. Also, there was a heavy reliance on working with large aerospace contractors who worked on major new weapons systems under cost-plus-fee contracts. It was thus not unexpected that NASA adopted a similar type of management system based on dividing work and a complex and often duplicative type of management system among its various distributed centers. Instead of generals, colonels, lieutenant colonels, majors, captains, lieutenants, and sergeants, corporals and privates, NASA came up with Administrator, Associate Administrator, Deputy Associate Administrators, and a long list of other titles, and then other classifications for technicians and support staff.¹⁵⁹

In order to review the potential issues that such an approach to NASA management might constitute, some useful insights can come from a careful look at the structure of NASA's Office of Safety and Mission Assurance (OSMA). Its management

¹⁵⁹ Joseph N. Pelton with Peter Marshall, *The Space Safety Institute: A New Way to Safety Certification in the "New Space Age"* (2022) PM Associates, Washington, D.C. pp 70-75

structure and the potential inefficiencies and constraints on performance can be seen from the fact that a separate group of personnel must be established at the various centers. This leads to a matrix-type tiered organization structure. This involves a series of functionalist groups with specialties in six different areas, and then groups in remote locations engaged in functions such as Independent Verification and Validation and safety support functions.

The chart below is in **Fig. 14. 3** presents an organization that is replete with a Director and a Deputy Director, Associate Directors, Chiefs, Associate Chiefs, Branch Heads, and other titles that seem a hybrid between a manager and a worker. These include IT Manager, Directorate Resources Manager, Manager Analyst, HR Business Partner, plus the personnel who work for them. This chart is also difficult to follow. This is because it disguises the fact that, in many cases, these activities and capabilities are being carried out by safety engineering personnel whose capabilities must be repeated over and over again at various Centers and facilities. Only in the cases of the Headquarters OSMA and the Wallops Island launch facility is it clear if someone is working at the Johnson, Glenn, Marshall, Goddard, Ames, the Jet Propulsion Lab, Kennedy, or Langley Centers, or some other facilities or offices in the highly distributed NASA organization.¹⁶⁰

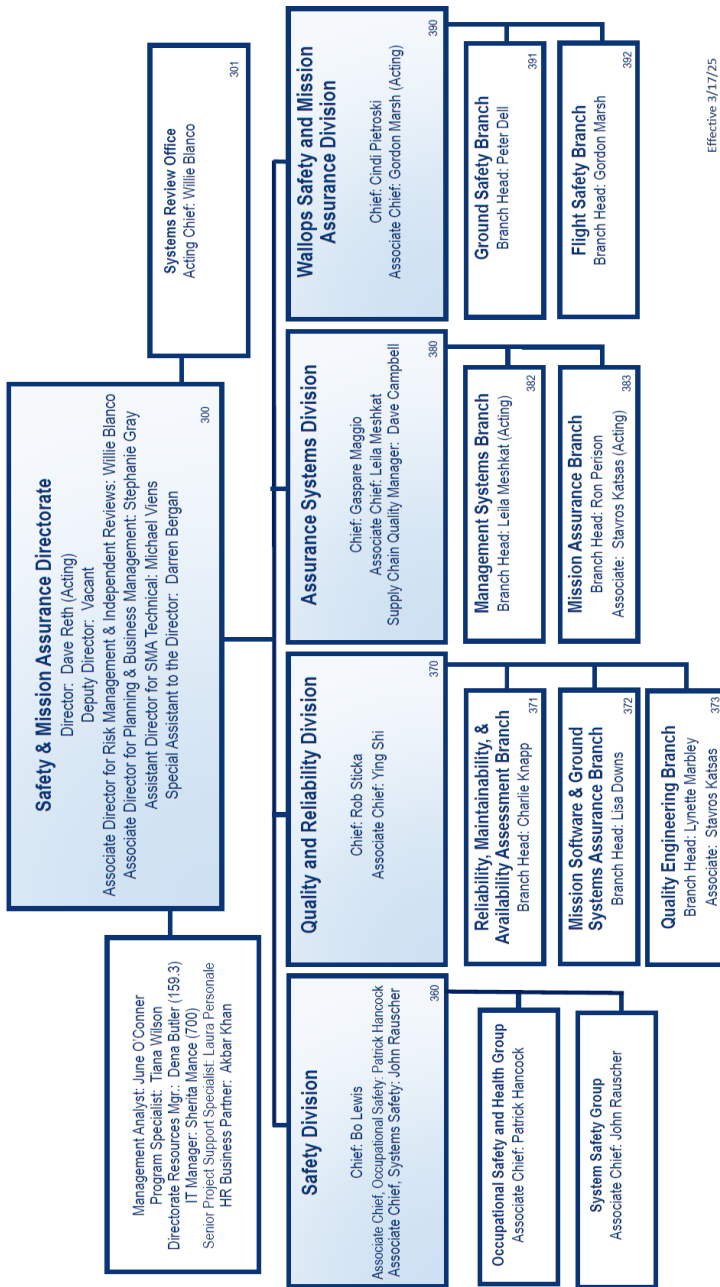
Modern business organizations have recognized the need to reduce tiers of administration and use computer networking to streamline administrative functions, with fewer tiers of administrators. The concept of “disintermediation” has eliminated tiers of administration in today’s business enterprises, where managers and workers operate interactively together through software and applications

¹⁶⁰ NASA Code 300 SMA Organization Chart (Text Version) (Last accessed April 8, 2025) https://sma.gsfc.nasa.gov/Code_300_SMA_Org_Chart

developed for this purpose. Governmental and military bureaucracies, however, have not necessarily followed suit. In order to create a sense of teamwork to strive toward common and clearly defined ambitious goals, a top-heavy and heavily tiered organization can be a deterrent to success. (See **Fig. 14.3**)

The organizational chart for the Office of Safety and Mission Assurance Directorate is very complex and heavily tiered, and it also tends to hide the duplicative structure. This is because of the need for safety experts, inspectors, and offices, not at one location, but repeated at many large centers that are, in most cases, geographically remote from each other. One of the consequences is that this type of dividing up expertise among the centers creates a situation where safety engineering capability is concerned, there is a pool of resources that can be assembled to address a problem. On the other hand, they are not well-positioned to work proactively together to create new concepts and designs to increase the safety of space systems at the time they are being conceived and engineered.

After the Challenger Accident, it was recommended that a new NASA Engineering and Safety Center be created, and this was eventually created. The “Center” that was created was not a Center at all. It consisted of hiring a number of safety engineers and safety standards experts and distributing them across the Centers. This means there were resources that could be drawn together to address problems as they arose, but there were no concentrated groups of experts working together in particular fields because they were distributed to different NASA Centers. Also, NASA signed up expertise outside of NASA at universities and other research institutions to be on call to respond to safety issues and problems as a part of the NES.



Effective 3/17/25

Fig. 14.3: The Organigram for the NASA Office of Safety and Mission Assurance (OSMA)
(Chart provided by NASA)

At the University of Indies that is distributed across a number of islands in the Caribbean region, they decided that the best strategy was to create centers of excellence where expertise would be clustered together such as doctors with expertise in tropical diseases, and at another campus on another island they would have experts in agriculture and forestry clustered together rather than splitting teams with special expertise apart and this model has worked well.

There does seem to be a strong, and perhaps urgent, need for NASA to strengthen its strategic planning processes in order to create more clearly defined goals with quantifiable goals and target dates for achievement. However, this cannot be done in isolation from other steps that are needed to review and modernize its management and organization. The goal of this review would be to become a more streamlined and less bureaucratic organization. This more agile type of organization could become more proactive and entrepreneurial in nature, as well as more focused on specific measures of success for the near, medium, and longer term.

Modernization of Contracting and Specification Development

Part of this reorganization and change would be to change the process of designing and initiating new space systems, programs, and initiatives to achieve more innovative designs and to do so in a faster manner. This would enable new systems to be implemented at a lesser cost, and using contractual systems that provide motivation to prospective contractors to produce the best and safest product or service in the shortest possible time. NASA has used two forms of contracting processes to design new systems, seek bids from contractors, and see these systems engineered, fabricated, and operated. One NASA contracting procedure used the traditional approach used by the U.S. Department of Defense. DOD

typically contracted for the development of new high-tech systems, such as new aircraft, on the basis of a cost-plus fee award, since it was new and sometimes truly unknown technology. The other approach that has now been used more frequently is to award fixed cost awards, where NASA has only developed performance specifications.

The cost-plus-fee type of award was also employed by NASA for many years. This was largely the approach used through the Apollo Program, the Space Shuttle development, and in the construction and operation of the ISS. They thus tended to follow the traditional model that has been the predominant approach, rather consistently used by the U.S. Department of Defense or by support entities such as the Aerospace Corporation, working for the U.S. Air Force.

This was the contracting approach used by the U.S. DOD for such new defense systems as high-performance fighter jets, bombers, and tanks. The typical contractual selection approach was to award the chosen contractor or contractors with open-ended budgets in what were known as cost-plus-fee contracts. Under this developmental contract award process, NASA system design engineers developed detailed technical specifications and did so on an in-house basis. Often, these technical design specifications were reviewed and approved by the U.S. Congress during hearings, and sometimes the design was included in legislative language. Then, contractors bid on developing this design, and after the competition ended, a contractor with a number of subcontractors was selected. The award was made on a cost-plus fee basis. This process proved to be a very long and protracted affair. In the case of the Space Shuttle design process, the White House review was intensely involved. It ordered changes in the specifications and specifically insisted that solid-fueled boosters be added to the design

after the Western Governors Conference officials urged this change be made on the grounds that this might reduce costs.

This process was followed for many decades, but this practice and compensation formula have proved to be exceedingly slow, costly, and inefficient. Its worst aspect was that it created exactly the wrong incentives. The cost-plus fee approach actually can create profit motives for the contractor to engage in delays and cost overruns. The larger the costs, the larger the fees.

Further the use of technical specifications as produced by NASA employees does not allow bidding contractors to compete to present design innovations that can lead to a better or more reliable product. Performance specifications also served to help avoid, or at least minimize, efforts by lobbyists or commercial interests to seek beneficial changes to the specifications, which can be the case with technical specifications.

In contrast, the commercial space industry that purchases applications satellites for telecommunications, remote sensing and other services have opted for a different approach. These organizations such as Intelsat, Eutelsat and SES have developed performance specifications and asked contractors to submit their most innovative design concepts and fixed cost bids.

This approach lets contractors and their design system engineers come forward with the best designs. It is much quicker to prepare performance specifications, and the requirement to submit a fixed price means contractors are motivated to complete the promised product to the target delivery date. This process serves to minimize the opportunity for intervention for political reasons in technical specifications, because there are only set

performance requirements. The results over many decades of practice is that this process is exceedingly slow, costly, and inefficient. Its worst aspect is that it creates the wrong incentives. The cost-plus-fee approach incentivizes delays, cost overruns, and the contractor's design team has no real opportunity to create design innovations.

Also, this approach allows the opportunity for the contractors to participate as “commercial partners.” Under this type of procurement, the winning contractor can seek to become a “partner” under NASA Space Act Agreements. This means they might provide matching funds for the successful development of a new system, on the basis that they could provide products and services in the future under contractual arrangements.

In this context, they have every incentive to create excellent results as well as to do so as quickly and efficiently as possible. The very costly, slow, and flawed development results in the case of the Space Launch System and Ares Launch Vehicle, which was its earlier conception, and the Orion astronaut spacecraft, that were devised and contracted on the basis of a cost-plus-fee contract, provides strong evidence that this type of procurement represents a flawed approach. It discourages entrepreneurial incentive, does not ensure increased safety, and can be very slow, and certainly exceedingly costly.

The NASA Inspector General, after a detailed audit and review of all payments, has indicated that the total costs of an entirely disposable SLS launch vehicle with its Orion spacecraft aboard represents a fully allocated cost, including developmental costs, is now on the order of \$ 4.1 billion dollars per launch. The NASA Inspector General, Paul Martin, was actually quoted as saying this expense was “unsustainable.”¹⁶¹

¹⁶¹ Eric Berger, “It’s huge, expensive, and years late but the SLS rocket is finally here,” *Arstechnica*, March 18, 2022

<https://www.bing.com/search?q=NASA+Inspector+General+sets+cost+of+>

These results with regard to the very slow, very costly, and technically troubled development of the SLS and the Orion Vehicle for the Artemis Program, suggest that changes in contractor competitions and contractual arrangements—including an opportunity for commercial partnerships - should be a key part of the overall reform process in NASA’s planning, organization, and operations.

The Need to Optimize NASA Staffing and Recruitment to Meet NASA Needs

NASA is a unique organization in many ways. It carries out a wide range of space science and research programs that require a wide range of laboratories, research equipment, and experimental satellites, as well as specialized facilities such as pristine clean rooms and rocket motor test facilities. It must train astronauts to perform difficult and demanding tasks using specially-designed space suits, cope with microgravity, and perform complicated and dangerous space walks. It develops launch vehicles and spacecraft that are sufficiently reliable to fly humans to space. It has developed space stations that have been able to sustain astronauts in space and carry out a wide range of experiments, from medical tests to growing crops in outer space. It is also developing sophisticated environmental control and life support systems as well as studying the astrophysics of the sun, the solar system, and even the deepest reaches of the Universe with the Hubble and now the James Webb Telescope.

