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## Innovations in the exploration of outer space

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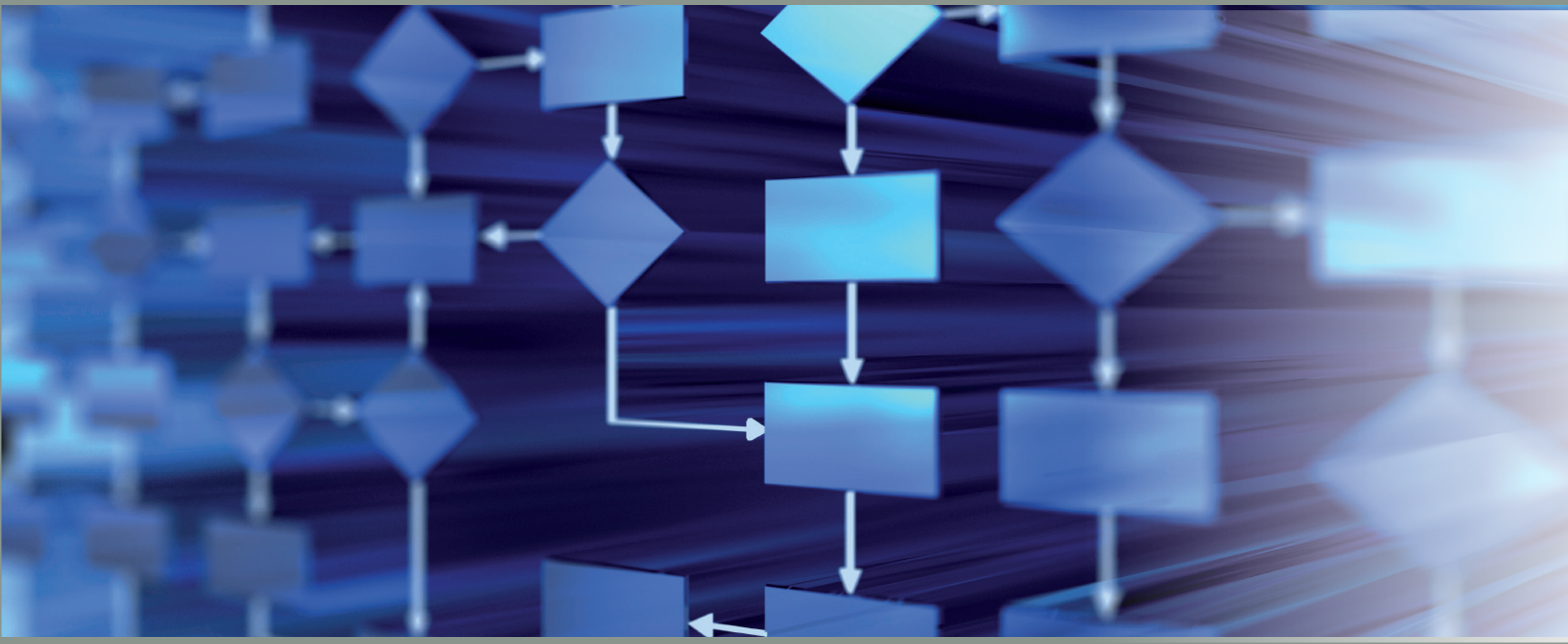

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# Innovations in the exploration of outer space

Henry R. Hertzfeld[1], Benjamin Staats[2], George Leaua[3]

## Abstract:

Human exploration of outer space has stimulated multiple innovations from both government and private sources. The decision to invest vast sums of money over a short period of time for the moon programs of the 1960s radically increased the level of innovation. Accomplishing this required new forms of energy for launch and space operations, reductions in the weight of components, and advanced computational capabilities, among many other technological improvements. The organization and management of bringing all of the components together was also essential. This report discusses economic aspects and overall benefits of those innovations as they fit into the prior and continuing push for advanced space capabilities.

**JEL Classification**: L98, H440, H54

**Keywords:** *space economics, NASA, government investment, technology transfer, spin-offs, batteries, composites, artificial intelligence*

## Disclaimer:

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## I. Introduction

The space programs in both the United States and the Soviet Union resulted from the Cold War tensions and the competitive race to demonstrate technological leadership and power. In particular this was driven by both the availability and threats associated with nuclear weapons and the fear of their deployment. The ability to deliver such weapons over long distances dictated the need for developing advanced rockets and guided missiles. Today's launch vehicles that provide access to outer space are direct descendants of these missiles, guidance systems, and associated ground equipment and facilities.

The military industrial complex, as it was known then, reflected the research and production element of these geopolitical realities of a post World War II era in the United States. Rapid economic expansion and national security characterized the decades of the 1950s and 1960s. This, in combination with a fast developing technical capability driven by both military and civilian research and development (R&D) efforts were the threads that were woven together and created the incredible technology challenge of not only reaching outer space but also of sending human beings to the Moon and successfully returning them safely to the Earth.

Essentially the time and conditions were ideal for accomplishing what had been previously regarded as impossible, or in the case of space exploration, material for science fiction literature.

This report will focus on the technological innovations that made possible these geopolitical-driven initiatives. Most people today visualize the images of powerful rockets, livable space capsules, and footprints and a flag on the Moon as the breakthrough markers. However, these are just the outward symbols of a vast array of capabilities that encompass space exploration.

In political and economic realms, it is rarely one thing that changes the world. It is the unpredictable coming together of many different factors at an opportune moment in time that made the breakthroughs possible. And, when that is coupled with a better understanding of science working together with applied engineering in many fields, the resulting success becomes possible. That is a result not of one invention or innovation, but of years of hard work, large funding initiatives, and the amalgamation of new and old technologies masterfully coordinated and incorporated into programs and projects.

The remarkable progress is also leveraged on another capability: the ability to take risks, organize and manage all of these variable inputs across multiple government and private research facilities, academic departments, and industrial contractors over relatively long periods of time. As one historian succinctly stated:

> *"If there was a secret to Apollo, it was … organizational reforms, which transferred Air Force methods to NASA, superimposed upon the technical excellence of STG*[4] *and MSFC (Marshall Space Flight Center) engineers.*

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[4] The *Space* Task Group (STG) was a working group of NASA *engineers* created in 1958, and tasked with managing America's human spaceflight programs. Headed by Robert Gilruth and

> *Europeans would eventually make a concerted effort to learn the managerial secrets of Apollo, but not before trying their own ideas, and failing miserably."*[5]

On top of those diverse factors, the ability to continue to attract funding and sustain political and institutional support was equally as difficult and unique as were the technical challenges.

The era of the 1960s in the United States and the Soviet Union, supported also by contributions from other nations, did just that: enabled all humanity to realize and celebrate the long-standing dreams of robotic and human space exploration.

Today, over 60 years later, the basic elements of extending human reach further into outer space as well as the more recent developments in using low earth orbit (LEO) for purposes extremely useful to life on the Earth remains very similar. The constant desire to accomplish more in space and to go further essentially depends on technological innovations oriented toward the very same goals that enabled the early space accomplishments: making materials lighter and stronger, developing more efficient uses of energy, and protecting equipment and people from the rigors of a harsh environment.

Figure 1, below, illustrates the important external factors need to bring the goals of technical requirements to successful implementation.

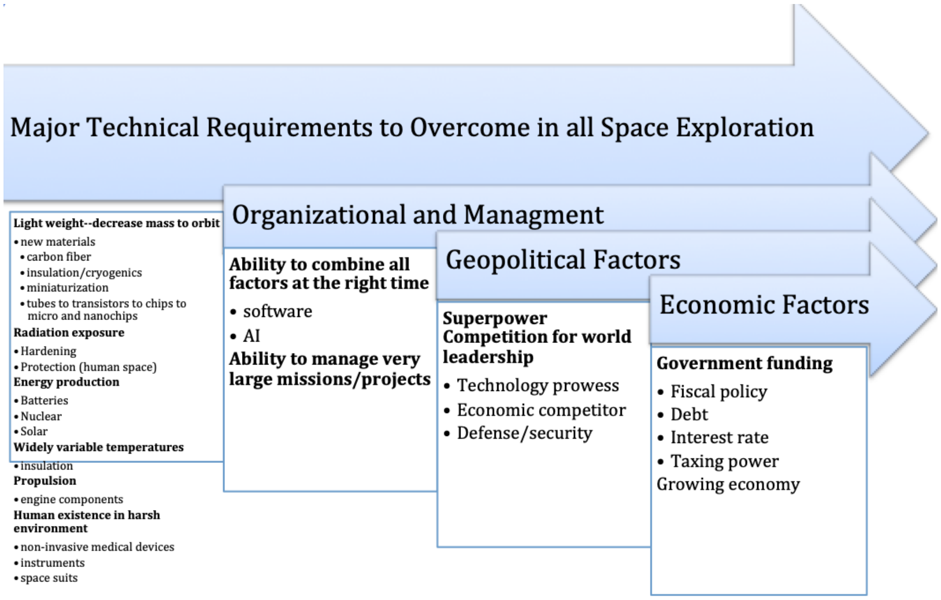

**Figure 1: Elements of Stimuli for Space Exploration**

Today, space exploration R&D initiatives are being performed by many nations. And, with maturing and widely disseminated publically funded space capabilities, along with rapidly growing privately funded commercial interests, nations and companies are

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based at the Langley Research Center in Hampton, Virginia, it managed Project Mercury and follow-on plans

[5] Ibid., 153.

finding ways to further advance, improve and overcome the very same basic technologically challenging issues that the early pioneers of space exploration faced. Successfully accomplishing these efforts, and making access to space less expensive and more available are the basic keys to the future promises of further exploring and using outer space.

## II. Geopolitical Factors

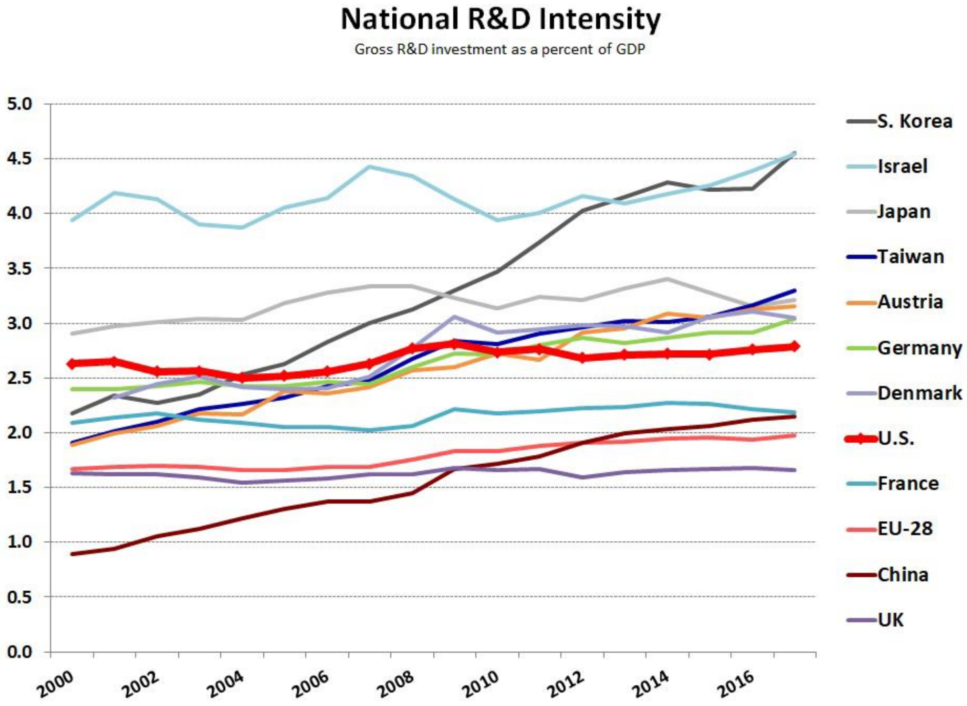
Massive government R&D investments are relatively rare for any nation and therefore, almost by definition, many factors beyond the stated use of the mission's end product are involved. The Cathedrals of the Middle Ages, the Coliseums of the Roman Empire, or the ancient Greek Temples were all huge investments and symbolic of the power of the sponsoring nation. In more recent times, the Manhattan Project to produce the atom bomb was about winning and ending WWII. And the Apollo Program to put a man on the Moon in less than 10 years was about showing the world that the United States had superior technological capabilities to those of the Soviet Union.

To accomplish these very expensive efforts, a nation needs, at a minimum, the successful coalition of political support, financial commitments, and a convincing argument that the technical knowledge and skills to complete the project are in the realm of possibility. If any one of those is not present, the proposed project will not be undertaken.