This requires a great diversity of skills, scientific education, talents, and financial and management skills. Much of what NASA does involves science and engineering capabilities and what might be called a scientific brain. However, most of what NASA spends its financial resources on are large contracts that

can last for many years or even over decades. There are huge outlays in contract procurements, plus the costs of operating and maintaining a vast complex of buildings, laboratories, satellites, space stations, telecommunications, monitoring, and tracking networks. NASA has a very large assemblage of scientific and engineering staff, but its operational and management abilities to oversee these billions of dollars in expenses have frequently come into question.

The dilemma is that NASA represents a very high-tech scientific enterprise, but its financial expenditures are largely involved with contract oversight and management, facility maintenance, construction, and operations. The operation of the ISS involves about \$4 billion a year. The detailed programmatic reviews undertaken by the NASA Inspector General very frequently demonstrate performance schedules not met, large overruns of budgets, and major research initiatives and developmental programs. Many of these new developments with price tags in the billions of dollars have been started and then canceled. This was often true in the case of the space shuttle operational cost when NASA was seeking to complete the construction of the ISS. There were cost overruns leading to the cancellation of other R&D efforts to meet these over-expenditures. The Artemis Program cost overruns and significant schedule delays with the SLS and Orion developments, and most recently with the VIPER robotic rover, demonstrate that this is a chronic problem with NASA management of contracts. The shift in contracting procedures discussed above to use performance specification and fixed cost contracts that are executed in the form of NASA Space Act Agreements that allow commercial partnerships, or what might be called co-developments, seems to represent a key opportunity for improvement.

Nevertheless, there appears to also be a need for NASA to be better organized and managed to match talents and training

needs, as well as better management training to meet a diversity of roles that are required for NASA to operate at maximum efficiency. In creating its strategic plans for the future, it is not only key to have clear technical, scientific, and programmatic goals, but also a greatly improved management and staffing system that can achieve better financial and schedule performance. NASA's consistent underperformance in this regard should become a target for significant improvement. The NASA Inspector General's final report on NASA's financial results and management on June 20, 2024, as published by the Governmental Accountability Office, noted a number of "Fast Facts" elements that were highly critical of its performance as follows:

"NASA is taking steps to better manage its major projects, but its acquisition management remains on our 'High Risk List.'" NASA's largest projects, like Orion, incur the most cost overruns." It went on to say that: ".....cost and schedule overruns decreased in 2024 in comparison to 2023, but this was largely because the SLS and the Orion developments were not finally over." ¹⁶²

Shift of NASA's Approach to Safety Programmatic Actions in the Pursuit of Astronaut Exploration Activities

Another critical area for NASA strategic planning and modernization program involves the very key issue of astronaut safety. It is a fundamental maxim of space safety planning and engineering that when a major new program is started, and particularly when it involves astronauts undertaking space exploration, that it is the safety considerations that should be the starting point. System

¹⁶² *Assessment of Major Projects GAO-24-106767* June 20, 2024
<https://www.gao.gov/products/gao-24-106767>

engineering teams should have “space safety engineering” personnel as an integral part of the process from the outset.

The current approach is for mission goals to be defined first. A systems engineering team should then develop technical specifications to meet those goals. Then, after several other steps have been taken, space safety engineers are asked to see if the design and engineering specifications might be altered and/or improved to make the design and the specification safer in some way. Space safety is not an added ingredient to be added like a seasoning for a stew. Optimized safety concepts and planning should be the lead feature in the mission design, engineering, and system architecture.

Space safety engineers should have been a key initial part of the systems planning and engineering process for the Artemis Program, which was started to send astronauts to explore the moon. These space safety engineers might have been able to ask a very basic question. This would have been to ask why start the mission by launching astronauts from the Earth? Would it not have been an easier, less costly, and safer undertaking if astronauts were simply taken to low Earth orbit and then started their mission from there?

On January 14, 2004, President George W. Bush gave a speech at NASA headquarters that was designed to launch the start of what was called the Constellation Program. This was to be a major new NASA undertaking to send astronaut missions to explore the Moon and then Mars. NASA leadership was charged with the development of the launch vehicles and spacecraft that could accomplish both the Moon missions and then go to Mars. The response was NASA’s new giant Ares launch vehicle and a new eight-passenger Orion spacecraft that would support these missions. This program never came to be for a number of reasons. It was a program that was found to be exceedingly expensive and experiencing difficulties of

various types when the status of the program was ordered by President Obama to be reviewed when he took office in 2009.

This Presidential Review Commission was chaired by Professor Norm Augustine, former head of Lockheed Martin, and other notable experts. This commission found that the program which had been envisioned to start missions to the Moon as soon as 2015, was well behind schedule and its projected costs were projected to be truly excessive. The Commission recommended concentrating on finishing the ISS construction, end the Ares launch vehicle development and seek alternative launch systems design. There were also considerable questions as to the large 8-person Orion spacecraft and suggestions that a four-person capsule might be an alternative to be considered. What was not said in this report was that the idea that an integrated design of space transportation systems for launch vehicles and astronaut capsules that would last for decades and take astronauts both to the Moon and Mars was not really a viable expectation.

Unfortunately, the retooled space transportation system that NASA presented as the revamp of the Constellation Program in the form of the Space Launch Vehicle and Orion Capsule proved to have the same types of problems and constraints of the original Moon-Mars exploration program. NASA has often sold new programs to the nation and to Congress on the basis that this new program will have lasting capabilities and be productive for not only the near term but for decades to come. This was not the case for the space shuttle that was to be a low-cost space truck that could fly missions one a week at a cost of \$50K per launch. The Ares launch vehicle would have never flown to Mars and certainly the \$4 billion dollar Space Launch System will not either.

The reasons why these expensive space transportation systems are not suitable for deep space astronaut exploration are

indeed numerous. These reasons include: (a) rapid technological progress in propulsion; (b) 3-D printing or additive manufacturing; (c) an accelerating rate of technical obsolescence in manufacturing systems due to automation and related AI and robotic systems; (d) the implications of reusable launchers for both safety and cost reductions; (e) the prospect of nuclear fuel electric propulsion for vehicles that might go to Mars; (f) advanced forms of contractual partnerships between NASA and the aerospace industry under NASA Space Act Agreements; and (g) the ongoing impacts of the “New Space” entrepreneurial revolution on the traditional aerospace industry.

Now, there are proven and reusable launch systems that ferry astronauts to and from the ISS in low Earth orbit. The logic of starting from there becomes a powerful option that has many arguments in its favor. A reusable launch vehicle that flies to low Earth orbit and then refuels can be flight tested before astronauts ever have to board such a launch vehicle.

It should be changed from a significant emphasis on the role of Independent Verification and Validation (IV&V) which can be significantly undercut by so-called “variances” to much greater attention to the creation of “safety design and engineering” within the initial conception of new space launch systems, spacecraft, and vehicles as well as in space stations and space habitats.

Safety must be included at the outset as an essential design requirement, and one key change would be to include “space safety” as a separate category for evaluation procedures. It is important to stress that, in addition to these reasons, the designs are not optimum for astronaut safety. There are new designs and concepts for protecting astronauts from cosmic radiation. Artificial gravitational capabilities may become technically and economically feasible, and more. Further,

innovations from the newer and more entrepreneurial aerospace industries, from a commercial partnership perspective, may well be involved in the final engineering and design of these 21st-century crewed transport systems. This is key to note because NASA currently has a system for evaluating and selecting the successful contractor and the winning design. Currently, NASA assesses these contractor proposals on the basis of the proposed technical design on the one hand and on the basis of the management and financial aspects of the proposal on the other hand.

It is strongly urged that such evaluation team evaluations by NASA should separate safety, reliability, and resilience out as a third and co-equal criteria for assessment and evaluation, rather than making it only one of many aspects of the technical evaluation. This shift in the evaluation process to give prominence to safety and reliability is of great importance. It seems to be increasingly true that private commercial aerospace design engineers will become the prime engineers of the transport systems that actually take astronauts to Mars. If this proves to be true, then the evaluation and selection of these new space transport systems, as proposed by aerospace contractors, becomes of utmost importance. Thus, NASA must be urged to revise the nature of its assessment criteria. It must place a high value on astronaut safety that is co-equal with the technical engineering and the financial and management activities. This is absolutely critical. It is a very important conclusion to stress as a key point that has emerged from this overall review of NASA plans for the future.

Streamlining of NASA Programs and Optimization of Commercial Innovations and Transfer of Hypersonic Transport and Electrical-Powered to the Dept of Transportation and FAA-AST.

This chapter has sought to balance the technical goals for NASA's future research and development with reforms in its management oversight and ability to marshal its numerous and varied resources to maximum advantage. One of the concerns is that NASA's focus is clearly predominantly on space systems. Its current prime activities involve the Artemis program, deep space research, space transport systems, and the successful deployment of astronauts to the lunar surface. The budget for hypersonic transport systems is only a small portion of the overall budget. In this area, more progress is being made in Europe and Japan and other countries in such areas as hypersonic air transport and in the development of electric powered aircraft than in the U.S. There seems to be merit in a detailed assessment of whether the U.S. R&D function in commercial aircraft might be transferred to another area, most likely the U.S. Department of Transportation and the Federal Aviation Administration.

In a similar vein, the so-called Aldridge Presidential Space Panel that was asked to review NASA activities, suggested that consideration might be given to transferring some of the NASA Centers into a new organization arrangement to become Federally Financed Research and Development Centers or even be transferred to be under the control of a leading research center such as is the case with JPL and Cal Tech. This type of review and consideration to give NASA a clearer focus on high-priority programs and achieve an even higher focus could also be considered as a way to achieve greater and better-focused objectives.

It seems quite useful to allow NASA to achieve greater focus, and there may be advantages to having an agency that has a prime focus on aviation transportation and the advancement of its efficiency, effectiveness, and safety.

Conclusions

NASA needs to have better-defined, more tangible technical goals with measurable indices to measure success and specific target dates for key milestones along the way. This type of new strategic planning for the future over the next three decades was addressed in some detail in Chapter 13. However, there must be more than just clear and well-understood goals for the accomplishment of future technical and systems. There must also be a well-structured management with an appropriate organizational structure and commitment from staff and their leadership to strive toward these goals as a team. This is hard for a large, highly distributed, and bureaucratic organization to achieve.

The previous chapter has set forth what are hoped to be seen as positive recommendations that could aid in moving forward with more clearly defined, shorter, medium, and longer-term strategic goals. This now follows with recommendations for organizational and management innovation and supporting efforts to move these strategic changes forward. This includes changes in contractual processes and partnership arrangements, better financial management, staffing recruitment, and what might be described as a cultural shift to achieve progress at a more rapid rate and with a more clearly defined sense of purpose. If these various types of changes could be embraced within NASA, it could spur new successes. The most important change would be to enable and stimulate a more entrepreneurial spirit, a more rapid-response organization,

and a pathway to faster innovation and goal-oriented change.

Specific recommendations are to undertake the following:

1. **Outreach initiatives:** NASA should continue to strengthen its outreach to universities, research institutes, space-related organizations, scientific fans of space innovation, and even the general public that is interested in space. The goal would be to seek the best and brightest ideas. There are low-cost and effective ways to seek innovative inputs through such means as contests, competitions, workshops, and well-crafted challenges. The example provided of the ESA-sponsored competition, with a rich list of fellow sponsors, demonstrates just how specific and technically exacting this process can be tailored to high-quality results. The inspiration of the X-Prize competition has helped to illuminate the idea, but much more can be accomplished.
2. **Reducing Bureaucratic Structure and Moving Toward Modern Business Behavioral Models:** NASA's structural makeup and ways of doing business have tended to resemble military organizational structures and processes that are highly structured and bureaucratic. This type of organizational structure, plus the high degree of decentralization, is not easy to change overnight. In the world of "NewSpace" innovation, this can become a liability and slow progress in achieving strategic goals and rapid progress. Outside professional consultants could help to implement constructive changes.
3. **Reform of Contract Procedures, Increased Use of Performance Specifications, and More Partnerships with Commercial Partners:**

More use of competitive commercial aerospace engineering and design innovation can be a pathway to faster results and more innovative designs. The use of NASA Space Act Agreements to forge commercial partnerships can help to cut costs, spur more rapid progress and achieve higher levels of innovation and more productive results.

4. **Prioritizing Space Safety Innovation, Making Space Safety Engineering a More Integral Part of New Space Systems and Program Conception & Design, Elevating “Safety” a Prime Goal:** The importance of commercial partnerships with contractors can be key. In giving new opportunities to commercial contractors to help with new space systems engineering, care must be taken. One of the keys would be to elevate astronaut safety in new space transportation systems as a prime goal, along with creating the best technically engineered specifications, as well as financial and management design. These three areas must be considered to be equally valued in the evaluation and selection process for contractor proposals.
5. **A New, More Focused Effort by NASA on Space Systems and Advancement of Deep Space Initiatives: NASA has many challenges ahead, and some organizational changes and possible shifts in NASA’s charter and the structure of its Centers could produce a key new focus in its prime space-related goals.** Options such as transferring new aircraft-related R&D to the Department of Transportation, shifting some of the NASA Centers over to universities, or making them FFRDCs that could work for a wider range of Federal Agencies might be worthy of careful review and consideration.

Chapter 15

Conclusions and Key Findings

Introduction

Ever since 2005, the authors of this study and book have been intensely involved in issues related to the human exploration of space and its challenges and opportunities. The prime areas of investigation have been related to the field of space safety with a focus on how NASA might be better equipped, organized, and focused on improvements in its space program activities. This research effort has been largely dedicated to exploring how NASA might better accomplish its broad mission and research goals with maximum efficiency and safety.

The first such study was carried out with fellow space scientists and engineers and colleagues at George Washington University, and it was supported by knowledgeable reviewers around the world. This space safety study was conducted in the wake of the tragic Columbia Space Shuttle accident and reviewed the results from the Columbia Accident Review Board and NASA's efforts to recover from this accident and restore the Space Shuttle launch system to its safe operation.

This has been followed in more recent years with a continuing series of space safety studies. These have led to books that have reviewed and assessed NASA's efforts to produce new and improved space systems, technologies,

launch systems, and astronaut spacecraft. These efforts have also included detailed reviews and analysis of space stations and improved ways to create space systems and capabilities that are safer and more resilient. All of these studies and reviews of the safety of NASA programs have been conducted from a broader perspective of also assessing the impact of the basic changes in the nature of commercial space-related activities—with a particular emphasis on the changes that have occurred with respect to the contributions and innovations represented by the so-called “New Space” companies. These companies have reinvigorated progress in virtually every aspect of space research. All of these studies, reports, and books are listed on the opening page of this book.

During this period, the world of space has seen incredible change. Private space commercial activities around the world have dramatically expanded. In terms of annual revenues and expenditures, commercial space and private investment and budgets now exceed those of the space agencies by a wide margin. NASA is planning to end the mission of the International Space Station in 2030. Current plans are for NASA to serve as an anchor client for at least two private commercial space stations for its low Earth orbit research activities rather than seeking to launch a U.S. governmentally owned and operated facility.

NASA is now increasingly focused on deep space activities. It is planning to send astronauts to the Moon in order to explore the lunar surface. These plans currently involve the extraction of ice from the South Polar areas that could be purified and processed to produce water and oxygen. Current goals are to place an international Lunar Gateway Space Station in a special orbit around the Moon that can see the same side of the Moon we see from Earth. It is also planning to set up a base camp at this remote and difficult-

to-reach part of the Moon. This is also a time of international competition in efforts to explore the Moon. These exploration efforts are aimed at gaining a better understanding of its resources and examining the potential for future use of lunar resources and possible development on the lunar surface. For example, the Chinese government is developing new powerful launchers to support this effort. It is also taking the lead in creating what is called the International Lunar Research Station.

The bottom line is that NASA is at a crossroads in its planning cycles with regard to its goals for the future, the planning and design of new space transportation capabilities to meet future deep space missions such as to Mars or beyond.

The goal of this book has been to accomplish several things. One aim was to update a number of areas where NASA is making progress in space systems and technology. These areas of key focus include the Artemis Program and potential future efforts to go to Mars. This review also includes updates and concerns about the Space Launch System, the Orion crew vehicle, the Human Landing System, and the planning and deployment of the Gateway lunar space station. It also includes key aspects of space safety and deep space exploration projects. Another aim was to review progress that NASA is making in a wide range of areas in terms of research and development to develop and implement new technologies needed for future space exploration projects.

Chapter 2 began with a review of what might be called NASA's learning curve as to ways to develop and implement new space systems, technologies, and space exploration capabilities over time. This historical review examines the history and the various lessons learned by NASA. This

review effort was undertaken to help NASA better plan for the future in order to meet new challenges more effectively. The goal was to assist NASA in improving its R&D programs and the design, development, and implementation of new space exploration activities. This review has thus reviewed the history and development concerns that occurred with respect to the design, specification, hardware, and transportation systems for the Mercury, Gemini, and Apollo Program, the follow-on Space Shuttle Program. These reviews of NASA activities also considered NASA contractual procurement practices during the development, manufacture, and assembly of the International Space Station, and most recently, NASA actions in pursuit of the current Moon-Mars Exploration Program, the Artemis Program, and the lunar Gateway space station.

This review of past NASA performance analyzes problems that can arise from space systems technical design engineering efforts that, in turn, lead to very detailed NASA technical design specifications. Technical design specifications, as developed by NASA engineers, became the basis for cost-plus-fee contracts that, for much of NASA's history, have also led to schedule delays and cost overruns. It also led to other problems associated with contractor and subcontractor activities and performance.

There have been concerns expressed for decades that the use of technical design specifications as developed in house by NASA scientists and engineers were not the best and efficient contractual mechanisms to be used, especially in the context of seeking bids based on a cost-plus-fee contracts.

These critiques indicated that this contractual award approach did not allow contractor bidders to be able to present their own design ideas and suggestions. Such

contractor design proposals could, in theory, add important safety design features. Further this process included limited opportunity for safety reviews and innovations to be introduced without contract modifications that typically added to both costs and fees.

A systematic review by safety design experts, however, occurred only after space system design engineering teams had developed technical design specifications in detail and were only assessed after the basic design and mission objectives had, in many cases, largely been locked into place. This was largely the case for the Saturn launch vehicle, the Command Module and the Lunar Module for the Apollo Program and for the overall design of the Space Transportation System and the Space Shuttle. These programs had very large costs, very demanding testing and IV&V requirements, and tremendously difficult development schedules. The almost unlimited funds available within the Mercury, Gemini, and Apollo Program that were required to meet the end-of-the-decade Kennedy mandate to go the Moon. This is a very demanding schedule and NASA technical design specifications resulted in very high-level costs for testing to meet specified performance limits raised by a factor of ten, multiple prototypes and costly overtime effort. This surge of funding to support the 1969 Moon Landing tended to mask the inefficiencies and difficulties associated with cost plus fee contracting arrangements and the NASA technical design specifications. The urgency of the quest to land astronauts on the Moon before the end of the decade trumped efforts to constrain costs.

The difficulties associated with the Space Transportation System (STS) and the Space Shuttle vehicle had similar problems with regard to cost-plus-fee contract awards and the use of NASA technical specifications as the basis for

contract performance. Since these space system developments had not been declared a national mandate program in the context of a Cold War conflict with the Soviet Union, these new developmental space programs had to be managed on a much tighter budget. One of the consequences of these budget constraints was an increase in variances granted by NASA engineers to safety standards.

These significant numbers of “variances to standards” were revealed with the investigations of the Challenger and Columbia Space Shuttle accidents and the very long delays associated with the recovery from these disasters and astronaut fatalities. In both space shuttle accidents, granted variances had a direct link to the resulting accident. As a result of the learning experience and sometimes harsh programmatic difficulties, NASA discovered new ways forward. This has led to totally new directions, such as moving away from technical design specifications and using performance standards instead. This allows the use of fixed cost contracts rather than open-ended cost-plus fee contracts. This shift in approach has also opened up opportunities for new “commercial partnerships” developed under NASA Space Act Agreements. Under these arrangements, contractors may even contribute to the development costs in return for the opportunity to provide future space transportation services, as well as other, more flexible arrangements that can provide commercial space suit design and service.

This historical analysis of NASA development, management, and contractual processes is important. A better understanding of past problems can reveal more creative ways forward. This can lead to better and safer designs, more creative and innovative management, and “win-win” NASA and commercial partnerships. Such innovations are critical to its future planning and the

development of improved and safer space exploration technology that can reduce cost, improve schedules, and also reduce risk. Chapter 14 returned to this topic that extends the results from the historical review and lessons learned to specific recommendations for NASA management reforms. This chapter thus suggests new and more focused NASA efforts to implement further management and contracting reforms and truly forward-looking strategic planning for the next 30 years.

Chapter 3 switched the focus from NASA's historical development to the specifics of innovations in space safety, the need for new ways to certify the safety of a wide range of new commercial services and partnerships. These include plans for at least two private commercial space stations in low Earth orbit, which NASA can use for NASA astronaut experimental work in lieu of building and launching a replacement for the ISS. NASA is increasingly moving toward new ways of working in partnership with aerospace companies under new types of cooperative programs. In general, there has been a wider range of commercial space activities that were first initiated by the development of commercial transportation options for the resupply of cargo to the ISS and then to develop commercial crew vehicles to transport astronauts to low Earth orbit. This change to commercialize space-based activities with commercial space adventure flights and even private space stations is creating a new need for safety testing, new international safety standards and specifications, and safety certification. There is an increasing need for a Space Safety Institute that can support safety testing and certification, as well as an expanding range of space safety standards. This is a role that NASA should not undertake itself, but should instead seek to create as an independent and highly competent capability. This might be established as a U.S.-based

institute that might expand into an international role as well.

There would be advantages to this new capability, in that it could also serve as an independent capability to assist NASA in its own safety assessments, standards, and certification programs. A key finding of the research and from the review in this book is that priority attention should be given to the creation of an independent Space Safety Institute as outlined in: *The Space Safety Institute: A New Way for Safety Certification for the “New Space” Age*. (Joseph N. Pelton and Peter Marshall, 2022, PM Associates, Washington, D.C.)

Chapter 4 sought to analyze certain weaknesses in how major new space exploration programs are initially defined and technically specified, safety engineering optimized, and certification achieved. There are also other new tools and processes related to the use of AI analytics, simulation, and computer modelling techniques that could provide new strengths to NASA space exploration programs. NASA should work with the White House, Congress, and other partner space agencies in the definition of its strategic planning process, and especially in the launch of major new space exploration projects. It is best for NASA to develop performance specifications for its initiatives. In addition to the advantages noted above, there is another clear advantage. Technical design specifications can be and indeed are reviewed, amended, and altered both by White House reviews and Congressional interventions.

This can lead to lobbying interference and manipulation that can serve to increase costs and lead to safety and risk issues. The classic example of this related to the revisions to the space shuttle and Space Transportation System design

to add solid boosters rather than having it be an all liquid-fueled rocket motor system where ignition could be halted.

In the development of specifications, it is possible to use AI systems, “smart” modeling, simulation, and analytical systems to include consideration of a much greater complexity of possible options. These innovations can add to the richness and possibly lead to a significant improvement in the design of new systems. This is likely to include a richer mix of technologies, safety enhancement features, and alternatives than a group of space system designers could develop using conventional design planning techniques. Such new design analytics can not only consider new technologies or system capabilities but also evaluate and prioritize a wide diversity of mission design elements and so-called “mission requirements.”

Thus, intensive big data analysis and related AI-design review capabilities can perform massive amounts of mission performance analytics. The AI-enabled space systems design can, at the outset, consider many key design issues and mission requirements well beyond technical design components. This type of design analytics should be used to create new mission performance specifications. These modeling and simulation processes can consider the relative strength of options. This could include fundamental options such as: (i) starting points for missions from the Earth versus low Earth orbit; (ii) number of astronauts to deploy versus substituting of ‘smart’ robots and supplementary robotic tools or instant access data base; (iii) changes in mission architecture or elements such as nature of deep space communications and networking design, type of launcher, astronaut crew vehicle, lander system, and/or robotic rover vehicle to be used in the mission design.

Such an approach would help develop both the best possible initial mission requirements and the actual performance specifications to be sent out to potential contractors for bids. These changes in NASA design and mission definition documents can increase the safety, reliability, resilience, efficiency, and coherence of the design. It should significantly optimize the safety and the best design of a new mission. This new way of designing systems, working on the basis of performance specification, and using ‘smart’ analytic tools is essential. It can greatly improve the nature of the mission architecture, hardware, software, work schedule, timing, cost, and efficiency of NASA’s future missions. While this is particularly true for astronaut space exploration programs, it is also true for the design of scientific missions and space applications.

In Chapter 5, we addressed new ways forward to advance the health and well-being of astronauts and also the best ways forward to increase the sustainability of space stations and space habitats for astronauts. There are many advancements that can contribute to astronaut health and well-being to be considered.

One area is to assess in greater detail where and when to substitute ‘smart’ robotics system capabilities for astronaut tasks. Increasingly capable robots can undertake dangerous, risky, or simply manual labor-related tasks. Further robots do not consume water and food and other supplies. Such considerations are key to planning for deep space exploration where resupply missions are difficult and costly.

Then, there are also new systems and technologies that support astronaut health. These improvements might include waste recycling systems, medications, and health supplements. Key space health and medicine research also

needs to address issues such as bone or muscle tone loss, radiation protection system designs such as “water wall” radiation shielding systems, and ways to provide for advanced medical testing and sensing in space, including miniaturization techniques. Also, there can even be such improvements as better lighting, food supply, noxious gas, and fire detection equipment for space habitats and vehicles. All of these potential improvements need to be included in strategic planning efforts to enhance astronaut health.

What is perhaps most important, however, would be to establish several truly longer-term objectives that would lead the way to major breakthrough achievements. These would be goals that must go beyond incremental improvements. The thought process might start with the development of a completely interactive and “stand-alone” biosphere capability. This would be a goal to be sought after, and which might be created both in outer space and here on Earth. It would be a closed or nearly closed system that can support both sustained flora and fauna life and other capabilities to support daily life. This is known as a “Bio-regenerative Life Support System (BLSS). This is what Biosphere II tried to do and failed. It would allow astronauts to grow food to eat and perhaps sustain animal life as well.