All of these projects required a long period of time and involved innovative efforts that were the physical and inspirational building blocks of the future. In this report the focus is on the space programs of nations, particularly the United States and how not only the technology but also the changing geopolitical environment over the past 60 years has shaped the worldwide innovations and contributions of that program. This has established a lasting foundation for the continued expansion and innovative commitment to space exploration.

### A. R&D and Space Investments in the United States

National investment in research and development has consistently been an important economic stimulus. As the graph below illustrates, over the past two decades many nations have rapidly increased their overall (public and private) R&D investments as measured by a percent of Gross Domestic Product.



Source: OECD, Main Science and Technology Indicators, August 2019. © 2019 AAAS

In the United States, the overall government spending on R&D is declining when viewed as a percentage of the government budget.[6] In fact, with the exception of the very large commitment to the Apollo program in the mid-1960s, the percentage of the non-defense R&D commitment has remained steady at approximately 2%. The defense R&D effort has declined, although in both cases the absolute monetary commitment has grown along with the growth of the overall budget and as shown below, space continues to be an important component of the R&D profile.

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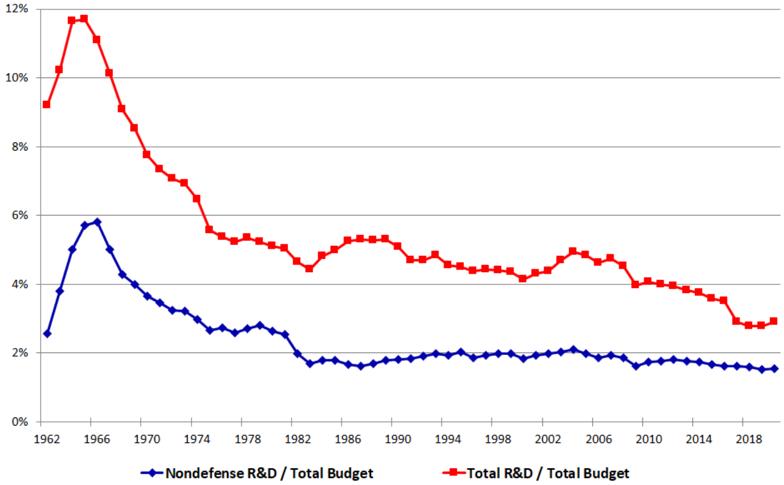
[6] The Biden Administration has proposed a large increase in Federal R&D for the 2022 Budget that includes more than a 5% increase for NASA. Whether this gets funding will depend on Congressional action this coming year.

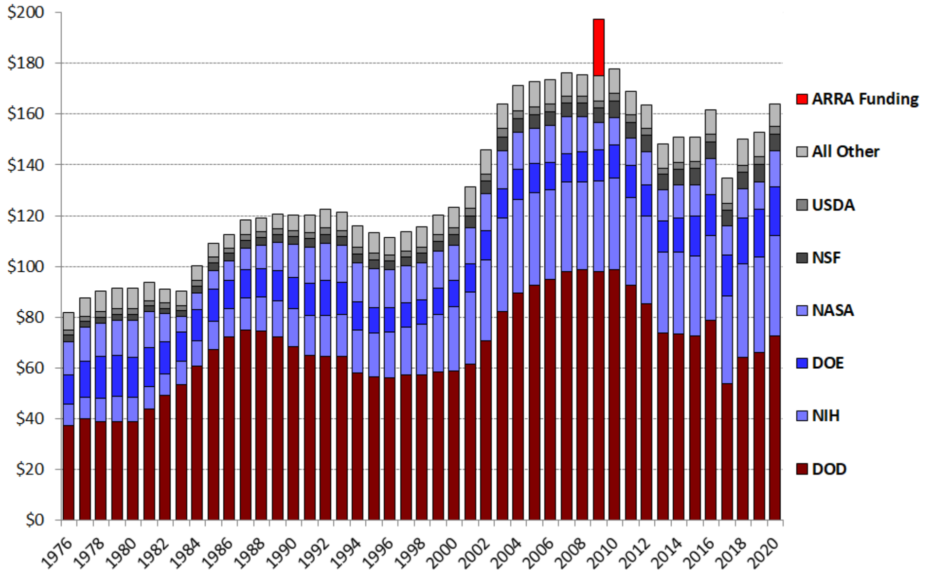


**R&D as Percent of the Federal Budget**

FY 1962-2020, in outlays

FY 2020 figures do not include emergency COVID-19 appropriations.
Beginning in FY 2017, federal agencies have revised what they consider R&D. Late-stage development, testing, and evaluation programs, primarily within the Defense Department, are no longer counted as R&D.
Based on data from the *Budget of the U.S. Government FY 2021* Historical Tables. © 2020 AAAS

When viewed by monetary commitments made by agencies, the following graph clearly illustrates that after 1976 the upward trend in expenditures is driven by investments in health and medical research (NIH) in both the mid-1980s and again in the early 2000s. The commitment to space R&D (NASA) has also grown steadily but it should be noted that in 1975 it had reached a low point after the cancellation of the Apollo program in the early 1970s.



**Trends in R&D by Agency**

in billions of constant FY 2020 dollars

NOTE: In FY 2017, federal agencies revised what they count as R&D. Late-stage development, testing, and evaluation programs, primarily within the Defense Department, are no longer counted as R&D.
Based on AAAS analyses of OMB and agency budget data and documents. © 2020 AAAS

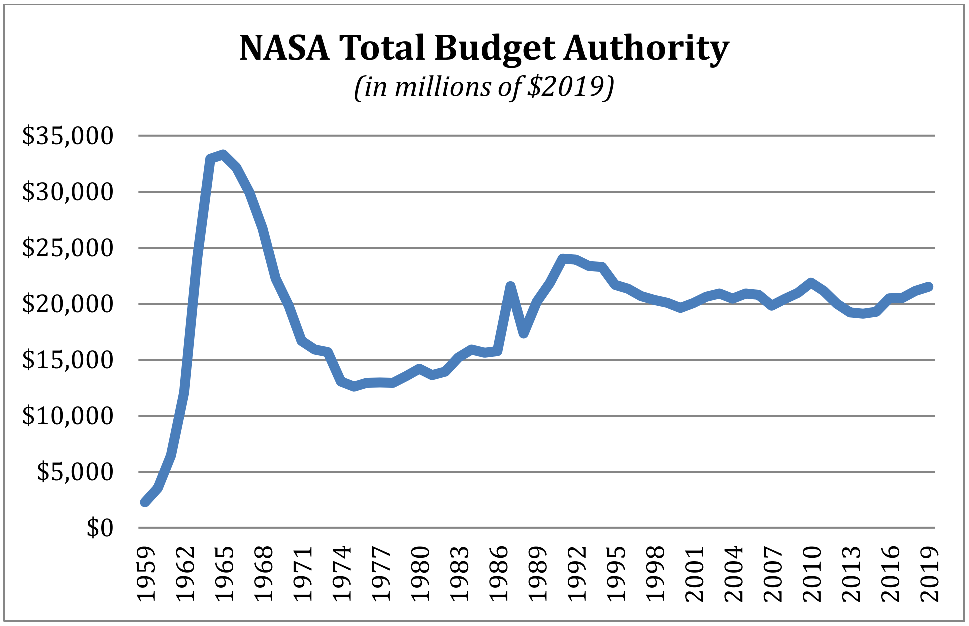
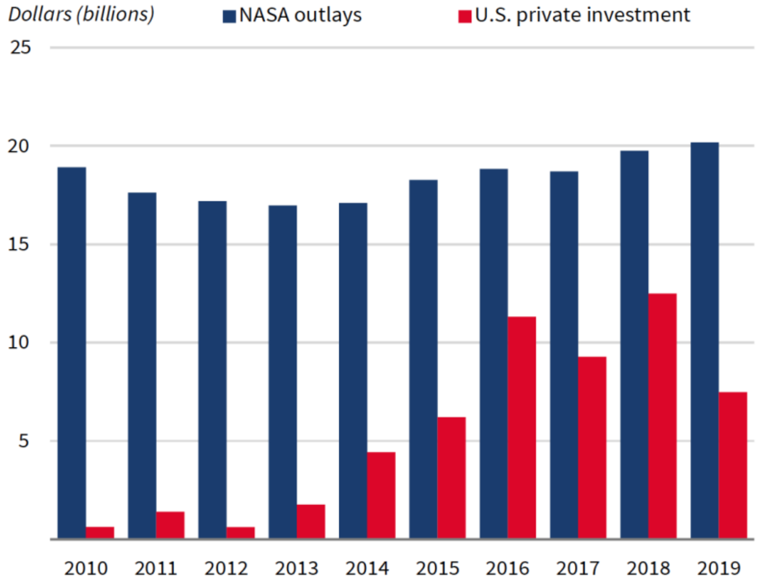


Figure 1: Source: 2019 U.S. President's Report on Aerospace

A review of the trend in NASA's Budget Authority over time clearly shows a continuing steady commitment since the mid-1970s. Earlier R&D, as discussed above, reflected the Apollo program. Today's R&D increases are focused on new technology development and a commitment to human space activity, especially toward a return to the Moon and further into outer space in the future.

Balancing this trend is the notable growth in private space R&D from being very modest before 2010 to demonstrating a rapid increase in the past 5 years. About one-third of this investment is in new launch vehicles and especially significant is that it comes from "angel" investors; those few billionaires able to invest without regard to short-term profits, shareholders, or other normal investment constraints. Another large component of this increase in overall private commitments to space can be explained by the inclusion of mergers and acquisitions in the total. Those numbers reflect a consolidation of some companies and the numbers reflect estimates of the valuation of these company's discounted future profits. (And with the very recent trend towards SPACs, those estimates have been reported as being very optimistic and possibly highly overstated.)

However, there are some very interesting new ventures and new private interest in space technologies and even discounting the above considerations, there is no doubt that the private sector interest in space is real, growing and reflected in the overall chart.

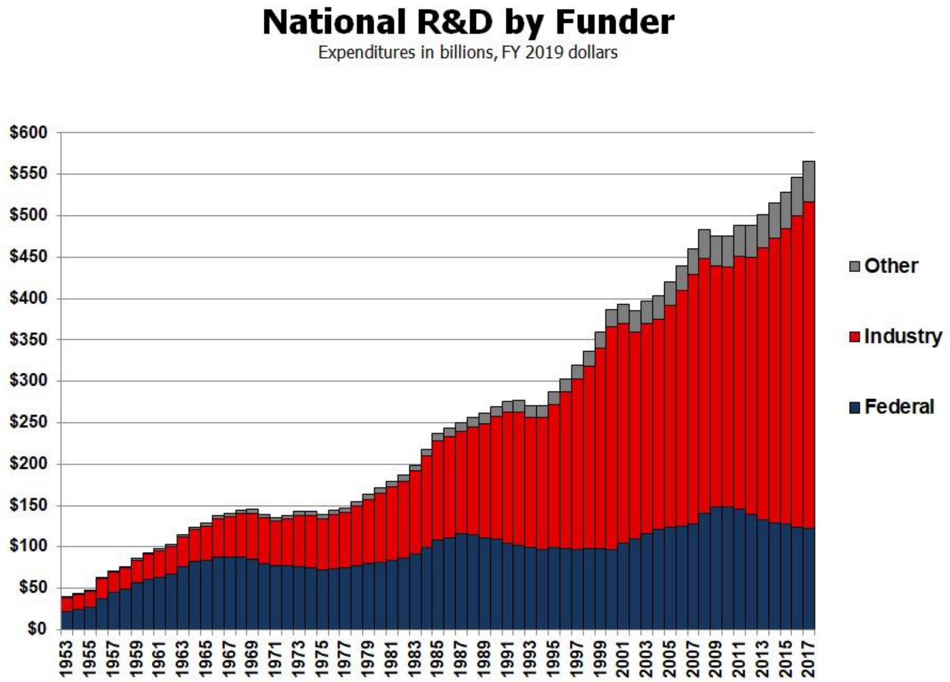


**NASA Outlays and U.S. Private Investment, 2010–19**

Sources: Office of Management and Budget; Space Capital; CEA calculations.
Note: NASA = National Aeronautics and Space Administration.

Source: U.S. 2021 Economic Report of the President, Ch. 8, page 229

Finally, the overall R&D and space investments in the United States also are driven by government policy decisions. These have shifted from overall stimulus spending by the government to providing incentives at the agency level towards joint (with industry) research programs and new acquisition and procurement initiatives that encourage the purchase of services and products from companies rather than R&D contracts. The graph below illustrates the overall relation between public and private R&D spending in the United States and in real dollars shows a strong overall growth pattern.



Source: Source: National Science Foundation, *National Patterns of R&D Resources* series. Constant-dollar conversions based on GDP deflators from *Budget of the U.S. Government FY 2020.* © 2019 AAAS

### B. 1950s and 1960s: Science, Cooperation, and the Apollo Program

New technology developments and innovations are further stimulated by both competition and by cooperation that occurs domestically among industries and companies as well as internationally among nations. Companies strive for leadership as a profit-seeking way of growing. Similarly, one-way nations work towards domestic growth and political strength is through the stimulation of new technology. Even the preamble to NASA's 1958 enabling legislation emphasizes that NASA should work toward preserving the United States as a leader in aeronautical and space technology[7] It is important to note that the Act recognizes that other nations may have technological specializations and that the U.S. should be "a" leader, not "the" leader in all disciplines and industrial endeavors.

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[7] NATIONAL AERONAUTICS AND SPACE ACT OF 1958, Pub. L. No. 85-568, 72 Stat. 426-438 (Jul. 29, 1958) As Amended: Section 102(d)(5).

In furtherance of this, the Act's preamble also establishes the basis for the United States and NASA to cooperate with other nations in space and aeronautical R&D.[8]

The aftermath of WWII left the world in a great power competition between the United States and the Soviet Union. One aspect of this competition was in the development of advanced rockets in both nations, mainly for military purposes. It was also evident that these missiles could eventually reach outer space and put satellites into orbit.

In response to the need for strategic reconnaissance over Soviet Union in the 1950s, the Eisenhower Administration directed the U.S. Air Force to develop an aircraft that could fly at very high altitude.[9] Lockheed developed the U-2 plane, which was used for intelligence gathering and flew at an altitude (about 65,000 feet) that was thought to be high enough to avoid Soviet countermeasures. But, in May 1960, the Soviet Union shot down a U-2 plane and captured its pilot, prompting the United States to reconsider this means of obtaining vital intelligence.

Although getting into space first was not a priority for the Eisenhower Administration.[10] The effects of the Soviet Union launching Sputnik 1 in October of 1957 shocked an surprised the world and the citizens of the United States. That event coupled with later embarrassments of the 1960 U-2 incident, and the growing public impression of a "missile gap" effectively challenged the United States' preeminence as a technological leader.

(Parenthetically, Sputnik 1, was actually part of a larger satellite the Soviet Union was developing as part of their efforts and contributions to the worldwide cooperation in scientific research known as the International Geophysical Year (IGY) during 1957-58. The U.S. Government was aware of this effort (the U.S. public was not). But the surprise was the separation of this smaller instrument from the larger satellite and its being placed on a rocket and successfully launched into space earlier than expected. The U.S. Government responded by proposing that space be considered as an open area, with scientific information freely shared by all nations. This principle became adopted by all nations and is now one of the basic tenants of space law through the space treaties that all space-faring nations have ratified.)

And, in spite of the power struggle between the U.S. and the U.S.S.R., there was also cooperation during this period of time. The IGY was one example, and there were many others, including provisions of the NASA Act of 1958 that called for international cooperation in civil space. The later (1975) Apollo-Soyuz project was a particularly important cooperative space mission between the two superpowers.

Returning to the period of the late 1950s, the United States responded to the shock of Sputnik 1 by establishing The National Aeronautics and Space Administration was founded in 1958. This was a new civilian agency in charge of the peaceful and scientific exploration of space. In contrast, the Soviet Union's space exploration projects were military and secret.

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[8] Ibid, Section 102(d)(7).

[9] John Logsdon. "The Penguin Book of Outer Space Exploration," 2018

[10] Walter A McDougall. "The Heavens and The Earth: A Political History of the Space Age," 1985, The Johns Hopkins University Press

In terms of aerospace technology, the period prior to WWII can be best characterized by several theoretical models being developed in different parts of the World along with inventions that ultimately came together to make the first rockets possible. The basic concepts of propulsion technology can be traced back to Chinese fireworks. However, it was not until the late 19th and early 20th century that scientists in different nations independently derived the equation behind rocket science. Notably, British mathematician William Moore and Russian scientist Konstantin Tsiolkovsky laid the theoretical groundwork for the design of rockets. European engineer Herman Oberth and American engineer Robert Goddard worked in parallel throughout the early 20th century on rockets that used multiple stages to escape Earth's atmosphere. Both Goddard and Oberth launched rocket prototypes aimed to prove their theoretical frameworks.

Upon the shoulders of these aerospace forefathers, German chief rocket engineer Werner Von Braun, and Russian lead designer Sergei Korolev were able to design the first generation of rockets. This early history of rocketry illustrates a phenomenon that can be observed throughout the history of scientific and technological developments: discoveries and inventions are often shared by people working independently around the world to achieve ambitious breakthroughs.

The information about scientific discoveries tends to be transmitted quickly, encouraging both subsequent collaboration and further innovations. As discoveries lead to the successful development of new technology, even the efforts to classify and control the export of some inventions does not interfere with the parallel independent development of similar end products. In fact, the successful demonstration of new capabilities such as rockets in the 20th Century, by a nation greatly reduces the risk of failure in other nations on continuing R&D funding towards competitive and complementary capabilities.

President John F. Kennedy, although not particularly interested in space exploration, was further embarrassed by the political damage of the Bay of Pigs fiasco in 1960.[11] In 1961 at a famous speech at Rice University, he announced a program to put a man on the Moon by the end of that decade and signaled to the rest of the world that the United States was determined to show it was the world’s leader in science and engineering.

Politically, the time was perfect to project the United States as a technological leader and to deflect the technological and other international embarrassments of the prior years. Coupled with this was the desire of NASA and the scientific and engineering community to land on the Moon. Programs designed to do that had been rejected by prior Administrations, but officials in the government were fully aware that accomplishing that was considered possible by the technical community.

The third element was financial. The Kennedy Administration faced a relatively small and declining budget deficit that coupled with a tax cut that stimulated economic growth in the nation helped support the large budget commitment to the Apollo program.

Given the unusual juncture of the political, technological and financial factors in the early 1960s, the United States was able to make the commitment to the Apollo program. As described below, after successfully putting men on the Moon, the support for a continued large space program began to erode. The “shine” wore off; the nation internally became

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[11] John Logsdon. "The Penguin Book of Outer Space Exploration," 2018

engrossed in major political divisions over the Viet Nam War, and the budget deficit grew rapidly since there was also no political will to impose a tax increase. There were also unsuccessful attempts to break-up NASA and transfer its research efforts to various other agencies.

### C. Changes and Challenges: 1970 to 2000

Still locked into Cold War politics, the Nixon Administration was able to reach an agreement with the Soviet Leadership under the Strategic Arms Limitation Talks, signing the Anti-Ballistic Missile (ABM) Treaty in 1972. The ABM treaty included formal prohibitions on interference with national technical means of verification (NTM) that include reconnaissance satellites capable of both observing the Soviet Union's militarization efforts and of verifying the treaty obligations.[12]

At the same time, the expenses of the moon landings coupled with the fact that the political reasons for the Apollo program had been successfully met, led to the cancellation of the program. Apollo 17 was the last time humans were to step foot on the moon. Only now, 60 years later is NASA moving towards going back; this time with different technical objectives but also stimulated by somewhat similar competitive pressures from Chinese space programs.

NASA's budget in 1975 was cut to its lowest level ever and the post-Apollo era of space exploration was shaped by a redirection of federal funding away from large-scale human exploration programs and a new wave of technological innovations, centered around cost reduction and reliability.

In addition, NASA was commissioned to design and fly the Space Shuttle, a new vehicle that could be reusable and provide human and robotic access to space. President Nixon approved the shuttle project for a series of reasons: firstly, for continuing the human spaceflight program as a symbol of U.S. space leadership, secondly for its national security uses, thirdly for political goals (job creation in Southern California and elsewhere), and lastly for the shuttle's promise of routine flights and lower costs in the long-run.

On an international scale, during the late 1960s and 1970s, a number of additional nations also developed space capabilities. The European Space Research Organization merged with the European Launch Development Organization to create the European Space Agency (ESA) in 1975. During the mid-1970s, Canada also started cooperating with the U.S. space program, notably for the development of the robotic arm Canadarm. By the 1980s many nations had developed telecommunications satellites and most nations were actively involved with Intelsat, an international, intergovernmental organization developing worldwide use of space telecommunications.

The Reagan administration promoted international space cooperation, through efforts after 1984 to reestablish space cooperation with the Soviet Union. "By demonstrating U.S. leadership through space cooperation, the space program remained an important instrument of U.S. foreign policy.[13] These cooperation efforts culminated with the 1993

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[12] James Clay Moltz. "Crowded Orbits: Conflict and Cooperation in Space." New York: Columbia University Press, 2014, p. 47

[13] Ibid., p. 388

agreement for the U.S.-European-Japan-Canadian program Space Station Freedom to include the Russian space station program and laying the groundwork for the International Space Station (ISS).

The fall of the Iron Curtain coupled with the political and economic upheaval in Russia during the 1990s changed the balance of World power. The Cold War ended, the United States and Russia were able to develop a semblance of cooperation, and even in space endeavors there was more openness and sharing. Some of that was an effort to prevent the cash-strapped Russian Government from selling sensitive technology to nations such as Iran and North Korea and also to prevent the proliferation of nuclear weapons.

At the same time the United States successfully flew and operated the "reusable" Space Shuttle and continued to advance in space technology efforts including the development of a viable commercial space program mainly fueled by the growing telecommunications satellite services industry.

### D. The 21st century

The national security and civil government programs which dominated the early years of the space age is currently being augmented with new commercial space actors. Some of these companies are oriented toward providing services to government agencies since this is a relatively stable and large market for space products. But some are looking to consumer and business markets.

This has been made possible in part by recent technological developments and innovations that have decreased some of the barriers to entry into the space industry. For instance, small satellites for telecommunications and remote sensing are less expensive to build than the highly sophisticated and large satellites. And, even though the price to launch payloads on a per kilogram basis remains very expensive, the lighter weight small satellites do cost less to launch (although the total life cycle cost of a constellation of small satellites may approach the high cost of launching one large satellite.) Reusable launch systems may eventually bring down launch costs, but that will depend on a number of other factors.[14] A competitive commercial space sector is becoming an important component of all space activities, in both the United States and in other nations as well. Governments around the world are encouraging commercial space activities, and have policies aimed at attracting new funding to promote growth in this economic sector.

From the very beginning of the space age in the United States national security space systems have been of paramount importance. By the mid to late 1990s, the United States defense establishment has developed and incorporated space systems into its functions to the point where those space assets become and still are integral components of military and security operations. The Global Positioning System (GPS) of satellites, for instance, is a U.S. DOD developed, owned, and operated position, navigation, and timing system. Many other space products such as remote sensing satellites also provide national security information services. The innovations, sometimes

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[14] James Clay Molts. "The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests," 2008, Stanford University Press

including classified technologies, have matured in many space systems to the point where they are stable, reliable, and operational.

Although R&D is funded and continues to provide upgrades and improvements in these systems, the functioning of many U.S. space systems is a mature technology. Other nations, similarly, have moved beyond the early stages of space exploration and are using very mature technologies.

The private sector has always built these systems for the U.S. Government. However, it was not until later in time, mainly during the first decade of the 21st Century, that companies and industries have begun to invest in and rely heavily on space systems in their day-to-day as well as long-term operations. Beginning with telecommunications services and expanding to other industries, the combination of information technology, remote sensing imagery, PNT (position, navigation, timing) data, and other space applications is matured into advanced industrial economies being dependent on the reliable operations of space systems.

This dependence on everyday activities of both citizens and business has been influenced by and partially responsible for the changing geopolitical structure of the 21st Century. It has also pushed space economic activity into being technology that is an integral part of an advanced industrial nation’s critical infrastructure.

Today, if the economic security of a nation is jeopardized by an interruption in space-based applications, it is just as important to that nation’s national security as would be interruptions in defense systems.

Coupled with this technology-driven dependence are innovations and advanced space technologies that permit many in-orbit activities that were not possible just a few years ago. Spacecraft that can maneuver easily, change orbits, approach other satellites, land on asteroids, the Moon, and other planets are now in production and operation. Current R&D and future innovations will only make them more capable. And, like all space activities, these are dual-use (government and commercial) products and can be used for either peaceful or aggressive purposes.

There is an important caveat to the focus on private sector investment and innovation in space technologies. Historically, the government investments in space have been what economists would label “supply push.” That is, the technical ability and funds to support the R&D for a public sector mission are driven mainly by non-market (i.e. cost/price) considerations. Private sector investments are largely, by definition, “demand pull” meaning that a price-signaling market exists for the product.

Currently, very few of the successful “new space” companies operate in a true price-driven market. Without government needs and sales to government(s), many of these companies would not exist. SpaceX, for example, had its initial infusion of substantial funding through NASA’s Commercial Orbital Transportation Services program in the early 2000s that provided hundreds of millions of dollars for a new launch vehicle to resupply the International Space Station (ISS). The initial funding was unique in that it was not a traditional grant or R&D contract, but rather was a Space Act Agreement[15]

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[15] A Space Act Agreement (often called in other U.S. agencies, an OTA (Other Transactions Agreement) is one that can be negotiated outside of the formal Federal Acquisition Regulations

where payment was based on achieving technological milestones. Also, SpaceX has been successful in winning more traditional very large and long-term government contracts from both NASA and DOD for launch services. They have many private customers as well, but without the government business, it is questionable whether there is enough launch business domestically and worldwide to support the company's products.