Another objective might be the design and creation of a detailed engineering design to be tested and verified with regard to a complete deep space habitat system, perhaps on Mars. What would be unique about this breakthrough development is that it would be designed to use locally mined materials, processing capabilities, and additive manufacturing to create this habitat. This would thus be completely, or almost completely, carried out by an army of ‘smart’ robotic systems to create this habitat and its supporting infrastructure. This would thus robotically build

a facility designed to accommodate astronauts that arrive after the habitat and support facilities are constructed, put in place, and fully tested. In some ways, the Lunar Gateway space station might be considered phase one of such an enterprise. It is possible that a few astronauts might be required in situ to actually realize such a Martian facility, but the idea would be to maximize construction efficiency and astronaut safety, while having perhaps 90% of the initial deep space effort performed by automated and robotic systems.

A third objective might be a viable and cost-effective design for a deep space habitat and transport system that is designed and optimized to meet astronaut health needs and would include artificial gravity as a key space safety and health optimization goal.

Next, Chapter 6 addressed one of the most challenging health and safety issues for astronauts, and this is exposure to cosmic radiation and the threat of fatal radiation sickness. There is some misunderstanding as to the nature of cosmic radiation hazards and why these dangers to astronauts traveling in deep space are quite different from those faced by astronauts traveling in low Earth orbit or aboard Chinese, U.S., or future-planned private and commercial space stations. The coronal mass ejections (CMEs) and UV and X-ray radiation from the sun are significantly ameliorated in their impact on astronauts traveling in low Earth orbit. This is due to the geomagnetosphere and the Van Allen belts that provide a form of radiation and an ionic particle protective system. Astronauts are indeed exposed to significant radiation sickness when aboard the ISS, but in deep space, cosmic radiation provides an even more serious threat. Further, radiation protective capabilities suitable for stopping radiation or CME dangers, as designed for Earth or in low

Earth orbit, would include something like lead shielding, which could create problems on the Moon, Mars, or deep space. This is because cosmic radiation and ionic particles can trigger chain reactions that could lead to dangerous results for astronauts. There are many new capabilities for protective systems, plus new radiation protection health standards needed for deep space travel. A number of actions and research agenda items are highlighted in this chapter, and these efforts should be undertaken with a sense of urgency.

Chapter 7 then addressed the ever-growing problem of space debris and the need for global agreement as to the truly serious hazard of space debris to astronauts, as well as the need for an international agreement on space traffic management and other actions to combat this danger. Current planning for activities involving the Moon and Mars is now leading to the launch of a number of satellites and even space stations. The mounting space debris problem that is increased by the launch of so-called “mega-constellations” of satellites, and the lack of key controls on the de-orbiting of satellites in Earth orbit, or other celestial bodies, is now an increasingly adverse and dangerous development. We need, with some urgency, new agreements on space traffic management and active debris removal processes. Global cooperation is needed to put in place the technical and institutional arrangements needed to address this problem--and we now need to act with much greater urgency. These actions need to include international agreement with regard to the amendment and improvement of the Liability Convention, global support for space traffic management, and complementary actions needed to provide for the long-term sustainability of space activities. There is a need for new technical capabilities for active debris removal, associated technology, and agreements with respect to Reconnaissance and Proximity Operations

(RPO). Such agreements, guidelines, and associated space robotic system controls are essential to implementing the needed actions to decrease space debris over time. There is also a particular need for action to protect space stations and international regulation with sanctions that can be implemented to prevent the onset of the so-called Kessler Syndrome. This is a potential threat to all forms of space activities due to runaway and increasing swarms of space debris.

Chapter 8 moved on to discuss true deep space exploration needs with respect to new, more energy-efficient, and faster space transportation requirements. Improved performance is required to provide timely mission resupply service and to create and operate vital support services. Such new capabilities would be key to supporting the viability of space habitats on the Moon, Mars, or any other deep space location. The basic thrust of R&D needs to focus on achieving as much self-sufficiency as possible and reducing the nature and the number of resupply missions. Further, there is the issue of what differences and adjustments would be required to provide basic support capabilities in distant outposts. Issues that are specifically addressed are: (i) navigation, tele-location, telecommunications and networking capabilities; (ii) energy and power supply; (iii) mining, material processing, additive manufacturing and construction; (iv) robotic systems; (v) on site information systems, medical response systems, and knowledge-based applications that are not subject to major communications delays; and (vi) needed transportation systems, rovers, and emergency response systems. There are many opportunities here for important new developments in all of these areas. These future needs are reviewed in some detail. Systematic advances are required in all of these key support services and capabilities. Such increased capabilities are needed to create viable and sustainable habitats that may become truly

viable and largely independent “biosphere-type” systems. Clearly, there is enormous potential in the development of all of the new space support system capabilities to be replicated and used in remote parts of Planet Earth.

Chapter 9 addressed the truly important need for safe space launcher systems, crew vehicles, and lander systems to support future space exploration. This is clearly an area where near-term, medium term and long-term strategic objectives are all very important.

Near-term efforts would address key performance and safety issues with regard to the Artemis Program. It would specifically seek to address the possible replacement of the uneconomic and troubled Space Launch System (SLS) launch vehicle. It would also examine the Orion capsule, where there are serious questions about the safety of the heat shield and other safety concerns raised in this and previous space safety system analyses. Equally, if not more important, this review would prioritize the full safety qualification of the SpaceX version of the Human Landing System and its alternative version under development by Blue Origin.¹⁶³

There are, however, many key medium and longer-term objectives that are of great importance as well. These objectives include: (i) perfecting reusable launcher systems; (ii) improved and more reliable chemical launch, including those manufactured by additive manufacturing; (iii) improved and higher thrust electrical ion engines; greener rocket fuel systems to replace solid fueled rocket propulsion; (iv) verification and safety certification of nuclear propulsion systems and especially expanded effort

¹⁶³ Joseph N. Pelton with Peter Marshall, *Safety First: A Review of NASA Spacecraft for Astronaut Missions (2024)* PM Associates, Washington, D.C. See Chapter 5,6 and 7.

with regard to nuclear electric propulsion, but also other nuclear propulsion systems for longer term use for deep space missions; (v) tether-based orbital lifting systems, and space elevators and funiculars; (vi) rail guns (or mass driver accelerators) for Earth, the Moon, Mars or free flying in outer space; (vii) gravity assist design optimization through improved AI modeling and simulation programming; (viii) development of directed energy systems for planetary defense against potentially hazardous asteroids and comets; and (ix) other advanced concepts that might include solar sails, direct nuclear based propulsion, and even use of electromagnetic field systems to create so-called “anti-gravity lift systems” and would require little consumption of fuels.

This “anti-gravity” or propulsion-less research, that would somehow not consume fuel and thrust reaction, is thus closely linked to unlocking the secrets of a Grand Unified Theory of everything and new research with regard to the potential of electrostatic systems. The most advanced and “outside-the-box” concepts introduced in this chapter are returned to and discussed in more detail in Chapter 13.

Chapter 10 addressed the need for new ways to think about the development of launch vehicles and especially seeks to probe the best way forward for crewed space planes as well as for spacecraft and landing systems for deep space. The development of the X-37a, which has now transitioned to the X-37b space plane, has been a success story and has added an important new capability. Parallel efforts by the European Space Agency, Japan, and China have also made significant progress in recent years, as reported on in the chapter.

The most significant development, however, may well be the Sierra Nevada Dreamchaser, which is now launched by the

new Vulcan Centaur launch vehicle. This vehicle is not reusable, but the BE-4 rocket engines that represent the main Vulcan propulsion system are reusable. It is therefore planned to recover these engines and to recondition them for re-use. The use of the Dream Chaser to resupply the ISS going forward may lead to its certification to carry astronauts to the ISS in the future. In the United Kingdom, there has also been significant progress with the single-stage to orbit Skylon space plane development that is powered by the SABRE engine. There is also the prospect of a new development effort by the Radian Aerospace Corporation that will undertake another single-stage orbital craft.

This accelerated commercial development of space plane capability in the U.S., in the U.K., and elsewhere appears to be moving forward. Once future safety certification is achieved, this may allow future use for both NASA and private crewed missions. In light of this progress, it may well be that NASA does not need to invest in significant new development in this area. Indeed, it may well be that NASA should consider turning over the development of new hypersonic transportation aircraft to the Department of Transportation, as has been recommended in Chapter 14.

The main development goal for NASA to focus on with the greatest effort is the development most appropriately concentrated on improved lander systems that are reliable and safe. For the Artemis Program, there is currently concern about the complete development of SpaceX and Blue Origin's Human Landing System (HLS). This is now a critical pathway for the Artemis Moon landing operations. This is a matter of not just the vehicular propulsion systems but especially with a robotically sophisticated navigational and guidance system able to land not at spaceport locations but on rough and uneven terrain in difficult to navigate and

complicated landing areas such as the Southern polar area of the Moon. Future efforts should concentrate not just on landing systems and their propulsion jets but also on sophisticated maneuvering, hovering, and soft-landing capabilities. The series of initial unsuccessful landings under the Commercial Lunar Payload Service suggests that this is a critical area for developmental focus. The proposal of SpaceX to use the main propulsion system of their modified Starship Vehicle rather than precision thrusters at this stage seems to be a premature and unwise step to authorize. This is not only the safety and the precision of the landing process, which is indeed a major concern, but there is the further concern that the heat from the landing process may create major, unhealthy and rather sustained debris and scorching of the lunar surface that could lead to tilting issues with the structure that is the height of a skyscraper.

Chapter 11 focuses on the design, engineering, fabrication, and safe operation of space habitats for deep space. This includes the concept of astronaut living facilities on deep space lunar or planetary-moon surfaces, as well as free-flying in deep space. The design, construction, and operation of these facilities will in many ways be “site specific” with regard to radiation protection, artificial gravity capabilities, and the use of solar mirrors or mirror concentrators for solar power, wind, or nuclear power sources. Many other features, however, are very likely to be common to remote deep space astronaut habitats. Areas of particular research focus that are covered in this chapter include the optimum design of: (i) environmental control systems, (ii) noxious gas and fire detector systems and sensors, and automated and AI enhanced control systems; (iii) space suits and apparel systems for living within pressurized and oxygenated habitat environments; and (iv) recycling and advanced waste management systems optimized for deep space environments where resupply

trips are limited and costly; and (v) remote medical care and especially the development of sophisticated medical imaging equipment and operating theaters that are optimized for remote deep space locations or space stations. This would suggest methods to miniaturize the size, mass, and type of materials used for such medical or other specialized scientific equipment. In this area, as well as many of the other R&D activities discussed in this book, the goal should consistently be to undertake in-house and funded-contractor studies. Also used should be entrepreneurial activities, competitions, research challenges, “blue sky” workshops, and design studios that can generate important new concepts and inventions, do so at low cost, and enlarge the field of public and professional engagement.

In Chapter 12, the authors addressed some of the most promising new technologies that will be needed to support long-term and sustainable astronaut operations for deep space outposts and habitats. This analysis begins with the promise that fusion-based electric ion engines could bring to missions to Mars. It has been calculated that such a transport system could cut the travel time to and from Mars in half. These would likely be missions that would start and stop in both low-altitude orbits of Earth and Mars. It is because of this potential and the rate of technological obsolescence of launch vehicles that underlined the “mistaken thought” that the Space Launch System and the Orion spacecraft would be operational for up to 30 years and would be the transport system that would go to Mars.

There are, of course, a range of other capabilities that NASA R&D should also address in terms of preparing for deep space missions, and with particular forethought with regard to missions to Mars. This chapter thus addressed the need for advancement in the following areas: (i) advanced tele-

presence, networking, telecommunications, tele-location and search and rescue capabilities; (ii) advanced AI enabled robotic systems that could simulate most astronaut functions; (iii) remote agriculture and genetic organic optimizations that are well suited for low gravitational and aeroponic and gaseous environments; (iv) advanced and sustainable energy systems. These are indicative of a broader list of other support systems, such as remote deep space surface transportation and navigation, oxygen generation, etc.

Chapter 13 addressed the need for NASA to strengthen its strategic planning processes. In the short to medium term, it needs more well-targeted and specific goals for technological and systems development. Perhaps the most challenging part of such an effort is to start first with truly ambitious' longer term and "outside-the-box" goals to be achieved within the next three decades. The final part of such an exercise would be seeking to align a series of specific, well-targeted, and time-limited research and development for the near term to lead to the future. Thus, initial research objectives for the near term need to eventually align with aspirational and much longer-term goals. The strategic planning goals that NASA releases publicly on its website, as shown in **Fig. 13.1**, are very broad, vague, and non-specific. They are unclear as to expected results and quantitative targets, as well as timing and performance criteria.

In essence, they are not useful tools for motivating leadership or staff to achieve challenging and difficult aims or spur them to exceptional performance. Strategic planning is not only an effort to define a series of future programs. Budgets explain how money is to be spent, such as for building and operating the International Space Station or undertaking a ten-year or longer-term effort to

explore the Moon with the Artemis Program and then go on to Mars. Such statements provide a useful summary of the money to be spent. This process may serve to explain a major budgetary expenditure. It is not a statement of a strategic goal. It is certainly not a way to send adrenaline flowing through the veins of highly motivated staff willing to give their all to make a deadline.