Similar stories exist for other companies. For example, companies developing techniques for monitoring satellite operations and improving conjunction analysis for accident avoidance purposes in space have received significant private venture capital and other funds. The U.S. Department of Commerce is actively working with those companies on this and both government agencies and private users of space such as telecommunications companies are future markets for their products and services. These companies openly admit that, at least for now, government contracts and investments are key to their existence and potential profitability.

Other examples of new space companies vying for selling innovative services to governments include Planet (with a constellation of small remote sensing satellites), Horizon360 (a satellite system providing maritime domain awareness information), and a host of newly formed companies developing SAR (synthetic aperture radar) systems.

Private companies in the United States have always been integral to space exploration. From the very beginning of NASA in 1958 about 80% of NASA's funding has been spent on contracts with industry. What has changed and greatly stimulated new space ventures over the past decade is a change in government policy from contracting on a cost-plus[16] basis for R&D to contracting for the purchase of finished goods and services built, not to government specifications, but to performance criteria. This also reflects the maturity of the space sector and the proven ability of private business to build on the past and successfully continue to innovate. The future is one of more private initiatives along with a maturing market with a growing non-government price competitive base.

With many nations now having the ability to access and use space, no longer is the 1960s type of space competition between two superpowers the appropriate geopolitical model to use in thinking about the future of space. Outer space is a unique and very risky environment and is not perfectly analogous to prior new industrial and infrastructure developments such as building canals, railroads, and highways. But it is becoming a location that will host all types of new activity and in the process become more valuable to human terrestrial life.

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(FAR). Historically, NASA has used this authority for joint industry research efforts that were non-monetary whereby a company could use a NASA research facility without charge, but NASA would share in the research information obtained by the company. The COTS program, as mentioned in the text, provided funds payable upon successful completion of specific development milestones. The much larger and more standard contracts SpaceX was awarded later for actual launch services were negotiated under the FAR rules.

[16] A cost-plus contract is one where a company receives from the government its actual costs of R&D and a pre-defined profit percentage. The shift to fixed price contracts also shifts any cost overruns to the contractor which is the most common type of contract in the private sector and reflects the confidence that a contractor can complete the contract on time and within the agreed cost.

How outer space will be managed, how nations will use space, and whether parts of space will be sustainable for economic activity in the future is still unknown. What we do know and can predict with reasonable certainty is that innovation will advance, technologies will become more sophisticated, and nations on Earth will value outer space more than in the past. The geopolitical changes and relationships among nations on Earth will inevitably be reflected in activities in outer space, whether for economic purposes or for other purposes. And the speed and sophistication of space technology development will be of utmost importance to nations as well as to commercial interests.

## III. Case studies: Examples of How Space Exploration Technological Goals Were Accomplished

The three primary case studies in space innovation that will be discussed in this report represent key elements in two categories of space endeavors. The first category is getting to space and the second is operating assets in space.

Accessing space involves the development, manufacturing and launching of vehicles and payloads into space. These vehicles are very complex, combining many different elements of chemistry, materials and electronics. This report will analyze major technological goals that are essential to space exploration. Supporting all of these innovations and moving them from ideas to successful integrated outcomes were the underlying systems organizing and managing these very complex space missions.

We have selected three specific case studies to illustrate the innovative process that was, and is continuing, to evolve and produce successful solutions to accessing space and operating in outer space.

They are:

- Energy, particularly energy storage improvements in battery technology, and the use of nuclear energy for long-term power as well as power deep into outer space beyond the capability of using photovoltaic sunlight;
- 2) Advances in electronics for space uses that have ranged from the progression of vacuum tubes to transistors to integrated circuits to microchips. Coincident and subsequent with that are software innovations mainly designed to solve specific space challenges as well as specific uses of artificial intelligence.
- 3) Lightweight materials as exemplified by the development and improvements in the manufacturing and use of carbon fiber composites,

All of the cases involve reducing both weight and volume in space launch and space operating equipment. This may seem contradictory since over time both the capability of launching larger, heavier, and more technically complex equipment to space is a very obvious technological improvement. Space assets such as the International Space Station (ISS), very large telecommunications satellites placed in geosynchronous orbits, and the large launch vehicles needed to place these objects in space are readily available and used.

The technological push to launch heavier and larger payload has also been the stimulus to make as many as components as possible lighter in weight and smaller. Quite clearly, the smaller, lighter and stronger the materials are, the more room there is for useful equipment, instruments, and other elements that need to be launched. Most of the weight of a launch vehicle is fuel, not payload. Therefore, weight-saving efforts have been paramount in space R&D from the very early days of the space age.

All three case studies emphasize this overlapping goal in different applications: photovoltaics and nuclear power; digitalization and automation; and lightweight structural materials.

Additionally these components need to be robust, stable and able to withstand high pressure and wide temperature changes. The ability to reduce the weight of components is one critical goal in designing these systems and is characterized by many innovations ranging from the miniaturization of electronic components to the development of new forms of materials that are very light and very strong.

The harsh environment of outer space also entails innovations in other areas such as the need for continuous energy to power spacecraft, protection from radiation and solar storms, and for human space flight, medical innovations to monitor the health and safety of astronauts.

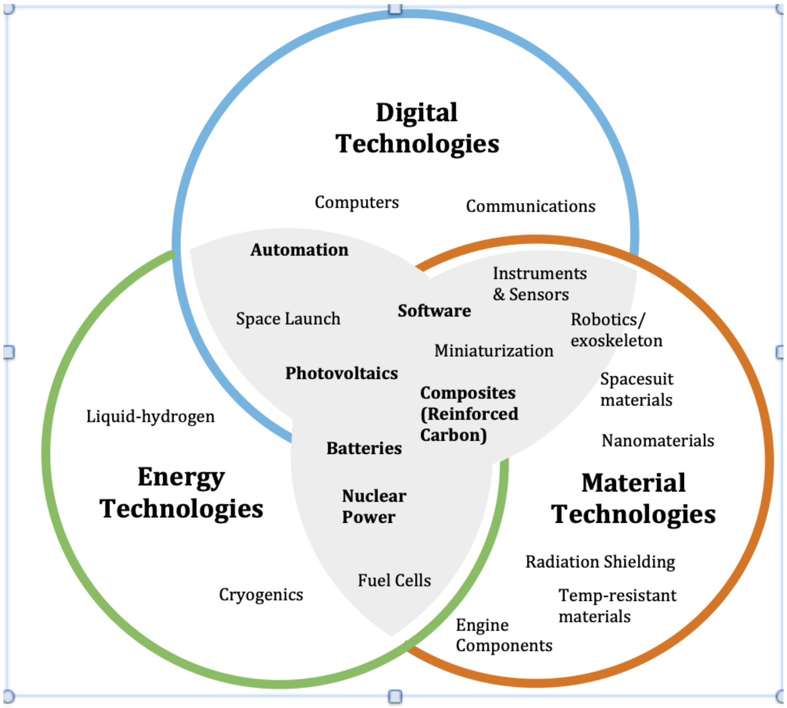
It is also important to note that all of these technologies were products of a number of on-going government, industrial, and commercial investments in research and development. Many were not invented specifically for use in space and many pre-date the space era.

However, the critical needs of space exploration, as described above, necessitated:

- The speed-up of further developing the technology as well as unique modifications for specific space-related uses of these inventions and innovations,
- The modification and improvements of existing products, and
- The integration of these products and capabilities for use in space endeavors.

Thus, the discussion below emphasizes the convergence and weaving of interrelated technologies/innovations for each of the identified challenges (getting into space and dealing with the challenges of space). The specific case studies help illustrate the details of innovation and how those innovations helped break through previous barriers. And, as Figure 3 below illustrates, almost all industrial categories of innovations overlap and contribute to solutions in virtually all of technological challenges space exploration entails.

Figure 2: The Overlap of Technical Challenges and Industrial Sectors



This figure also illustrates how difficult it is to separate and classify technical innovation in the complex space sector.

Inventions can be specific to industrial categories, academic disciplines, or even companies.

Innovations, as the term is used in this report, are more general and discussed as associated with larger sectors of economic activities.

For space purposes, this report broadens the categorization to R&D aimed at solving specific problems that Agencies need to overcome in accessing space and in sustaining activity in outer space.

Accomplishing extraordinary space missions requires reliable, consistent, and safe energy sources. The innovations behind the development of energy sources for space are often not recognized or publicized. Energy-related innovations are a key factor in making so many other previously impossible space endeavors possible especially in deep space exploration, human space flight, and space-based terrestrial services. Innovations in three sets of space energy-related technologies: photovoltaics, nuclear energy, and batteries are described below.

## A. Photovoltaics

Photovoltaic systems are often the most commonly recognized parts of a spacecraft’s energy system since they are very large. Although solar panels may visually look identical to the versions seen from the early days of the space age, there lies a deep history of innovation that iteratively improved photovoltaic technology. These incremental advancements are directly linked to space-related R&D for meeting space mission requirement. As single-junction silicone solar cell improvements relatively stalled at approximately 20% efficiency in the 1980s, a small research cohort at the National Renewable Energy Lab (NREL) was focused on

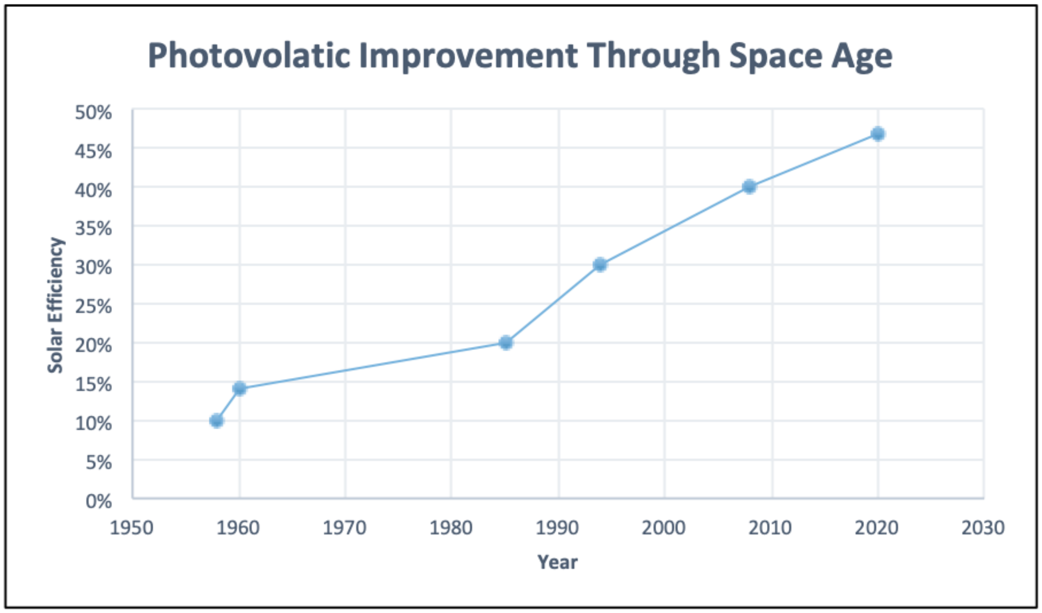


Figure 4: Progress of photovoltaic development. Note that this data represents efficiency achieved under ideal lab conditions. Practical state-of-the-art solar efficiency employed in space is approximately 30%. (Credit: DoE)

“tandem-junction” solar cell design that would prove to be the foundational innovation for current state-of-the-art multi-junction (MJ) solar cell designs.[17] The innovation of the MJ solar cells have improved efficiency levels to 25-35% and are the favored photovoltaic technology of modern spacecraft designers.[18] The design and materials of modern MJ solar arrays enables them to focus and intensify sunlight absorption from multiple wavelengths and are more resilient against space radiation.[19] The technology continues to iteratively innovate as demonstrated by the recent world record for efficiency achieved in 2020 with a six-junction solar cell set that achieved 47.1% efficiency.[20]

Two themes associated with the innovation of MJ solar cells are important to recognize: first, the research was widely considered futile, even by those within the research community; second, despite this, it was still supported and funded by the Department of Energy (DoE).[21] Irrespective of the low-probability of success, government funding for the basic research was available in the absence of commercial investment unwilling to take the risk on projects without near-term financial returns.

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[17] “NREL Scientists Spurred the Success of Multijunction Solar Cells” (National Renewable Energy Labs, September 2012), https://www.nrel.gov/docs/fy12osti/53604.pdf.