This chapter calls for NASA to set clear goals, such as creating sustainable and healthy space habitats in outer space. This might start with artificial gravity capabilities that are comparable to what we experience here on Earth. There is the suggested further research goal of developing what is called a Bio-regenerative Life Support System (BLSS) that would complement this space habitat goal. This target for R&D would be to design a completely interactive plant, animal, micro-organism, and environmental system that can sustain life that is essentially a closed—or near closed—system that can sustain complete life cycles from seed to death, to seed and death again, and so on. There could be other goals that involve not only breakthrough technical or systems goals but also improvements in international agreements to cope with space debris and other legal or institutional reforms.

The key is to develop truly demanding, longer-term aims and goals that are sufficiently far-sighted. Such thirty-year goals could only be achieved by NASA and associated commercial and international researchers and engineers making consistent progress over a long period of time. These goal areas might even include such ideas as the design and deployment of magnetic shields for ‘terraforming’ Mars that would prevent the solar wind from stripping away its atmosphere. Such a magnetic shield, if deployed and sustained for decades, could, over time, allow a breathable atmosphere to form. Beyond this, NASA and other national

and international entities might even be able to join together and create a more secure geo-magnetosphere for Earth. This is needed to protect modern society from violent storms from the sun, and to prevent cataclysmic coronal mass ejections from destroying electric power grids, pipelines, satellite networks, communications systems, and the Internet. These would wreck and disrupt modern civilization on a global scale. Other goals would include viable space colonies on Mars or in free space. Further, these goals would not need to be entirely technical.

A number of NASA's strategic goals might relate to stated aims in areas such as costs, organizational reforms, entrepreneurial efficiencies, safety engineering and standards, contracting and commercial partnership arrangements, regulatory, legal, and international partnership improvements. This is indeed what Chapter 14 addressed as a complement to NASA's efforts to undertake a strengthened technical and systems strategic planning process.

Finally, Chapter 14 thus addressed concerns that some have expressed about NASA having become a "jobs providing program." These critics have said that NASA has too many Centers and facilities distributed around the nation. These criticisms also indicate that NASA's very large programs such as the Apollo Program, the ISS, the Space Shuttle, and now the Artemis program, are based on very large contracts, sub-contracts, and sub-sub-contracts with layers of waste and decentralization in order to distribute contracts to a wide circle in all 50 states. Certainly, NASA facilities are sprawled across the nation. These criticisms also focused on the bureaucratic nature of NASA's organizational structure, which has too many layers of staffing. Its highly distributed Centers also create inefficiency. This is due to the need to repeat staffing with particular capabilities and high levels of

education and training at all of NASA's major Centers, NASA Headquarters, and other offices and facilities.

This chapter sought to complete the elements needed to transform NASA from a large government agency to a more mission-oriented technical and scientific agency with the right staffing, strategic planning goals, and objectives for future success. There is a clear need for a long-range vision of what NASA can achieve over a longer-term plan of action. Our analysis calls for consideration of some reorganization, to close some Centers, and to do so by having them become Federally Funded Research and Development Centers that can work for the entire government, or to be transferred to a university, which is how the Jet Propulsion Center currently operates. It suggested that the responsibility for hypersonic aircraft development be transferred to the Department of Transportation and perhaps, in particular, to the FAA-AST. The main thrust of the recommendations here is for NASA to become better focused, organized, and motivated by clear, quantitative, and measurable goals with timelines for achievement, as well as a clearer, longer-range vision.

Concluding Views

NASA has a long and illustrious history with many notable accomplishments. Not only were there the Mercury, Gemini, and then the momentous Apollo programs with the seven successful lunar landings of astronauts on the Moon, but also the amazing saving of the Apollo 13 voyage that brought the astronaut crew safely back to Earth. Other significant milestones were the Hubble and James Webb space telescopes, and funding support for the Arecibo Radio Telescope in Puerto Rico. It has supported a range of Explorer missions that have, among other things, confirmed the background noise from the Big Bang and dozens of key

scientific discoveries. Also, there were the various robotic remote sensing and scientific discovery satellites that have gone to the Moon, to Mars, and the Sun, plus the rest of the planets and many of their moons. These NASA scientific and exploratory missions have given us a great deal of knowledge about the chemical makeup and origins of not only the solar system but the universe at large.

The spin-off contributions from NASA with regard to medicine, medical equipment and medication, engineering and science, farming and agriculture, chemistry, transportation and propulsion, materials and devices for building construction and insulation, additive manufacturing, and more are of significant value. NASA's ongoing research and development have resulted in tens of thousands of patents, new consumer products, and new insights into the origins of the universe, the nature and structure of its vast galaxies, and a more complete understanding of the laws of nature and the fundamental forces that exist within the space-time continuum.

As remarkable as these accomplishments have been, there is always room for improvement. The Space Launch System and the Orion capsule that were developed to support the Artemis Program are, in many ways, overly costly and technologically obsolete. The developments that have come from the reinvigorated “NewSpace” companies have shown what innovative space commerce can do to discover new knowledge. The development of reusable launch vehicles, space planes, rocket engines, and even current planning for commercial space stations indicates the potential for NASA to work in partnership with commercial aerospace and robotics corporations under NASA Space Act Agreements. This has created joint funding opportunities that have led to new arrangements for NASA to buy services from

commercial vendors for flying astronauts to the ISS or even the supply to NASA of space suits for astronauts.

This new way of contracting that uses “performance specifications” can encourage more innovation, greater safety and risk minimization design, and lower costs and better performance. It can allow contractors to submit competitive designs and offer new safety innovations, and provide the opportunity to provide future commercial services as well. The new era of entrepreneurial enterprise and innovation in the aerospace field has allowed NASA to leave low Earth orbit activities much more to commercial space companies and concentrate on deep space exploration and scientific discovery. All of this “good news” indicates useful advances for NASA programs. But there is much more to be done.

NASA has the potential to renew and reinvigorate itself by seeking to move forward with a dynamic and changing strategic planning process to achieve more with less. It could be organized to become more focused and centralized, change its commercial contracting awards process to be more productive and innovative by use of “performance specifications”, fixed cost contracts with fixed performance schedules, as well as clear terms and incentives for meeting clearly defined goals. This process could typically allow for purchasing products and services on a competitive basis that would allow for lower costs, competitive sourcing, and lower net costs for NASA operations. If all of this is done to high standards and with the use of effective space safety engineering and exacting astronaut safety standards, this can be a win-win-win-win result for all. This approach can benefit NASA as well as aerospace contractors, astronauts, and their safety, and the U.S. taxpayer.

There are seldom opportunities for taxpayers to expect and receive a four-way good news story, but such a possibility exists if NASA does pursue a new way forward. This does require NASA to achieve a more focused strategic planning process. It requires moving forward with ‘performance specifications’ on which contractors can compete for the best design for the best and safest technology. One key change that is recommended in this respect is that clearly specified space safety standards become a clearly defined and independent area for contractor bid evaluation that is co-equal with technical engineering design, management, and cost evaluation criteria. These new NASA reforms require rapid updates of new technical capabilities in the design and production of new space systems and transport vehicles that recognize the speed of technological progress.

NASA must abandon selling the idea that the new systems they are proposing will have a meaningful purpose for thirty years of operation. AI-based design innovation, additive manufacturing, enhanced computer modeling and simulations, quantum computing, and ‘smart robotics’ are accelerating the speed of innovation, and NASA and the U.S. Congress must recognize this fundamental shift. A good part of the challenge to NASA will involve developing a good strategic planning process that allows for more rapid design, prototyping, manufacturing, and testing of new space systems.

NASA also needs to achieve more vertical integration and a reorganization that allows more centralization with fewer Centers and an organizational structure that does not have so many management layers. Deep space-related space exploration, scientific investigation, and applications are much more challenging and costly than low Earth orbit activities. This means that NASA must focus on innovation that allows remote space activities on the Moon or Mars or

elsewhere to be much more self-sufficient and less reliant on supply missions and more self-sustaining in terms of food, water, waste management, and essential supplies.

One key strategy is to use smarter robotic systems, autonomous systems and AI enabled additive manufacturing to create space habitats and eventually even space colonies that can evolve to be independent in many regards. The objective should be to develop remote space habitats and colonies that would be able over time to be able to engage in active trade with planet Earth.

This actually suggests that NASA requires more than good strategic planning. It also needs to create a compelling narrative. This would emphasize the degree to which NASA is about the future, about progress, and the creation of sustainable technology, not only for outer space but also for the future of Earth. These NASA-led innovations should be keyed to allowing humanity to live not a few more years or even centuries, but rather many millennia, or perhaps to outlive the sun and survive for eons to come. The potential of what humanity might become in a billion years is almost unimaginable.

Scientist and Science Fiction writer Kim Stanley Robinson, who was cited earlier, has written a book titled “Ministry of the Future.” This is a book about developing new economic and financial arrangements, technical and scientific inventions, and regulatory changes that might be needed to cope with the challenge of climate change. Today, climate change has become what environmentalist Tim Morton has come to call a “Hyper-object.” Morton has defined this concept to mean the equivalent of a problem so vast, technically complicated, expensive to address, and mired in regulatory argument and conflict that the ordinary citizen has simply dismissed it as a problem that they can

personally relate to or hope to solve. They thus say: “Oh well, that is a problem (they would never say 'Hyper-object') that I cannot solve, so I will ignore it and leave it to others to solve.”

NASA has the challenge of creating not a narrative about climate change and its solution, but rather a narrative about how they are the U.S. governmental agency that is providing the technology, scientific know-how, and new capabilities that humanity will need for the future. NASA must create a new vision as a sort of “Ministry of the Future” that creates a vision of positive scientific discovery, invention, and technical capabilities that can allow humanity to not only survive but thrive not only for the 21st century but for millennia to come. It is hoped that the ideas, recommendations, suggested technical, operational, and organizational changes, and initiatives set forth in this book will carry NASA forward on a new pathway to success. With luck, someday it can be said that NASA’s leadership and strategic planning indeed created the pathway to the future.

Appendix 1

Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space

https://www.unoosa.org/documents/pdf/PromotingSpaceSustainability/Publication_Final_English_June_2021.pdf

A. Policy and regulatory framework for space activities

Guideline A.1 Adopt, revise, and amend, as necessary, national regulatory frameworks for outer space activities

1. States should adopt, revise, and amend, as necessary, national regulatory frameworks for outer space activities, taking into account their obligations under the United Nations treaties on outer space as States responsible for national activities in outer space and as launching States. When adopting, revising, amending, or implementing national regulatory frameworks, States should consider the need to ensure and enhance the long-term sustainability of outer space activities

2. With the increase in outer space activities by governmental and non-governmental actors from around the world, and considering that States bear international responsibility for the space activities of non-governmental entities, States should adopt, revise or amend regulatory frameworks to ensure the effective application of relevant, generally accepted international norms, standards and practices for the safe conduct of outer space activities.

3. When developing, revising, amending or adopting national regulatory frameworks, States should consider the provisions of General Assembly resolution 68/74, on recommendations on national legislation relevant to the peaceful exploration and use of outer space. In particular, States should consider not only existing space projects and activities but also, to the extent practicable, the potential development of their national space sector, and envisage appropriate, timely regulation in order to avoid legal lacunae.

Guideline A.2 Consider a number of elements when developing, revising, or amending, as necessary, national regulatory frameworks for outer space activities.

1. When developing, revising, or amending, as necessary, regulatory measures applicable to the long-term sustainability of outer space activities, States and international intergovernmental organizations should implement international obligations, including those arising under the United Nations space treaties to which they are party.

2. In developing, revising, or amending, as necessary, national regulatory frameworks, States and international intergovernmental organizations should:

- (a) Consider the provisions of General Assembly resolution 68/74, on recommendations on national legislation relevant to the peaceful exploration and use of outer space;
- (b) Implement space debris mitigation measures, such as the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, through applicable mechanisms;
- (c) Address, to the extent practicable, risks to people, property, public health, and the environment associated with the launch, in-orbit operation, and re-entry of space objects;
- (d) Promote regulations and policies that support the idea of minimizing the impacts of human activities on Earth as well as on the outer space environment. They are encouraged to plan their activities based on the Sustainable Development Goals, their main national requirements, and international considerations for the sustainability of space and the Earth;
- (e) Implement the guidance contained in the Safety Framework for Nuclear Power Source Applications in Outer Space and satisfy the intent of the Principles. Relevant to the Use of Nuclear Power Sources in Outer Space through applicable mechanisms that provide a regulatory, legal, and technical framework that sets out responsibilities and assistance mechanisms, prior to using nuclear power sources in outer space;
- (f) Consider the potential benefits of using existing international technical standards, including those published by the International Organization for Standardization (ISO), the Consultative Committee for Space Data Systems and national standardization bodies. In addition, States should consider the utilization of recommended practices and voluntary guidelines proposed by the Inter-Agency Space Debris Coordination Committee and the Committee on Space Research;
- (g) Weigh the costs, benefits, disadvantages and risks of a range of alternatives and ensure that such measures have a

clear purpose and are implementable and practicable in terms of the technical, legal and management capacities of the State imposing the regulation Regulations should also be efficient in terms of limiting the cost for compliance (eg, in terms of money, time or risk) compared with feasible alternatives;

(h) Encourage advisory input from affected national entities during the process of developing regulatory frameworks governing space activities to avoid unintended consequences of regulation that might be more restrictive than necessary or that conflicts with other legal obligations;

(i) Examine and adapt existing relevant legislation to ensure its compliance with these guidelines, considering the need for transition periods appropriate to their level of technical development

Guideline A.3 Supervise national space activities.

1. In supervising space activities of non-governmental entities, States should ensure that entities under their jurisdiction and/or control that conduct outer space activities have the appropriate structures and procedures for planning and conducting space activities in a manner that supports the objective of enhancing the long-term sustainability of outer space activities, and that they have the means to comply with relevant national and international regulatory frameworks, requirements, policies and processes in this regard

2. States bear international responsibility for national activities in outer space and for the authorization and continuing supervision of such activities, which are to be carried out in conformity with applicable international law. In fulfilling this responsibility, States should encourage each entity conducting space activities to:

(a) Establish and maintain all the necessary technical competencies required to conduct the outer space activities in a safe and responsible manner and to enable the entity to comply with the relevant governmental and intergovernmental regulatory frameworks, requirements, policies, and processes;

(b) Develop specific requirements and procedures to address the safety and reliability of outer space activities under the entity's control, during all phases of a mission life cycle;

(c) Assess all risks to the long-term sustainability of outer space activities associated with the space activities conducted by the entity, in all phases of the mission life cycle, and take steps to mitigate such risks to the extent feasible.

3. In addition, States are encouraged to designate a responsible entity or entities to plan, coordinate, and assess space activities with the aim of promoting their effectiveness in supporting the Sustainable Development Goals and in supporting the objectives of the guidelines for the long-term sustainability of outer space activities in a broader perspective and vision

4. States should ensure that the management of an entity that conducts outer space activities establishes structures and procedures for planning and conducting space activities in a manner that supports the objective of promoting the long-term sustainability of outer space activities. Appropriate measures to be taken by management in this regard should include:

(a) A commitment at the highest levels of the entity to promoting the long-term sustainability of outer space activities;

(b) Establishing and fostering an organizational commitment to promoting the long-term sustainability of

outer space activities within the entity, as well as in relevant interactions with other entities;

(c) Urging, to the extent practicable, that the entity's commitment to the long-term sustainability of outer space activities is reflected in its management structure and procedures for planning, developing, and conducting outer space activities;

(d) Encouraging, as appropriate, the sharing of the experiences of the entity in the conduct of safe and sustainable outer space activities as a contribution by the entity to enhancing the long-term sustainability of outer space activities;

(e) Designating a contact point within the entity responsible for communication with relevant authorities to facilitate efficient and timely sharing of information and coordination of potentially urgent measures to promote the safety and sustainability of outer space activities.

5. States should ensure that appropriate communication and consultation mechanisms are in place within and among the competent bodies that oversee or conduct space activities. Communication within and among relevant regulatory bodies can promote regulations that are consistent, predictable and transparent so as to ensure that regulatory outcomes are as intended.

Guideline A.4 Ensure the equitable, rational, and efficient use of the radio frequency spectrum and the various orbital regions used by satellites.

1. In fulfilling their obligations under the Constitution and the Radio Regulations of the International Telecommunication Union (ITU), States should pay particular attention to the long-term sustainability of space activities and sustainable development on Earth and to

facilitating the prompt resolution of identified harmful radio frequency interference

2. As provided for in article 44 of the ITU Constitution, radio frequencies and any associated orbits, including the geostationary-satellite orbit, are limited natural resources that must be used rationally, efficiently and economically, in conformity with the provisions of the Radio Regulations, so that countries or groups of countries may have equitable access to those orbits and frequencies, taking into account the special needs of developing countries and the geographical situation of particular countries.

3. Consistent with the purpose of article 45 of the ITU Constitution, States and international intergovernmental organizations should ensure that their space activities are conducted in such a manner as not to cause harmful interference with the reception and transmission of radio signals related to the space activities of other States and international intergovernmental organizations, as one of the means of promoting the long-term sustainability of outer space activities.

4. In their use of the electromagnetic spectrum, States and international intergovernmental organizations should consider the requirements for space-based Earth observation systems and other space-based systems and services in support of sustainable development on Earth, in accordance with the ITU Radio Regulations and the ITU Radiocommunication Sector (ITU-R) Recommendations.

5. States and international intergovernmental organizations should ensure the implementation of the radio regulation procedures established by ITU for space radio links. Moreover, States and international intergovernmental organizations should encourage and support regional and

international cooperation aimed at improving efficiency in decision-making and implementation of practical measures to eliminate identified harmful radio frequency interference in space radio links

6. Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the low-Earth orbit (LEO) region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region. Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the geosynchronous Earth orbit (GEO) region should be left in orbits that avoid their long-term interference with the GEO region. For space objects in or near the GEO region, the potential for future collisions can be reduced by leaving objects at the end of their mission in an orbit above the GEO region such that they will not interfere with, or return to, the GEO region.

Guideline A.5 Enhance the practice of registering space objects.

1. States and international intergovernmental organizations, acting in accordance with their obligations under article VIII of the Outer Space Treaty and the Convention on Registration of Objects Launched into Outer Space and taking into consideration the recommendations contained in General Assembly resolutions 1721 B (XVI) and 62/101, should ensure the development and/or implementation of effective and comprehensive registration practices, as proper registration of space objects is a key factor in the safety and the long-term sustainability of space activities. Inadequate registration practices may have negative implications for ensuring the safety of space operations.

2. To that end, States and international intergovernmental organizations should adopt appropriate national or other relevant policies and regulations to harmonize and sustain over the long term such registration practices on the widest possible international basis. When registering space objects, States and international intergovernmental organizations should bear in mind the need to provide timely information that contributes to the long-term sustainability of outer space activities and should consider also providing information on space objects, their operation and their status, as set out in General Assembly resolution 62/101.

3. Prior to the launch of a space object, the State from whose territory or facility a space object will be launched should, in the absence of prior agreement, contact States or international intergovernmental organizations that could qualify as the launching States of that space object to jointly determine how to proceed with the registration of that particular space object. Following the launch of a space object, and considering relevant criteria in the Convention on Registration of Objects Launched into Outer Space (Registration Convention), States and/or international intergovernmental organizations that were involved in the launch should coordinate among themselves, to include those States and international intergovernmental organizations that may exercise jurisdiction and control over the non-registered space object, to register the space object.

4. In the event that a State or international intergovernmental organization receives, from another State or international intergovernmental organization, an enquiry seeking clarification about the registration/non-registration of a space object that could presumably be under its jurisdiction and/or control, that State or international intergovernmental organization should

respond, as soon as practicable, in order to facilitate the clarification and/or resolution of a particular registration issue. In certain circumstances, a State may choose to communicate an enquiry through or copy an enquiry to the Office for Outer Space Affairs. In such cases, the requested State is encouraged to reply likewise.

5. The Office should be effectively engaged, within its standing responsibilities and existing resources, in executing integrated functions pertaining to: (a) the accumulation of information on orbital launches performed (ie, completed launches resulting in the placement of objects into Earth orbit or beyond) and on orbital objects (ie, space objects that have been launched into Earth orbit or beyond); and (b) the assignment of international designations to orbital launches and orbital objects in accordance with Committee on Space Research notation, as well as the provision of such designations to the States of registry. States and international intergovernmental organizations should support efforts by the Office to promote initiatives that would enable States to adhere to registration practices and consider implementing and sustaining the provision of registration information in furtherance of General Assembly resolution 62/101.

6. The launching States and, where appropriate, international intergovernmental organizations should request all necessary information from space launch service providers and users under their jurisdiction and/or control to meet all registration requirements under the Registration Convention and encourage their receptiveness to and consideration of the provision of expanded registration information. States and international intergovernmental organizations, having institutionalized the practice of providing expanded registration information, should strive

to sustain such practice and identify circumstances complicating the achievement of that task.

7. States and international intergovernmental organizations should take into account General Assembly resolution 62/101 and consider providing information on any change of status in operations (inter alia, when a space object is no longer functional) and, following the change in supervision of a space object in orbit, information about changes in the orbital position. States and international intergovernmental organizations should be aware of the importance of achieving and sustaining a practicable degree of coherence and uniformity in applying the provisions of this paragraph. Varying implementation practices, inasmuch as such may relate to the contents and attributes of information furnished, may necessitate addressing appropriate interpretative aspects. In such cases, States and international intergovernmental organizations should, through dedicated consultative process within the Committee on the Peaceful Uses of Outer Space, consider, acquire and develop shared positions with respect to providing information on any changes in space objects' status of operations and in the orbital positions of space objects.

8. In cases where a launched space object contains other space objects planned for future separation and independent orbital flight, States and international intergovernmental organizations should, when entering these objects in their registry and when furnishing registration information to the Secretary-General of the United Nations, indicate (for example, in the form of side notes) the number and names of space objects that may, in the future, separate from the main space object, on the understanding that those space objects should not be given

different or modified names when they are subsequently registered.

9. In accordance with article IV, paragraph 2, of the Registration Convention, and considering General Assembly resolution 62/101, on registration practices, as well as principle 43 of General Assembly resolution 47/68, States and international intergovernmental organizations should provide information to the Office through internationally accepted mechanisms on all space activities or objects that involve the use of nuclear power sources in outer space.

B. Safety of space operations

Guideline B.1 Provide updated contact information and share information on space objects and orbital events.

1. States and international intergovernmental organizations should exchange, on a voluntary basis, and/or make readily available regularly updated contact information on their designated entities authorized to engage in exchanges of appropriate information on on-orbit spacecraft operations, conjunction assessments and the monitoring of objects and events in outer space, in particular those entities that are responsible for processing incoming incident reports and forecasts and adopting precautionary and response measures. This may be achieved either by providing such information to the Office for Outer Space Affairs so that the Office can make it available, within its standing mandate and existing resources, to other States and international intergovernmental organizations and/or by providing it directly to other States and international intergovernmental organizations, with the understanding that contact

information for national focal points, at a minimum, will likewise be communicated to the Office.

2. States and international intergovernmental organizations should establish appropriate means to enable timely coordination to reduce the probability of and/ or to facilitate effective responses to orbital collisions, orbital break-ups and other events that might increase the probability of accidental collisions or may pose a risk to human lives, property and/or the environment, in the case of uncontrolled re-entries of space objects

3. States and international intergovernmental organizations should exchange, on a voluntary basis and as mutually agreed, relevant information on space objects and information related to actual or potential situations in near-Earth space that may affect the safety of outer space operations. The information exchanged should, to the extent practicable, be reliable, accurate and complete, and be concluded to be so by the providing entity. The information to be exchanged, including time reference and period of applicability and other relevant information, should be provided in a timely manner and on a mutually agreed basis.

4. States and international intergovernmental organizations should, through a dedicated consultative process, preferably under the auspices of the Committee on the Peaceful Uses of Outer Space, taking into account the work of relevant technical bodies, consider, acquire specific understanding of, and develop shared positions on the practical issues and modalities, as appropriate, relating to the exchange of relevant information on space objects and events in near-Earth space obtained from different authorized sources, in order to achieve harmonized and standardized record-keeping on space objects and events in outer space 5States

and international intergovernmental organizations should consider the options for effectively accumulating and providing access to information on objects and events in outer space on a timely basis and for achieving consistency in the understanding and use of such information as one of the means to support their activities aimed at maintaining the safety of space operations. The options for consideration could include: standards and formats for representing information to enable the interoperability of information shared on a voluntary basis; bilateral, regional or multilateral arrangements to exchange information; bilateral, regional or multilateral coordination among providers of information to enable cooperation and interoperability; and the establishment of a United Nations information platform. Those options could serve as a basis for a distributed international information system for multilateral cooperation in sharing and disseminating multi-source information on objects and events in near-Earth space.

Guideline B.2 Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects

1. States and international intergovernmental organizations should promote the development and use of techniques and methods to improve the accuracy of orbital data for spaceflight safety and the use of common, internationally recognized standards when sharing orbital information on space objects.
2. Recognizing that spaceflight safety strongly depends upon the accuracy of orbital and other relevant data, States and international intergovernmental organizations should promote techniques and the investigation of new methods to improve such accuracy. Those methods could include

national and international activities to improve the capabilities and geographical distribution of existing and new sensors, use of passive and active on-orbit tracking aids, and combining and validating data from different sources. Special attention should be paid to encouraging the participation and capacity-building of developing countries with emerging space capabilities in this domain.

3. When sharing orbital information on space objects, operators and other appropriate entities should be encouraged to use common, internationally recognized standards to enable collaboration and information exchange. Facilitating greater shared awareness of the current and predicted location of space objects would enable timely prediction and prevention of potential collisions

Guideline B.3 Promote the collection, sharing and dissemination of space debris monitoring information.

States and international intergovernmental organizations should encourage the development and use of relevant technologies for the measurement, monitoring and characterization of the orbital and physical properties of space debris. States and international intergovernmental organizations should also promote the sharing and dissemination of derived data products and methodologies in support of research and international scientific cooperation on the evolution of the orbital debris population.

Guideline B.4 Perform conjunction assessment during all orbital phases of controlled flight.

1. Conjunction assessments should be performed for all spacecraft capable of adjusting trajectories during orbital phases of controlled flight for current and planned

spacecraft trajectories. States and international intergovernmental organizations should, through national mechanisms and/or international cooperation, perform conjunction assessments during all orbital phases of controlled flight for their current and planned spacecraft trajectories. With due consideration to article VI of the 1967 Outer Space Treaty, States should encourage entities, including spacecraft operators and conjunction assessment service providers under their jurisdiction and/or control to perform conjunction assessments through national mechanisms, when applicable International intergovernmental organizations should perform such assessments through their respective mechanisms.