[18] “State-of-the-Art: Small Spacecraft Technology” (Moffett Field, CA: NASA Ames Research Center, October 2020), 25.

[19] Rahul Rao, “High-Efficiency Solar Cells Power Satellites—Can They Come Down to Earth?,” *IEEE Spectrum*, May 11, 2021, https://spectrum.ieee.org/energywise/green-tech/solar/high-efficiency-solar-cells-power-satellites.

[20] “News Release: NREL Six-Junction Solar Cell Sets Two World Records for Efficiency,” *National Renewable Energy Labs*, April 13, 2020, https://www.nrel.gov/news/press/2020/nrel-six-junction-solar-cell-sets-two-world-records-for-efficiency.html.

[21] “NREL Scientists Spurred the Success of Multijunction Solar Cells.”

Despite their ubiquity, the operational use of photovoltaic systems during space missions have revealed limitations that should be noted. First, photovoltaic systems can only generate energy to electrical systems with exposure to light. In other words, photovoltaic systems in Earth’s orbit or on the Moon do not generate energy when in the shadow of the Earth. Second, less light availability or intensity means less energy. Thus, as systems are further away from the Sun, they generate less energy, or in the case of Mars rovers, accumulated dust can severely impact space missions.[22] As a result, photovoltaic systems on Mars’ surface rely on random windstorms or “cleaning events” to clean off the layers of idle dust.

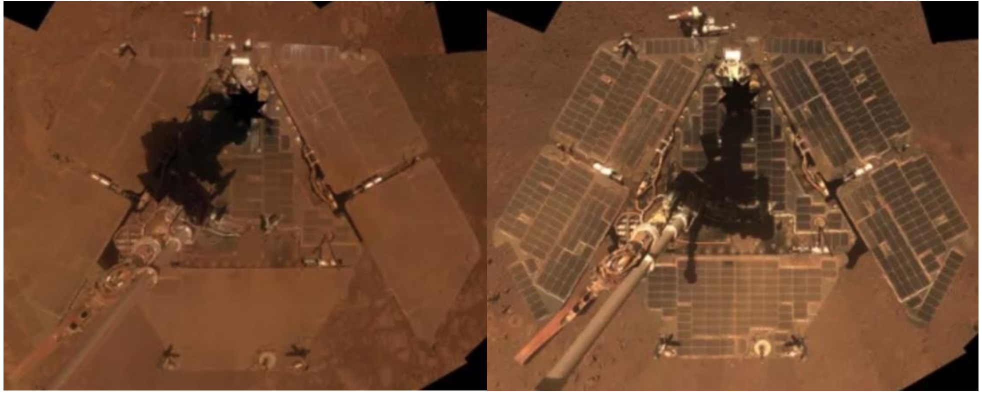

Figure 5: Self-portraits of NASA's Mars Exploration Rover Opportunity before (January 2014) and after (March 2014) a major “cleaning event” (Credit: NASA)

While photovoltaics will have a critical role in meeting the energy requirements of bold and previously impossible space endeavors, it is not the only energy-related technology that enables such feats. Exploiting the renewable energy resource of light from the sun is highly advantageous for space missions, but another proven technology used in lieu of, or in combination with photovoltaics, is nuclear energy.

**Space Nuclear Power**

Nuclear power for the purposes of meeting energy requirements in space has been pursued since the 1950s. The long history of performance, reliability, and safety enhancements laid a secure foundation for future uses of nuclear power.[23] However, despite the potential for exponential efficiency improvements over other energy sources, only a limited set of nuclear energy technologies have been thoroughly exploited.

Small-scale nuclear power reactors and nuclear propulsion systems illustrate their great potential but are very costly. Given the space industry’s tendency to prioritize near-Earth programs, other energy sources such as photovoltaics have proven acceptable over risking large investments into R&D for nuclear power sources. For example, despite the success of the Systems for Nuclear, Auxiliary Power-10A (SNAP-10A) in demonstrating

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[22] Ian O’Neill, “Opportunity: The Amazing Self-Cleaning Mars Rover,” *Space*, April 2014, https://www.space.com/25577-mars-rover-opportunity-solar-panels-clean.html.

[23] Gary L. Bennet, “First Flights: Nuclear Power to Advance Space Exploration” (International Air & Space Symposium and Exposition, Dayton, Ohio: American Institute of Aeronautics and Astronautics, 2003), 9–10.

the ability to remotely and safely operate a nuclear reactor in space in 1965, the necessity for such expensive technology proved difficult to continue funding.[24] Combined with the height of the Apollo program, NASA budget reductions, and the retraction of space programs inward towards Low-Earth Orbit (LEO), the program slowly gave way to other funding priorities.

Budget support for nuclear power was scarce throughout the space age. Project Rover and its Nuclear Engine for Rocket Vehicle Applications (NERVA) demonstrated a proof of concept for nuclear thermal propulsion technology in 1973.[25] After spending approximately $1.4 billion ($8 billion today) the program was terminated.[26] A follow-on program called the Space Nuclear Thermal Propulsion (SNTP) began a little over a decade later, only to be eventually terminated in 1994 after expending approximately $200 million ($350 million today) due to changing national priorities, changing security requirements, and domestic economic pressures.[27]

Shortly after, when the United States attempted to test Russia's latest Thermionic Operating Reactors Active Zone (TOPAZ) nuclear reactor it had bought after the fall of the Soviet Union, the research efforts were cancelled in 1997 after costs exceeded $100 million.[28] More recently, the Jupiter Icy Moons Orbiter (JIMO)/Prometheus, a joint NASA and DoE nuclear electric propulsion (NEP) program, was terminated in 2005 despite several technological advancements after NASA, "reevaluated its budgetary priorities."[29] Subsequent intermittent funding has severely hindered any advancement in NEP technology readiness level since 2005.[30]

However, Radioisotope Power Systems (RPS) are an exception, with hundreds of space applications since 1961.[31] The United States, Russia, China, and the European Space Union have all continued to innovative RPS technologies by improving the design and materials that have led to greater efficiencies and increased safety measures.[32]

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[24] Bennet, "First Flights: Nuclear Power to Advance Space Exploration," 9.

[25] Ibid., 18.

[26] R.A. Haslett, "Space Nuclear Thermal Propulsion Program Final Report" (Bethpage, NY: Grumman Aerospace Corporation, May 1995), 3–7, https://apps.dtic.mil/dtic/tr/fulltext/u2/a305996.pdf.

[27] Ibid., 1–1.

Eljay B. Bowron, "TOPAZ II Space Nuclear Power Program - Management, Funding, and Contracting Problems" (Government Accountability Office, December 1, 1997), 2, https://www.gao.gov/assets/osi-98-3r.pdf.[28] {Citation}

[29] National Academies of Sciences, Engineering, and Medicine, "Space Nuclear Propulsion for Human Mars Exploration" (Washington, DC: The National Academies Press, 2021), 38, https://www.nap.edu/catalog/25977/space-nuclear-propulsion-for-human-mars-exploration.

[30] Ibid., 63.

[31] Gary L. Bennett, "Radioisotope Power: Historical Review," *Earth Systems and Environmental Sciences*, January 2021. Specifically, the United States has flown 42 RTGs.

[32] Robert L. Cataldo and Gary L. Bennet, "U.S. Space Radioisotope Power Systems and Applications: Past, Present, and Future" (NASA Glenn Research Center, July 2012), 4–20.

## B. Digital Processing

### *1. Computers*

Borrowing from the legacy of aeronautical technologies, space systems gradually employed computerized systems to assist with various tasks such as navigation and guidance. Developed first for the U.S. Air Force for fighter jet planes, these systems were also extremely important in space exploration.

The key difference between the two applications was the different roles humans had in spacecraft as compared to piloting airplanes. Project "Apollo exemplified broad changes in human-machine relationships", even though it did not directly cause these changes.[33] In the decades following the Apollo program, NASA engineering practices were changed by the emergence of computer-based engineering capabilities.[34] At the same time, the new systems were becoming "increasingly complex, difficult to test, and designed to operate at an increasingly high-performance envelope."[35] While computers opened up new possibilities for human spaceflight technologies, they also forced aerospace engineers to quickly adapt to new challenges in the post-Apollo era. Today, Artificial Intelligence is promising a new wave of innovations in space exploration technologies and management, currently exemplified by NASA's Mars 2020 mission.

The very high costs of accessing space underscored the need for smaller and lighter components of technology systems onboard spacecraft. Integrated circuits, commonly known as microchips, are circuits in which all the electronic components are assembled on the surface of a thin semiconductor material, such as silicone.[36] Integrated circuits have been particularly attractive for spacecraft, mainly because they tend to be notably smaller than traditional electrical circuits, consume less power, increase operational speed, and even promise reduced costs per electronic function.[37] However, the same characteristics were advantageous for innovations in aircraft and missile technologies, which preceded space systems. By the time NASA sought to integrate microchips into their Apollo spacecraft, the U.S. Department of Defense had been driving the demand for integrated circuits production. Even though the U.S. Air Force was interested in microchips, the computer industry was not yet interested in the disruptive technology.[38] Decades after their invention, integrated circuits proved to be a technology with a wide

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[33] David A. Mindell. "Digital Apollo: Human and Machine in Spaceflight (Cambridge, MA: MIT Press, 2008)", hereafter "Digital Apollo"

[34] Steven J. Dick, Roger D. Launius. "Critical Issues in the History of Spaceflight" 2006, National Aeronautics and Space Administration Office of External Relations History Division, Washington, DC, NASA SP-2006-4702, hereafter "Critical Issues in the History of Spaceflight"

[35] Ibid.

[36] "Patent Expert Issues: Layout Designs (Topographies) of Integrated Circuits," https://www.wipo.int/patents/en/topics/integrated_circuits.html

[37] Mathematica, INC. "QUANTIFYING THE BENEFITS TO THE NATIONAL ECONOMY FROM SECONDARY APPLICATIONS OF NASA TECHNOLOGY -EXECUTIVE SUMMARY", 1976, Prepared by MATHEMATIC, INC., Princeton, N.J. 08540, for *NASA Headquarters*, hereafter "MATHEMATICA"

[38] "Three Takeaways from Computer Chip Patent Wars", 2016, *Beem* patent law, https://beemlaw.com/three-takeaways-from-computer-chip-patent-wars/

array of applications in virtually all electronic products, from the Apollo guidance computer to today’s smartphone.[39]

Due to the distance to the lunar surface and the constant but limited speed of light, NASA was compelled to produce an increased level of autonomy for the Apollo missions. Engineers were concerned with solving the navigation, guidance, and flight control problems that could arise given the distance and time delay (latency) in communications with the new spacecraft.[40] To respond to these challenges, the microelectronic computer was the best technological solution. The decision to use silicone microchips was a bold one at the time since the technology had not been yet widely tested.[41] The partnering of NASA with MIT proved useful as both groups of engineers learned to employ the latest principles of software engineering in real-time applications.[42]

As one author suggested: "consider[ing] interconnections, reliability, ruggedness, and documentation, the Apollo guidance computer is at least as impressive for its time as the current desktop computers are today. And the Apollo software was an equally intricate ballet of many people’s work and ideas."[43] Apollo engineers opted for a system that would perform only one task at a time. This design had the advantage of ensuring that the entire computing power would be used to run the most important program at a critical time, without diverting resources to operations that could be performed at later stages of the landing process or that were optional.[44] The AGC had to be resilient enough to withstand failure. Unlike bugs, systemic software failures could not be successfully predicted or completely avoided by design. MIT's solution to keeping the AGC running and functional was to ensure the computer was capable of restarting in case of software failure.[45] This was accomplished through a unit-logic device that was composed of three analog circuit computers instead of one. Thus, if one computer would fail, the other two would 'outvote' the dissonant one, and the system would restart it.[46] Luckily, no AGC ever experienced a hardware failure during a mission. But the computer's robustness saved at least two missions from probable abort.[47]

The Apollo program was the most ambitious US space effort, both in terms of the costs and the challenges that needed to be overcome. The cost of the AGC was upwards of $10 million (inflation adjusted over $60 million today).[48] It successfully assisted the astronauts in landing on the lunar surface. The AGC involved multiple technological innovations of its time, including microchips, and was not welcomed by all NASA engineers and astronauts due to its disruptive nature. It was only now that we can look back to the legacy of the Apollo computer and its impact on future computers onboard spacecraft, as well as in the consumer market.

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[39] "MATHEMATICA"

[40] "Computers in Spaceflight: The NASA Experience", Chapter Two "Computers on Board The Apollo Spacecraft"

[41] "Computers in Spaceflight: The NASA Experience", Chapter Two, "MIT chose a hardware and software contractor"

[42] Ibid.

[43] "Digital Apollo"

[44] Ibid.

[45] "Computers in Spaceflight: The NASA Experience", Chapter Two "The Apollo guidance computer: Software"

[46] Paul Ceruzzi. "Apollo Guidance Computer and the First Silicon Chips," 2015, Smithsonian National Air and Space Museum, https://airandspace.si.edu/stories/editorial/apollo-guidance-computer-and-first-silicon-chips

[47] "NASA SPACEFLIGHT"

[48] "Computers in Spaceflight: The NASA Experience", Chapter Two "Evolution of the hardware: Old technology versus new block I and Block I designs"

The legacy of the Apollo program extends beyond national pride and projected technological superiority. NASA and MIT Instrumentation Lab's efforts to digitize aerospace systems led to an in-house technology transfer and the invention of the fly-by-wire system. The Digital Fly-by-Wire (DFBW) is a system composed of multiple computers that instantly analyze a pilot's control inputs and mediates their transmission to the flight control elements. The computers analyze the controls against variables such as the aircraft's speed, weight, and even atmospheric conditions, to produce optimized control signals.[49] The DFBW systems increased safety, reduced the aircraft's weight, and even increased maneuverability.[50]

The DFBW technology circled back from the F-8 plane into the Space Shuttle prototype Enterprise in 1976, as part of the flight control system (FCS) computer for the orbiter.[51] The FCS was comprised of four computers for guidance, navigation, and control algorithms for the entire flight. The complex system performed multiple functions, including flying the Shuttle "as a boost vehicle, as a spacecraft, as a reentry vehicle, and as a conventional aircraft."[52] The FCS software was comprised of approximately 2 million lines of code, implemented incrementally over 15 years, and which was supported by the work of approximately 275 people.[53] Even though the Space Shuttle was retired by NASA in 2011, digital innovations in spacecraft continued to advance rapidly as private space companies are racing to build a commercial space infrastructure.

### 2. *Artificial Intelligence*

Artificial Intelligence is currently a technology that promises to revolutionize virtually any digital economic sector. AI can be broadly described as the varied multitude of algorithms capable of accomplishing tasks that traditionally required human intelligence to complete. As an example, Airbus has been using AI to identify patterns in production problems for new systems, reducing the time required to address disruptions.[54] But similar systems can also be fed visual geospatial data to determine optimal crop yields, or signal natural disasters, or discover new solar systems from Hubble telescope data.[55]

The Mars 2020 mission's Perseverance rover and Ingenuity helicopter both employ AI algorithms that chart the Martian surface in real-time for successful navigation around obstacles and geographical features. NASA developed AI to substitute for the decision-making of mission controllers on Earth since the amount of telecommunications latency

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[49] Gray Creech. "Digital Fly By Wire: Aircraft Flight Control Comes to Age," 2003, NASA Dryden Flight Research Center, https://www.nasa.gov/vision/earth/improvingflight/fly_by_wire.html

[50] Ibid.

[51] Gray Creech. "Digital Fly By Wire: Aircraft Flight Control Comes to Age," 2003, NASA Dryden Flight Research Center, https://www.nasa.gov/vision/earth/improvingflight/fly_by_wire.html

[52] Glenn M. Minott, John B. Peller, Kenneth J. Cox. "SPACE SHUTTLE DIGITAL FLIGHT CONTROL SYSTEM," N76-31146

[53] National Research Council. "Statistical Software Engineering," 1996, Washington, DC, The National Academies Press, https://doi.org/10.17226/5018

[54] OECD. "THE DIGITALISATION OF SCIENCE, TECHNOLOGY AND INNOVATION: KEY DEVELOPMENTS AND POLICIES," 2019, DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INNOVATION COMMITTEE FOR SCIENTIFIC AND TECHNOLOGICAL POLICY

[55] Lonnie Shekhtman. "Nasa NASA Takes a Cue From Silicon Valley to Hatch Artificial Intelligence Technologies", 2019, NASA's Goddard Space Flight Center, https://www.nasa.gov/feature/goddard/2019/nasa-takes-a-cue-from-silicon-valley-to-hatch-artificial-intelligence-technologies

between the Earth and Mars makes real time decisions for robotic missions impossible.[56] The previous Spirit and Opportunity Mars rovers were less autonomous, and more dependent on the commands of ground controllers and therefore could do less and incorporated a much higher level of failure risk.[57]

Successive inventions made computer processing faster, chips lighter in weight, and specialized integrated software. As a result, space systems became more capable of fulfilling their ambitious missions. However, as with other comprehensive technologies, developing new systems and modifying existing systems, involves many inventions and takes years to perfect and gain acceptance among the human engineers and astronauts. New systems are also very expensive, often requiring public funding in the R&D stage before becoming economically viable for commercial purposes.

### C. Materials: Carbon Fiber Composites

Unlike the development of energy and digital capabilities, the following discussion of carbon fiber composite materials focuses on a very narrow and specific technology. But like the other examples in this report, carbon fibers were a well know material (going back to the invention of the electric light bulb in the late 19th Century) with known properties of strength, conductivity and light-weight. [58]

The first uses of CF in aerospace structural applications came from R&D efforts at both the U.S. Department of Defense and the National Aeronautics and Space Administration (NASA) where the material's extraordinary mechanical properties were valuable enough to justify its high price. In 1974, filament-wound rocket motor cases were developed for the Department of Defense, and the next year NASA began to include CF parts in satellites where any weight savings would make a significant difference in the fuel required for a launch. The 1970s also saw CF used in composite secondary structures and control surfaces of military aircraft, and the first flight of the F/A-18 Hornet in 1978 was a breakthrough in significant use of CF composite primary structures.[59]

The R&D efforts at NASA were focused on the use of the material in aircraft, and over a period of 40 years the structural weight of composites in aircraft increased from 1% to 50%.[60]

In the challenge of designing and using spacecraft, one of the early applications of composites to launch vehicles was the cargo bay doors on the space shuttle. The doors are constructed of a graphite/epoxy material which reduces the weight by 23% over that of aluminum honeycomb sandwich. This is a reduction of approximately 900 lbs., which

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[56] John Bluck. " NASA Develops Robust Artificial Intelligence for Planetary Rovers," 2004, NASA Ames, https://www.nasa.gov/vision/universe/roboticexplorers/robust_artificial_intelligence_jb.html

[57] ibid.

[58] Tenney, Davis, Johnston, Pipes, and McGuire, Structural Framework for Flight I:NASA's Role in Development of Advanced Composite Materials For Aircraft and Space Structures, NASA/CR–2019-220267 Volume I.

[59] Ibid.

[60] Tenny, Davis, Johnston, Pipes, McGuire, Structural Framework for Flight I: NASA's Role in Development of Advanced Composite Materials For Aircraft and Space Structures, NASA Langley Research Center, Contract NNL09AA1Z, April 2019

brings the weight of the doors down to approximately 3,264 lbs. The composite doors can withstand 163-decibel acoustic noise and a temperature range of minus 170ºF to plus 135ºF.

**Space Shuttle Doors**

The doors are made up of subassemblies consisting of graphite/epoxy honeycomb sandwich panels, solid graphite/epoxy laminate frames, expansion joint frames, torque box, seal depressor, centerline beam intercostals, gussets, end fittings, and clips. There are also aluminum 2024 shear pins, titanium fittings, and Inconel 718 floating and shear hinges. The assembly is joined by mechanical fasteners. Lightning strike protection is provided by aluminum mesh wire bonded to the outer skin.

Today, there are many varieties of composite materials as well as different fabrics use for different purposes. The manufacturing techniques developed to make the various types of laminates and combinations of fibers, epoxies, and other inputs into the final composite structures has become so complex as an R&D effort itself, a full discussion of it is beyond this short case study.

But that complexity also highlights the extent of the R&D behind the use of this material and the recurrent theme in this report of the need to constantly innovate and solve very specific technological aerospace problems with specialized components. Since the demand for these specialized products is limited, the resulting costs are very high. Secondary uses at a commercial scale may then only become cost effective with an increase in demand for multiple applications.

Like any material, carbon fiber composites are not a perfect substitute for other structural metals. They are, as mentioned above, relatively expensive. The also don’t bend well and are quite brittle. Further, the manufacturing process is highly specialized and not one for inexperienced companies. In its early development there were instances of structural problems, sometimes as a result of mistakes in the bonding of joints in the laminate sections. To improve the manufacturing process, the U.S. Department of Energy established a Carbon Fiber Technology Facility as part of its Oak Ridge Laboratory in 2013 with the goal of reducing manufacturing costs and improving quality.

The DOE effort also illustrates the importance of spin-off efforts in new technologies. Wind turbine blades are now the largest use of carbon fiber composites, easily surpassing the significant, but comparatively small market for aerospace equipment.

The uses of carbon fiber composite material have expanded over time to many industrial applications, each integrating specific designs and materials to meet the needs of the individual users. And, most visible to the general pubic, are the incorporation of composites into consumer products ranging from fishing rods and tennis racquets to bicycle frames.

### D. Summary of Case Study Findings

What is important to note are the commonalities among all of the case studies with respect to innovation in space exploration. They can be summarized as follows:

- None of the major innovations were the result of a single invention or discovery.
- The improvements in each technology were incremental over a long period of time and involved significant up-front government R&D investments and a relatively long time frame.
- Government decision makers allowed researchers to undertake high risk/low probability of success projects.
- The high cost was, in each successful innovation, balanced and warranted by the specialized needs of space exploration, particularly in the reduction of weight and/or high performance.
- Each use involved meeting alterations and special designs to solve specific problems associated with the end use, in this case. NASA R&D in different aspects of aviation and/or space.
- The materials or end products all had many other uses in different industrial and commercial sectors, although the integration of uses for space was unique to NASA or other space missions. These improvements tended to be very expensive to produce; well beyond immediate commercial adaptation.
- It is also evident that there is a large amount of overlap in the development process. As mentioned above, for example, there are numerous examples of materials such as carbon fiber composites contributing also to the improvements in battery and energy technologies.
- Commercial and industrial uses often involved less expensive versions of the materials, software, and other components and most often followed successful government demonstration and use of the technology.
- All of the technologies, in spite of their advanced performance, also exhibited serious weaknesses and were/are not always perfect substitutes for other materials or uses.

A common factor in the above list highlights the different options available to government investments in R&D compared to those of a private, profit-oriented firm. The government, investing for the public good, can overcome the three major barriers to entry for a new technology that industry cannot:

1. *Extremely high cost,*
2. *Limited and specialized use, and*
3. *The "luxury" of often having a longer time frame for success.*

## IV. Looking to the Future

It is important to note that the cost behind the major innovations described above is often beyond the realm of what the private sector initiatives would invest in for commercial purposes.[61] The very large upfront R&D investments for these specialized purposes clearly required public investments as well as supporting massive efforts at integration, testing, and acceptance to successfully implement and demonstrate these technological innovations.

The story of space exploration and innovation to accomplish national goals has over time enabled private enterprise to build on the maturity of space flight and applications and to profit from both government and private demand for using space. Looking to the future, that will create a more mixed formula for innovation in space with companies building on the experiences of the past and able to fund additional innovation aimed at products they can profitably produce and sell. The role of government funding of large-scale exploration into deep space will be augmented by these new opportunities.

However, the basic technical problems of getting to space and exploring space remain the same as they were at the beginning of the space era: access, cost, and safety. Looking ahead, it is relatively safe to predict that future innovations in space technologies will continue to develop improvements toward the same technological goals and make space exploration more efficient while enabling sojourns deeper into space, longer-lasting, safer, and possibly even less expensive.

For example, one of the most recently successful and visible NASA challenges was developing the Ingenuity helicopter designed to fly in the very thin Martian atmosphere. This helicopter flew successfully for the first time in May of 2021. Clearly, to meet the extreme conditions of Mars it incorporated new adaptations of the technologies described in the case studies: advanced batteries, lightweight composites, and artificial intelligence.

> "To create the solar-powered Ingenuity, NASA engineers took advantage of recent advances in lithium batteries, cameras, microprocessors and computer software—and took into account the extreme conditions they knew the craft would encounter. The helicopter had to be featherweight yet sturdy enough to withstand the shake, rattle and roll of a rocket launch and the violent descent to the surface. It also had to be able to survive the extreme freeze and thaw cycles in deep space and on Mars."[62]

In recent years other new innovative space-related techniques developed by private companies have been successfully completed. Reusable launch vehicles or, more

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[61] Nelson, R.R., The Simple Economics of Basic Research, Journal of Political Economy ,Volume 67, Number 3, Jun., 1959

[62] Hotz, Lee, 'Tiny Copter Set for Giant Leap on Mars, Wall Street Journal, April 5, 2021.

accurately, recovering and reconditioning the expensive 1st stage of a launch vehicle not only offer the promise of cheaper flights, but also set the path toward systems that can land and take off autonomously from other celestial bodies. SpaceX was the first company to demonstrate and use this technology, and other companies are following their lead.