2. States and international intergovernmental organizations should develop and implement in an appropriate manner approaches to and methods for conjunction assessment that may include: (a) improving the orbit determination of relevant space objects; (b) screening current and planned trajectories of relevant space objects for potential collisions; (c) determining the risk of collision and whether an adjustment of trajectory is required to reduce the risk of collision; and (d) sharing information on the proper interpretation and usage of the conjunction assessment results, as appropriate. States and international intergovernmental organizations should, where applicable, encourage entities under their respective jurisdiction and/or control, including spacecraft operators and conjunction assessment service providers, to develop or help develop such approaches and methods to conjunction assessment.

3. Spacecraft operators, including those of non-governmental entities, that are unable to perform conjunction assessments should seek support, via State authorities, as necessary and in accordance with relevant

applicable regulations, from appropriate around-the-clock conjunction assessment entities International intergovernmental organizations that are unable to perform conjunction assessments should seek support through their respective mechanisms

4. States and international intergovernmental organizations should, in a dedicated international consultative process, acting through their designated entities, as appropriate, share knowledge and experience related to the interpretation of conjunction assessment information with the objective of developing methods and consistent criteria for assessing probability of collisions and making avoidance manoeuvre decisions and agreeing on classes of methods applicable to different types of conjunctions. States and international intergovernmental organizations that have developed practical methods and approaches for conjunction assessments and collision avoidance manoeuvre decision-making processes should also share their expertise by, inter alia, providing training opportunities for emerging spacecraft operators and disseminating best practices, knowledge and experience.

5. States and international intergovernmental organizations should encourage conjunction assessment service providers under their jurisdiction and control to consult on screening criteria and notification thresholds with spacecraft operators and pertinent parties before providing conjunction assessment services, as practicable

Guideline B.5 Develop practical approaches for pre-launch conjunction assessment

1. States and international intergovernmental organizations are encouraged to advise launch service providers under their jurisdiction and control to consider conducting pre-launch conjunction assessment for space objects to be

launched. To facilitate and promote such pre-launch conjunction assessment practices, States and international intergovernmental organizations are encouraged, with the involvement of launch service providers and, as necessary, other relevant entities under their jurisdiction and control, to develop, implement and improve the corresponding methods and procedures.

2. States and international intergovernmental organizations are encouraged to advise launch service providers under their jurisdiction and control to seek support, as necessary, via designated entities authorized to engage in exchanges of information on pre-launch conjunction assessment, as appropriate and in accordance with relevant applicable regulations, for pre-launch conjunction assessment from appropriate conjunction assessment entities.

3. When performing a specific pre-launch conjunction assessment, launch service providers are encouraged to coordinate, via designated entities authorized to engage in exchanges of information on pre-launch conjunction assessment, with pertinent States and international intergovernmental organizations concerning the given assessment, if necessary.

4. States and international intergovernmental organizations should, with the involvement of launch service providers and other relevant entities under their jurisdiction and control as necessary, develop common international standards for describing relevant information required for pre-launch conjunction assessment in order to facilitate the provision, as mutually agreed, of pre-launch conjunction assessment support

5. States and international intergovernmental organizations are encouraged to exchange their analytical assessment of

the trends in the change of the risk of collision of space objects to be launched with other space objects operating near the planned insertion orbit.

6. States and international intergovernmental organizations are encouraged to consider providing, using, as appropriate, applicable existing and/or new dedicated mechanisms, information on launch schedules useful for assessing changes in the future population of space objects, pre-launch notifications containing information on the launch plan that would be useful for assisting in the identification of newly launched space objects, and notices for mariners and pilots on restricted zones at sea and in airspace. The contents and attributes of such information should be appropriate for its intended use.

7. States and international intergovernmental organizations should, through a dedicated consultative process within the Committee on the Peaceful Uses of Outer Space, consider, acquire and develop shared positions on information to be provided for pre-launch conjunction assessment

Guideline B.6 Share operational space weather data and forecasts

1. States and international intergovernmental organizations should support and promote the collection, archiving, sharing, intercalibration, long-term continuity and dissemination of critical space weather data and space weather model outputs and forecasts, where appropriate in real time, as a means of enhancing the long-term sustainability of outer space activities.

2. States should be encouraged to monitor, to the extent feasible, space weather continuously and to share data and

information with the aim of establishing an international space weather database network.

3. States and international intergovernmental organizations should support the identification of data sets critical for space weather services and research and should consider adopting policies for the free and unrestricted sharing of critical space weather data from their space- and ground-based assets. All governmental, civilian and commercial space weather data owners are urged to allow free and unrestricted access to and archiving of such data for mutual benefit

4. States and international intergovernmental organizations should also consider sharing real-time and near-real-time critical space weather data and data products in a common format, promote and adopt common access protocols for their critical space weather data and data products, and promote the interoperability of space weather data portals, thus promoting ease of data access for users and researchers. The real-time sharing of these data could provide a valuable experience for sharing in real time other kinds of data relevant to the long-term sustainability of outer space activities.

5. States should encourage entities under their jurisdiction and/or control to:

(a) Incorporate in satellite designs the capability to recover from a debilitating space weather effect, such as by including a safe mode;

(b) Incorporate space weather effects into satellite designs and mission planning for end-of-life disposal in order to ensure that the spacecraft either reach their intended graveyard orbit or de-orbit appropriately, in accordance with the Space Debris Mitigation Guidelines of the

Committee on the Peaceful Uses of Outer Space. This should include appropriate margin analysis.

6. International intergovernmental organizations should also promote such measures among their member States.

7. States should undertake an assessment of the risk and socioeconomic impacts of adverse space weather effects on the technological systems in their respective countries. The results from such studies should be published and made available to all States and used to inform decision-making relating to the long-term sustainability of outer space activities, particularly with regard to mitigating the adverse impacts of space weather on operational space systems.

Guideline B.7 Develop space weather models and tools and collect established practices on the mitigation of space weather effects

1. States and international intergovernmental organizations should undertake a coordinated approach to identifying and filling gaps in research and operational models and forecasting tools required to meet the needs of the scientific community and of the providers and users of space weather information services. Where possible, this should include coordinated efforts to support and promote research and development to further advance space weather models and forecasting tools, incorporating the effects of the changing solar environment and the evolving terrestrial magnetic field as appropriate, including within the context of the Committee on the Peaceful Uses of Outer Space and its Subcommittees, as well as in collaboration with other entities such as the World Meteorological Organization and the International Space Environment Service.

2. States and international intergovernmental organizations should support and promote cooperation and

coordination on ground- and space-based space weather observations, forecast modelling, satellite anomalies and reporting of space weather effects in order to safeguard space activities. Practical measures in this regard could include: (a) Incorporating current and forecast space weather thresholds into space launch criteria; (b) Encouraging satellite operators to cooperate with space weather service providers to identify the information that would be most useful to mitigate anomalies and to derive recommended specific guidelines for on-orbit operations. For example, if the radiation environment is hazardous, this might include actions to delay the uploading of software, implementation of manoeuvres, etc.; (c) Encouraging the collection, collation and sharing of information relating to ground- and space-based space weather-related impacts and system anomalies, including spacecraft anomalies; 26 (d) Encouraging the use of a common format for reporting space weather information. In relation to the reporting of spacecraft anomalies, satellite operators are encouraged to take note of the template proposed by the Coordination Group for Meteorological Satellites; (e) Encouraging policies promoting the sharing of satellite anomaly data related to space weather-induced effects; (f) Encouraging training on and knowledge transfer relating to the use of space weather data, taking into account the participation of countries with emerging space capabilities.

3. It is acknowledged that some data may be subject to legal restrictions and/or measures for the protection of proprietary or confidential information, in accordance with national legislation, multilateral commitments, non-proliferation norms and international law.

4. States and international intergovernmental organizations should work towards the development of international standards and the collection of established

practices applicable for the mitigation of space weather effects in satellite design. This could include the sharing of information on design practices, guidelines and lessons learned relating to mitigation of the effects of space weather on operational space systems, as well as documentation and reports relating to space weather user needs, measurement requirements, gap analyses, cost-benefit analyses and related space weather assessments.

5. States should encourage entities under their jurisdiction and/or control to: (a) Incorporate in satellite designs the capability to recover from a debilitating space weather effect, such as by including a safe mode; (b) Incorporate space weather effects into satellite designs and mission planning for end-of-life disposal in order to ensure that the spacecraft either reach their intended graveyard orbit or de-orbit appropriately, in accordance with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. This should include appropriate margin analysis.

6. International intergovernmental organizations should also promote such measures among their member States.

7. States should undertake an assessment of the risk and socioeconomic impacts of adverse space weather effects on the technological systems in their respective countries. The results from such studies should be published and made available to all States and used to inform decision-making relating to the long-term sustainability of outer space activities, particularly with regard to mitigating the adverse impacts of space weather on operational space systems

Guideline B.8 Design and operation of space objects regardless of their physical and operational characteristics

1. States and international intergovernmental organizations are encouraged to promote design approaches that increase the trackability of space objects, regardless of their physical and operational characteristics, including small-size space objects, and those that are difficult to track throughout their orbital lifetime, as well as facilitate the accurate and precise determination of their position in orbit. Such design solutions could include the use of appropriate on-board technology.

2. States and international intergovernmental organizations should encourage manufacturers and operators of space objects, regardless of their physical and operational characteristics, to design such objects to implement applicable international and national space debris mitigation standards and/or guidelines in order to limit the long-term presence of space objects in protected regions of outer space after the end of their mission. States and international intergovernmental organizations are encouraged to share their experiences and information on the operation and end-of-life disposal of space objects, in furtherance of the long-term sustainability of space activities.

3. Due to the importance of small-size space objects to all space programmes, in particular, for developing countries and emerging spacefaring countries, the implementation of the present guideline supports the development of space programmes, including the launching and operation of small-size space objects or any other space objects that are difficult to track, in a way that promotes the long-term sustainability of outer space activities.

Guideline B.9 Take measures to address risks associated with the uncontrolled re-entry of space objects

1. States and international intergovernmental organizations should have in place procedures for furnishing to other States and/or the Secretary-General of the United Nations, via designated entities, as soon as practicable and with updates if necessary, information on the forecasted uncontrolled re-entry of potentially hazardous space objects that are under their jurisdiction and control, and communicating and coordinating the mitigation of risks associated with such events. States and international intergovernmental organizations without space object tracking capabilities should seek support from other States and international intergovernmental organizations with such capabilities. If a State or international intergovernmental organization has early information on forecasted uncontrolled re-entry of potentially hazardous space objects that are under the jurisdiction and control of another State or international intergovernmental organization, it should share such information with that State or international intergovernmental organization via their designated entities. If a State or international intergovernmental organization has early information on the forecasted uncontrolled re-entry of potentially hazardous space objects whose jurisdiction and control is not identified, it should share such information with other States and/or the United Nations via designated entities.

2. States and international intergovernmental organizations with relevant technical capabilities and resources and/or States and international intergovernmental organizations which exercise jurisdiction over the objects forecast to re-enter the atmosphere should assist each other (in a proactive manner and/or in responding to a request) to

improve the reliability of results when predicting the uncontrolled re-entry of potentially hazardous space objects, such as by tracking the objects and generating information on their trajectory. States and international intergovernmental organizations should cooperate to build capacity in the area of monitoring uncontrolled space object re-entries.

3. When feasible and without prejudice to furnishing preliminary information on possible hazardous events associated with the uncontrolled re-entry of space objects, the procedures referred to above should be employed during the final phase of the orbital flight of a space object. The procedures should be used until the termination of the ballistic flight of the space object has been confirmed, as well as in the event of the identification of the space object or its fragments that reach the surface of the Earth.

4. States and international intergovernmental organizations should furnish in a timely fashion relevant information they may have at their disposal, as practicable, to support addressing risks from uncontrolled re-entries. The contents and attributes of such information should, to the extent practicable, be relevant to raising awareness, where appropriate, of possible contingencies associated with high-risk uncontrolled re-entries. States and international intergovernmental organizations should designate appropriate entities that are authorized to provide, request and receive such information.

5. States and international intergovernmental organizations should consider applying design techniques to minimize the risk associated with fragments of space objects surviving uncontrolled re-entry.

6. Without prejudice to article 5 of the Agreement on the Rescue of Astronauts, the Return of Astronauts and the

Return of Objects Launched into Outer Space, the State(s) having jurisdiction over the territory on which a space object or its component parts have been discovered or are presumed to have reached the surface of the Earth, should respond to any request for timely consultations by the State or international intergovernmental organization with jurisdiction and control over the object. In such consultations, the State or international intergovernmental organization exercising jurisdiction and control over the object should advise and, if mutually agreed, assist the potentially affected State(s) in the search for and identification, assessment, analysis, evacuation and return of the object or its fragments State(s) on whose territory a space object or its component parts have been discovered or are presumed to have reached the surface of the Earth should respond to requests from the State or international intergovernmental organization with jurisdiction and control over the object to follow appropriate procedures for, inter alia, identification, assessment, and analysis of the space object or its component parts, to avoid the harmful effects of any hazardous materials which could have survived the uncontrolled re-entry.