This and similar advances signal a new stage in aerospace R&D and innovation. Although this was not done directly with government funding, there is no doubt that government launch contracts are crucial to SpaceX. The company has not publically disclosed the actual cost of developing this new capability, nor has it revealed the costs of refurbishing a recovered 1st stage. Thus one can only speculate on the possible cost savings, keeping in mind that the price a company charges for a launch may not be a reliable measure of the actual costs of manufacturing and launching.

Yet another recent innovation is the successful use of a privately developed spacecraft to service a satellite that was low on fuel. This capability, called the Mission Extension Vehicle (MEV), was developed by Northrup-Grumman and is being performed by and for commercial use. The technology development behind this innovation has been on-going for many years at NASA's Goddard Space Flight Center and stems from the need to repair the Hubble Telescope in 1993, almost 30 years ago. This type of rendezvous and proximity operation (RPO) in orbit is very difficult technologically, if for no other reason than all objects in orbit are travelling at very high speeds (up to 17,500 mph) and to safely and robotically connect two orbiting spacecraft is an extremely difficult operation.

As we go deeper into space and farther away from the Earth, it will become increasingly necessary for advanced computers and guidance systems to operate independently from commands from the Earth. Artificial intelligence, driven by small, lightweight and extremely powerful computers and digital techniques will be needed.

While there are many other obstacles to overcome with future space endeavors, continuous, long-term, reliable, and sufficient energy systems will be an unrelenting challenge. Despite the combination of innovative energy technologies in the Mars 2020 mission that have achieved a previously impossible endeavor, it, and many other space missions also highlight the daunting energy challenges that lie ahead for aspiring future space missions.

Another example is the R&D behind advances in safe nuclear propulsion engines for on-orbit operations such as satellite servicing, exploring and finding resources in space and on the Moon, Mars, or other celestial bodies such as asteroids.

Continued efficiency and productivity of these capabilities will be critical to enabling future space endeavors. Improved photovoltaics, nuclear energy, and battery technologies are all sure to play increased roles as they gain greater efficiencies.

Lithium-ion battery technology has improved significantly over the last few decades but advancements in efficiency appear to be slowing as the potential practical limit of 300 Wh/kg is reached.[63] There are certainly innovation gaps on improving the cycle life and longevity of lithium-ion batteries that are potential opportunities, but what battery and

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[63] Barde, "1989 - 2019: Three Decades of Power Systems Evolution Through the Prism of ESPC," 2.

electrochemistry technology will follow lithium-ion? It may not even be a “battery” in the traditional sense.

Underlying the innovations that we have realized in making space exploration possible, and those that we will develop in future space exploration, are several absolutes:

- First, it will be absolutely necessary for initial public investments in space exploration because, as with all prior innovations in these endeavors, developing new or advanced technologies is expensive and often entails a high degree of risk, particularly in the early stages of development. These barriers to entry are real and it is rare that a private company can overcome them without at the very least a working partnership with a sovereign entity.
- Second, space exploration is very complex undertaking and it is impossible without the ability to organize and combine many different elements over a relatively long time period. An organization, whether governmental or private, must have the necessary management skills and the necessary vision and support from politically driven budgets and from corporate funders to plan, manage, accept inevitable failures, and persevere to be successful.
- Third, there will need to be a market for space products and services. That market will be terrestrial and it will be realized by a combination of government purchases and business/consumer purchases.

The present is built on the past and the future is built on the present. This report has documented a selection of the types of innovations that created the space age as well as are advancing our capabilities and making spacecraft more efficient, productive, reliable, and useful today.

In addition to making space exploration possible and more efficient, innovative space technologies also have had a measurable economic benefit terrestrially. Besides enabling spin-off products and services that have become multi-billion dollar industries such as satellite television and radio broadcasts, space capabilities and applications are the backbone of increased efficiency and productivity. These effects are apparent but often hidden and not recognized by consumers and the general public.

Weather forecasts that are speedier and more accurate are one example. Rarely do people watching the evening news and weather think about the space infrastructure that goes into launching the satellites, taking measurements of the Earth, sending to ground stations and then translating them to forecasts. Or, even more significantly are the timing instruments on the GPS satellites. They provide the backbone coordination that enables cell phone operations, enables more efficient distribution of electric power and other utilities and the navigation information now common in automobiles.

This report has barely touched on these terrestrial innovations that are either space-based or dependent on space-based assets. But as difficult as it is to measure the embedded productivity effects of space capabilities and technologies, it should be noted that the innovations that have made space exploration possible also have, and will continue to, stimulate significant benefits and impacts on our lives here on Earth.

# V. Appendix

## A. Energy Technology Supplement

### *1. General*

This appendix fully details how the energy-related case studies on photovoltaics, nuclear energy, and batteries enabled and enhanced space exploration goals. First however, is a brief discussion of energy-related innovations in space launch which some readers may have thought were overlooked.

The basis of today's chemical space rockets is rooted in Konstantin Tsiolkovsky's "Exploration of Outer Space by Means of Rocket Devices" publication from 1903 and Robert H. Goddard's rocket apparatus patented in 1914. However, in the race to the Moon, one of the most innovations in rocket technology may have been the rapid design and construction of the powerful Saturn V rocket. The Saturn V rocket was a technical gamble because it, "went well beyond the existing rocket technology" of the time but resulted in one of the most amazing combinations of engineering and technology.[64] Three significant aspects of rocket technology were made possible by innovations early on: the use of liquid hydrogen fuel as an energy source, cryogenics, and engine components. The combination of these innovations culminated in the success of the Saturn V rocket that successfully launched humans to the Moon multiple times.

While liquid hydrogen proved as the most effective chemical propellant available (and still is today), it proved to be challenging and costly

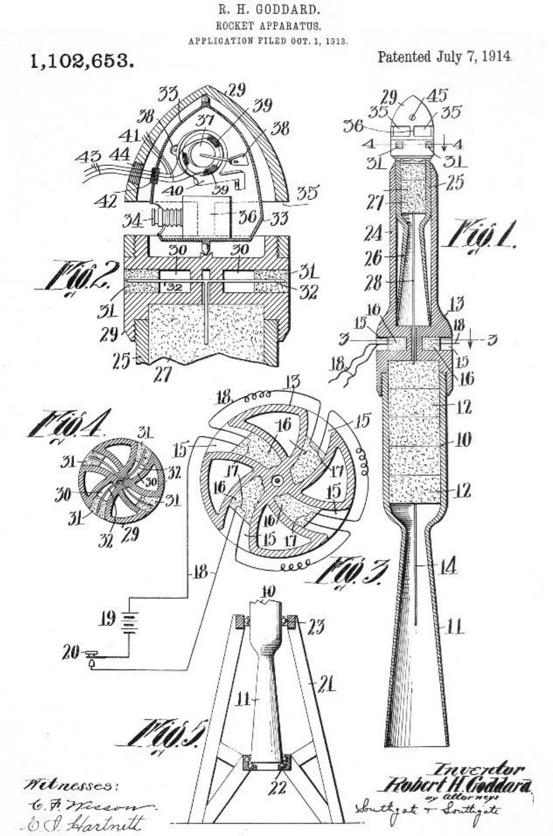

Figure 1: This drawing shows Robert Goddard's rocket apparatus, US Patent no. 1,102,653. Goddard's May 1926 rocket consisted of two tanks, one holding liquid oxygen, the other gasoline, feeding a rocket nozzle at the bottom—a configuration still used today (Credit: National Air and Space Museum)

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[64] Virginia P. Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA Scientific and Technical Information Division, 1991), 166.

to safely store and handle.[65] Subsequently, in support of the space effort, major breakthroughs in cryogenic technology resulted which improved the design and production of cryogenic rocket engines that could adequately utilize liquid hydrogen fuel.[66] As a result of the improved performance (and higher temperatures) of using liquid hydrogen, many of the engine components required upgrading as well. This led to a number of innovative advancements such as regenerative cooled tubular walls within the thrust chambers, improved fabrication of turbopumps within the F-1 engines, and several other improvements of lightweight components and material applications.[67]

Regrettably, there have been few innovative technological breakthroughs in space launch, like the Saturn V in rocketry, since the early years of the space age. There have been the reusability innovations achieved during the shuttle era and very recently with SpaceX's Falcon rockets, but neither of these have fundamentally improved or overcome the energy challenges of getting to space. As a result, an analysis of innovations in space launch reveals only a fraction of the energy-related inventions and innovations that have made so many other previously impossible space endeavors possible. Thus, the energy case studies explore how energy-related technologies and innovations enabled and enhanced the many successful space endeavors though the space age.

### *2. Photovoltaics*

Photovoltaics is simply the conversion of light into electricity to be used for energy. A photovoltaic module is also known as a solar panel or solar array that consists of solar cells. These are the most commonly recognized parts of a spacecraft's energy system

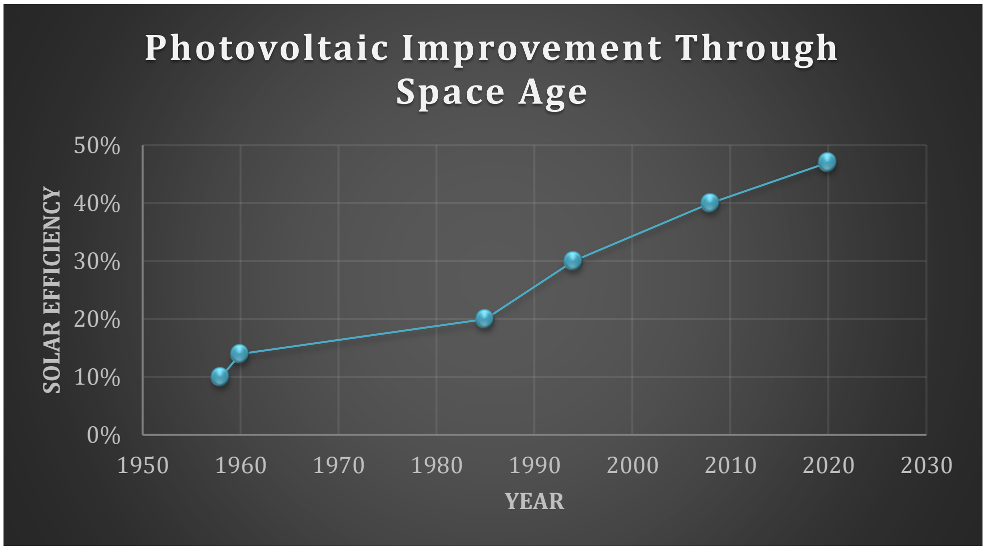

Figure 2: Progress of photovoltaic development. Note that this data represents efficiency achieved under ideal lab conditions. Practical state-of-the-art solar efficiency employed in space is approximately 30%. (Credit: DoE)

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[65] Ibid., 150–51, 162.
[66] Roger E. Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: NASA History Office, 1996), 89.
[67] Ibid., 91–94.

because they are so ubiquitously employed and so visible given their typically large surface areas. Given the Earth's relative proximity to the Sun as a constant light source, the utility of photovoltaics is unquestioned and has been an essential part of the space industry's energy requirements since its beginning. As such, there has been a history of innovation and incremental technological improvements in photovoltaics for space applications.

Initial space solar cells were single-junction and only achieved around 10% efficiency at the beginning of the space age in the late 1950s.[68] Then in the 1980s, silicone-based space solar cells achieved roughly 16-20% efficiency.[69] The innovation of multi-junction (MJ) solar cells favored by modern spacecraft designers have improved efficiency to levels between 20-30% as seen in Figure 3.[70] Over the course of several decades, the incremental advancements in photovoltaics is the result of an apparent slog, but has historically been predominantly stimulated by space requirements.