Guideline B.10 Observe measures of precaution when using sources of laser beams passing through outer space

When governmental and/or non-governmental entities under the jurisdiction and control of States and international intergovernmental organizations use lasers that generate beams passing through near-Earth outer space, States and international intergovernmental organizations should analyse the probability of accidental illumination of passing space objects by laser beams; conduct a quantitative evaluation of the laser radiation power at the distance of crossing space objects; if possible,

perform an assessment of the risk of malfunctioning of, damage to, and/or break-up of space objects due to such illumination; and, as necessary, observe appropriate measures of precaution.

C. International cooperation, capacity-building and awareness

Guideline C.1 Promote and facilitate international cooperation in support of the long-term sustainability of outer space activities

States and international intergovernmental organizations should promote and facilitate international cooperation to enable all countries, in particular developing and emerging spacefaring countries, to implement these guidelines. International cooperation should, where appropriate, involve the public, private and academic sectors, and may include, inter alia, the exchange of experience, scientific knowledge, technology and equipment for space activities on an equitable and mutually acceptable basis.

Guideline C.2 Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate, for information exchange

1. States and international intergovernmental organizations should share, as mutually agreed, experiences, expertise and information relating to the long-term sustainability of outer space activities, including with non-governmental entities, and develop and adopt procedures to facilitate the compilation and effective dissemination of information on the ways and means of enhancing the long-term sustainability of space activities. When further developing

their information-sharing procedures, States and international intergovernmental organizations could take note of existing data-sharing practices used by non-governmental entities.

2. The experiences and expertise acquired by those engaged in space activities should be regarded as instrumental in the development of effective measures to enhance the long-term sustainability of outer space activities. States and international intergovernmental organizations should therefore share relevant experiences and expertise to enhance the long-term sustainability of space activities.

Guideline C.3 Promote and support capacity-building

1. States and international intergovernmental organizations with experience in space activities should encourage and support capacity-building in developing countries with emerging space programmes, on a mutually acceptable basis, through measures such as improving their expertise and knowledge on spacecraft design, flight dynamics and orbits, performing joint orbital calculations and conjunction assessments, and providing access to appropriate precise orbital data and appropriate tools for the monitoring of space objects through relevant arrangements as appropriate.

2. States and international intergovernmental organizations should support current capacity-building initiatives and promote new forms of regional and international cooperation and capacity-building that are in accordance with national and international law to assist countries in gathering human and financial resources and achieving efficient technical capabilities, standards, regulatory frameworks and governance methods that support the long-

term sustainability of outer space activities and sustainable development on Earth.

3. States and international intergovernmental organizations should coordinate their efforts in space-related capacity-building and data accessibility in order to ensure efficiency in the use of available resources and, to the extent that it is reasonable and relevant, avoid unnecessary duplication of functions and efforts, taking into account the needs and interests of developing countries. Capacity-building activities include education, training and sharing of appropriate experience, information, data, tools and management methodologies and techniques, as well as the transfer of technology

4. States and international intergovernmental organizations should also undertake efforts to make relevant space-based information and data accessible to countries affected by natural disasters or other catastrophes, guided by considerations of humanity, neutrality and impartiality, and to support capacity-building activities aimed at enabling the receiving countries to make optimal use of such data and information. These space-based data and information with appropriate spatial and temporal resolution should be freely, quickly and easily available for countries in crisis.

Guideline C.4 Raise awareness of space activities

1. States and international intergovernmental organizations should raise general public awareness of the important societal benefits of space activities and of the consequent importance of enhancing the long-term sustainability of outer space activities. To this end, States and international intergovernmental organizations should:

(a) Promote institutional and public awareness of space activities and their applications for sustainable

development, environmental monitoring and assessment, disaster management and emergency response;

(b) Conduct outreach, capacity-building and education on regulations and established practices relevant to the long-term sustainability of space activities;

(c) Promote activities of non-governmental entities that will enhance the long-term sustainability of outer space activities;

(d) Raise awareness among relevant public institutions and non-governmental entities about national and international policies, legislation, regulations and best practices that are applicable to space activities.

2. States and international intergovernmental organizations should promote public awareness of space applications for sustainable development, environmental monitoring and assessment, disaster management and emergency response through information-sharing and joint efforts with public institutions and non-governmental entities, taking into account the needs of current and future generations in designing space education programmes. States, international intergovernmental organizations and non-governmental entities should pay special attention to courses on enhancing knowledge and practice of the utilization of space applications to support sustainable development. States and international intergovernmental organizations should initiate the voluntary collection of information on public awareness and education tools and programmes with a view to facilitating the development and implementation of other initiatives with similar objectives.

3. States and international intergovernmental organizations should foster outreach activities by or with industry, academia and other relevant non-governmental entities. Outreach, capacity-building and educational initiatives could take the form of seminars (in person or broadcast over

the Internet), published guidelines to complement national and international regulations or a website with basic information on a regulatory framework and/or a contact point within the Government for regulatory information. Appropriately targeted outreach and education can assist all entities engaged in space activities in gaining a better appreciation and understanding of the nature of their obligations, in particular relating to implementation, which can lead to improved compliance with the existing regulatory framework and the practices currently being employed to enhance the long-term sustainability of outer space activities. This is particularly valuable where the regulatory framework has been changed or updated, resulting in new obligations for participants in space activities.

4. Cooperation between Governments and non-governmental entities should be encouraged and fostered. Non-governmental entities, including professional and industry associations and academic institutions, can play important roles in increasing international awareness of issues associated with space sustainability, as well as promoting practical measures to enhance space sustainability. Such measures could include adoption of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space; compliance with the ITU Radio Regulations related to space services; and the development of open, transparent standards for the exchange of data necessary to avoid collisions, harmful radio frequency interference or other harmful events in outer space. Non-governmental entities can also play important roles in bringing stakeholders together to develop common approaches to certain aspects of space activities that can collectively enhance the long-term sustainability of space activities.

D. Scientific and technical research and development Guideline

D.1 Promote and support research into and the development of ways to support sustainable exploration and use of outer space

1. States and international intergovernmental organizations should promote and support research into and the development of sustainable space technologies, processes and services and other initiatives for the sustainable exploration and use of outer space, including celestial bodies
2. In their conduct of space activities for the peaceful exploration and use of outer space, including celestial bodies, States and international intergovernmental organizations should take into account, with reference to the outcome document of the United Nations Conference on Sustainable Development (General Assembly resolution 66/288, annex), the social, economic and environmental dimensions of sustainable development on Earth.
3. States and international intergovernmental organizations should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets and that maximize the use of renewable resources and the reusability or repurposing of space assets to enhance the long-term sustainability of those activities.
4. States and international intergovernmental organizations should consider appropriate safety measures to protect the Earth and the space environment from harmful contamination, taking advantage of existing measures,

practices and guidelines that may apply to those activities, and developing new measures as appropriate.

5. States and international intergovernmental organizations conducting research and development activities to support the sustainable exploration and use of outer space should also encourage the participation of developing countries in such activities.

Guideline D.2 Investigate and consider new measures to manage the space debris population in the long term

1. States and international intergovernmental organizations should investigate the necessity and feasibility of possible new measures, including technological solutions, and consider implementation thereof, in order to address the evolution of and manage the space debris population in the long term. These new measures, together with existing ones, should be envisaged so as not to impose undue costs on the space programmes of emerging spacefaring nations.

2. States and international intergovernmental organizations should take measures at the national and international levels, including international cooperation and capacity-building, to increase compliance with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space.

3. Investigation of new measures could include, inter alia, methods for the extension of operational lifetime, novel techniques to prevent collision with and among debris and objects with no means of changing their trajectory, advanced measures for spacecraft passivation and post-mission disposal and designs to enhance the disintegration of space systems during uncontrolled atmospheric re-entry.

4. Such new measures aimed at ensuring the sustainability of space activities and involving either controlled or uncontrolled re-entries should not pose an undue risk to people or property, including through environmental pollution caused by hazardous substances 5Policy and legal issues, such as ensuring that these new measures are compliant with the provisions of the Charter of the United Nations and applicable international law, may also need to be addressed.

About the Authors



Dr. Joseph N. Pelton, Ph.D., is the Dean emeritus and former Chairman of the Board of Trustees of the International Space University. He is the Founder of the Arthur C. Clarke Foundation and the founding President of the Society of Satellite Professionals International—now known as the Space and Satellite Professionals International (SSPI). Dr. Pelton currently serves on the Executive Board of the International Association for the Advancement of Space Safety. He is the Director Emeritus of the Space and Advanced Communications Research Institute (SACRI) at George Washington University, where he also served as Director of the Accelerated Master's

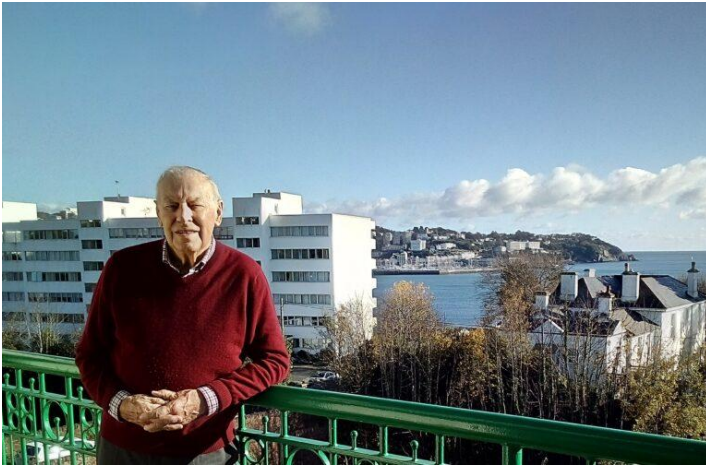
Program in Telecommunications and Computers from 1998 to 2004. Previously, he headed the Interdisciplinary Telecommunications Program (ITP) at the University of Colorado-Boulder. Dr. Pelton has also served as President of the International Space Safety Foundation and President of the Global Legal Information Network (GLIN). Further, he served as the founding Chairman of the Board of The Global Alliance for International Collaboration in Space (GALIX). Earlier in his career, he held a number of executive and management positions at COMSAT and INTELSAT, the global satellite organization, where he was Director of Strategic Policy.

A prolific author and futurist, Dr. Pelton has now published over 70 books and over 400 articles, encyclopedia entries, op-ed pieces, and other research publications during his career. He has been a speaker on national media in the U.S. (PBS New Hour, Public Radio's All Things Considered, ABC, and CBS) and internationally on BBC, CBC, and FR-3. He has spoken and testified before Congress and the United Nations and delivered talks in over 40 countries around the world. His honors include the Sir Arthur Clarke, International Achievement Award of the British Interplanetary Society; the Arthur C. Clarke Foundation Award; the ICA Educator's award; the ISCe Excellence in Education Award; and being elected to the International Academy of Astronautics. Most recently, in 2017, he won the Da Vinci Award of the International Association for the Advancement of Space Safety and the Guardian Award of the Lifeboat Foundation.

Dr. Pelton is a member of the SSPI Hall of Fame, Fellow of the IAASS, and Associate Fellow of the AIAA. Pelton's *Global Talk* won the Eugene Emme Literature Award of the International Astronautics Association and was nominated for a Pulitzer Prize. His most recent books are: *Space*

Systems and Sustainability, Preparing for the Next Cyber Revolution, Space 2.0: Revolutionary Advances in the Space Industry, The New Gold Rush: The Riches of Space Beckon, The Handbook of Space Satellites, Global Space Governance: An International Study, and the second editions of *The Handbook of Satellite Applications* and *The Farthest Shore: A 21st Century Guide to Space*. Prior to the current book, Peter Marshall and Joseph Pelton prepared *The 2005 Space Safety Report*, followed by the series of publications listed at the start as ‘Space Safety Publications Sponsored by the SSC Trust Fund’.

He received his degrees from the University of Tulsa, New York University, and from Georgetown University, where he received his doctorate.



Peter Marshall began his career as a journalist, including some 10 years with BBC radio and television news, where he became a News Editor. In 1966, he moved to Visnews of London (then part-owned by the BBC and now Reuters-TV), a global TV news agency where he became General Manager. He was a pioneer in the use of satellites for TV news coverage and distribution, and in 1986 he moved to Washington DC to create the Broadcast Services Division of the intra-governmental body INTELSAT.

With the emergence of deregulation and competition in the satellite communications area, he returned to the private sector as President of Keystone Communications. This organization, now part of Globecast (a subsidiary of France Telecom) is the largest provider of global satellite broadcast services.

Peter Marshall is a past Chairman of the Royal Television Society in the UK, past President of the Society of Satellite Professionals (SSPI) in the USA and he was elected to the SSPI's "Hall of Fame" in 2006 in recognition of his pioneering work for the industry. He also served for a

number of years as a member of the Board of the Arthur C. Clarke Foundation.

He is now a writer and consultant, based in his native U.K., and he has collaborated with Dr. Pelton on seven books and major research projects, including *Space Safety 2005, Communications Satellites – Global Change Agents* (published by Lawrence Erlbaum in 2006), *Space Exploration and Astronaut Safety* (published by AIAA in 2007) and *License to Orbit – the Future of Commercial Space Travel* (published by Apogee Books in 2011).