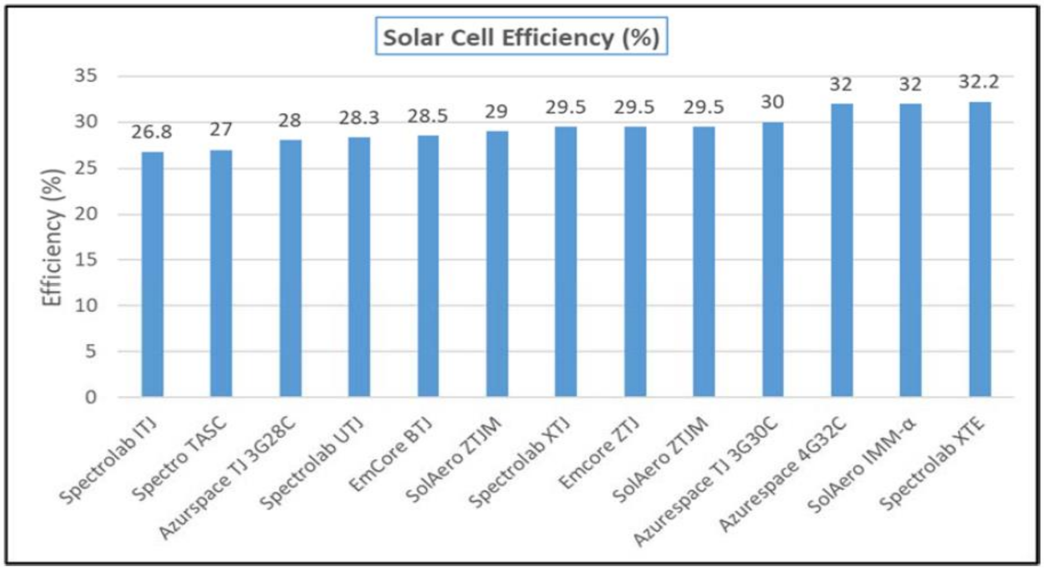

Figure 3: Current range of the state-of-the-art solar cell efficiency technology (Credit: NASA)

The innovation of complex multi-junction III-V (MJ) solar cells has led to recent efficiency gains that were previously unprecedented. As single-junction silicone solar cell improvement relatively stalled at approximately 20% efficiency in the 1980s, research at the National Renewable Energy Lab (NREL) was focused on "tandem-junction" solar cell design that would prove to be the foundational innovation for current MJ solar cell

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[68] Henri Barde, "1989 - 2019: Three Decades of Power Systems Evolution Through the Prism of ESPC" (European Space Power Conference, France: European Space Agency, 2019), 2.
[69] "Best Research-Cell Efficiency Chart," *National Renewable Energy Labs*, August 2019, https://www.nrel.gov/pv/cell-efficiency.html.
[70] "State-of-the-Art: Small Spacecraft Technology" (Moffett Field, CA: NASA Ames Research Center, October 2020), 25.

designs.[71] Jerry Olson, the NREL researcher initially only achieved 10% efficiency, but realized the potential for improvement and submitted a patent for "tandem-junction" MJ solar cells in 1984.[72] After the patent was awarded in 1987, the tandem-junction solar cell achieved 22% efficiency in 1988 followed by 30% in 1996.[73] Following that, MJ solar cell improvements and designs began to proliferate across the space industry and now serve as the foundation for state-of-the-art photovoltaics. Generally, multi-junction solar cells are designed with multiple materials that absorb energy from different wavelengths; they are built with multiple mirrors or lenses to focus and intensify the sunlight absorption; designed to be more lightweight than silicone designs; and are more resilient against space radiation.[74] The current world record for efficiency was set in 2020 with a six-junction solar cell set that achieved 47.1% efficiency.[75]

MJ solar cells have dominated the space industry since the 1990s.[76] However, despite their ubiquitous employment across most space endeavors, recent decades have revealed some inherent limitations as discussed in the case study. First, photovoltaic systems in general can only generate energy to electrical systems with exposure to light. Second, tied to the first issue is the limitation that less light availability means less energy. In other words, photovoltaic systems in Earth's orbit or on the Moon do not generate energy when in the shadow of the Earth. However, generally speaking, this is only temporary and often times short in duration. Yet, on Mars, photovoltaic systems are further away from the Sun, so they generate less energy relative to systems closer to Earth, but a biggest challenge is Mars' dust. The MJ solar cells on the photovoltaic systems on the Mars Spirit and Opportunity Rovers experienced power level issues throughout their operations with dust covering their solar panels.[77] As a result, photovoltaic systems on Mars' surface rely on random windstorms or "cleaning events" to clean off the layers of idle dust (reference Figure 4). More recently in 2021, the Mars Lander, Insight, had to go into hibernation after just two years of operation because the Martian dust had covered the solar panels so densely that its solar panels were producing just 27% of their energy capacity.[78]

While photovoltaics is sure to continue playing a critical role in meeting the energy requirements of bold and previously impossible space endeavors, it is not the only

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[71] "NREL Scientists Spurred the Success of Multijunction Solar Cells" (National Renewable Energy Labs, September 2012), https://www.nrel.gov/docs/fy12osti/53604.pdf.

[72] Jerry M. Olson, Current and Lattice Matched Tandem Solar Cell, United States Patent Office 4667059 (Washington D.C., filed October 22, 1985, and issued May 19, 1987).

[73] "NREL Scientists Spurred the Success of Multijunction Solar Cells."

[74] Rahul Rao, "High-Efficiency Solar Cells Power Satellites—Can They Come Down to Earth?," *IEEE Spectrum*, May 11, 2021, https://spectrum.ieee.org/energywise/green-tech/solar/high-efficiency-solar-cells-power-satellites.

[75] "News Release: NREL Six-Junction Solar Cell Sets Two World Records for Efficiency," *National Renewable Energy Labs*, April 13, 2020, https://www.nrel.gov/news/press/2020/nrel-six-junction-solar-cell-sets-two-world-records-for-efficiency.html.

[76] Ibid.

[77] Ian O'Neill, "Opportunity: The Amazing Self-Cleaning Mars Rover," *Space*, April 2014, https://www.space.com/25577-mars-rover-opportunity-solar-panels-clean.html.

[78] Morgan McFall-Johnsen, "NASA's Insight Mars Lander Is About to Go into Hibernation. If Its Batteries Ran Out, It Could Die.," *Business Insider*, April 16, 2021, https://www.businessinsider.com/nasa-insight-mars-lander-hibernating-so-batteries-dont-die-2021-4.

energy-related technology that enables such feats. While exploiting the renewable energy resource of light from the sun is highly advantageous for space missions, another proven technology used in lieu of, or in combination, is nuclear energy.

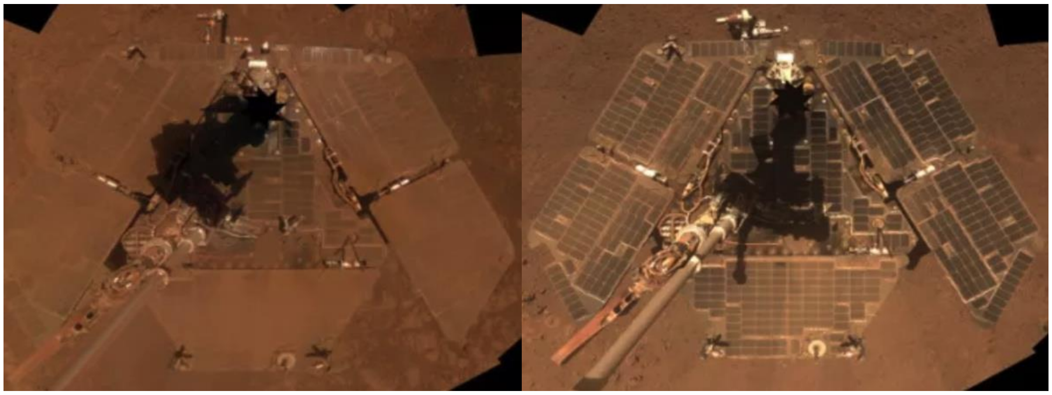

Figure 4: Self-portraits of NASA's Mars Exploration Rover Opportunity before (January 2014) and after (March 2014) a major "cleaning event" (Credit: NASA)

Although solar arrays have many innovative technological improvements over the span of the entire space age, none have been much of a breakthrough besides the MJ solar cells. Solar arrays are generally rated at around 20% efficiency with some state-of-the-art nearing roughly 30% efficiency. Emerging advancements can achieve over 40% efficiency, but these are not widely available yet. Besides the MJ solar cell innovation history, more significant innovations in photovoltaics consist primarily of reduced costs and utility. The breakthroughs in the potential for nuclear energy and the innovation story of space batteries tell a much more comprehensive innovation story of breakthroughs in energy-related technologies.

### *3. Space Nuclear Power*

The application of nuclear power for the purposes of meeting energy requirements in space have been pursued since the 1950s. The long history of performance, reliability, and safety have laid a secure foundation for future uses of nuclear power.[79] These efforts fall into roughly three categories: radioisotope power systems (RPS) that provide energy and heat to spacecraft; small-scale nuclear power reactors that also provide energy to spacecraft; and nuclear propulsion that is far more efficient than the chemical fuels currently used for rockets.[80] Each of these applications of nuclear power have demonstrated their utility in a range of deep space mission, Mars missions, and even in orbit around Earth. However, despite the potential for exponential efficiency improvements over other energy sources and the demonstrated safety and reliability enhancements, only a limited set of RPS and nuclear reactor technologies have been

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[79] Gary L. Bennet, "First Flights: Nuclear Power to Advance Space Exploration" (International Air & Space Symposium and Exposition, Dayton, Ohio: American Institute of Aeronautics and Astronautics, 2003), 9–10.

[80] Jim Thomson, "Nuclear Power in Space - Past, Present, and Future," *Nuclear Future* 17, no. 2 (April 2021): 18, 20.

thoroughly exploited. The high costs associated to the research and development of nuclear power technologies, particularly for propulsion, appear to be the major barrier to fully exploiting nuclear power technologies. Otherwise, the other limiting barriers have been the limited number of space missions requiring nuclear energy, the lack of utility to space programs that can use other means of energy, and the sensitive nature of nuclear technology in general. Nevertheless, each of nuclear power categories will be briefly explored to illustrate how the nuclear related technologies and their associated innovations have supported the incremental improvements related to overcoming the many challenges posed by the harsh space environment.

*Small-Scale Nuclear Reactors:* This form of nuclear technology produces energy for a spacecraft in much the same way a nuclear power plant would, except it is significantly smaller in scale. Basically, the small-scale nuclear reactor performs controlled nuclear fission in a series of chain reactions to produce energy. One of the earliest employments of this technology was the BES-5 nuclear reactor that powered over 30 Radar Ocean Reconnaissance Satellites/Upravlyaemy Sputnik Aktivnyy (RORSAT/US-A) constellation launched by the Soviet Union between 1967 and 1985.[81] The most famous of these is the Cosmos 954 that failed to separate its BES-5 reactor prior to reentering Earth's atmosphere and ended up scattering radioactive debris across northern Canada in 1978.

A subsequent improved small-scale nuclear reactor called the Thermionic Operating Reactors Active Zone (TOPAZ) was designed in the late 1980s by the Soviet Union that improved upon the BES-5 reactor by decreasing the weight (from 385kg to 320kg), increasing operational life to one year, and improving safety.[82] Unique to the TOPAZ reactors were their employment of zirconium hydride (ZrH) moderator blocks to act as a safety mechanism.[83] Should a TOPAZ reactor have a loss of coolant and the control system fail to shut down the reactor, the ZrH moderator served as a built-in redundant safety mechanism that released hydrogen upon the excess increase of heat that then shuts down the reactor.[84] Today, the Department of Energy is manufacturing and testing ZrH)

The TOPAZ-II reactors bought by the United States for testing in 1992 upon the collapse of the USSR were never tested in-orbit.[85] The planned testing included a technology demonstration for both in-orbit performance of the TOPAZ-II as well as potential for its utility for nuclear electric propulsion (NEP).[86] As discussed in the case study, despite the

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[81] Ibid., 19–20.
[82] Ibid., 20.
[83] National Academies of Sciences, Engineering, and Medicine, "Space Nuclear Propulsion for Human Mars Exploration" (Washington, DC: The National Academies Press, 2021), 21, https://www.nap.edu/catalog/25977/space-nuclear-propulsion-for-human-mars-exploration; David Buden, "Summary of Space Nuclear Reactor Power Systems" (Albuquerque, NM: Idaho National Engineering Laboratory, August 1993), 40, https://inis.iaea.org/collection/NCLCollectionStore/_Public/25/070/25070118.pdf.
[84] Buden, "Summary of Space Nuclear Reactor Power Systems," 43.
[85] Thomson, "Nuclear Power in Space - Past, Present, and Future," 20.
[86] Buden, "Summary of Space Nuclear Reactor Power Systems," 40.

U.S. effort to conduct demonstration tests, the program was terminated in March 1997 after costs exceeded $100 million without any in-orbit tests.[87]

However, TOPAZ-II was not the only small-scale nuclear reactor that the United States attempted to test and evaluate. From 1958 to 1972, the United States developed small-scale nuclear reactors and launched into space its first and only nuclear reactor in 1965 called the Systems for Nuclear, Auxiliary Power-10A (SNAP-10A).[88] The program was a relative success, successfully demonstrating the ability to remotely and safely operate a nuclear reactor in space.[89] However, there appeared to be a lack of need for nuclear reactors in space at that time. Combined with the height of the Apollo program in the years following the success of SNAP-10A, the NASA budget reductions as Apollo drew down and the Vietnam War intensified, and the retraction of space programs inward towards Low-Earth Orbit (LEO), led to the program's erosion. Interestingly though, like the TOPAZ-II, the SNAP program advanced key nuclear electric propulsion (NEP) technologies.[90]

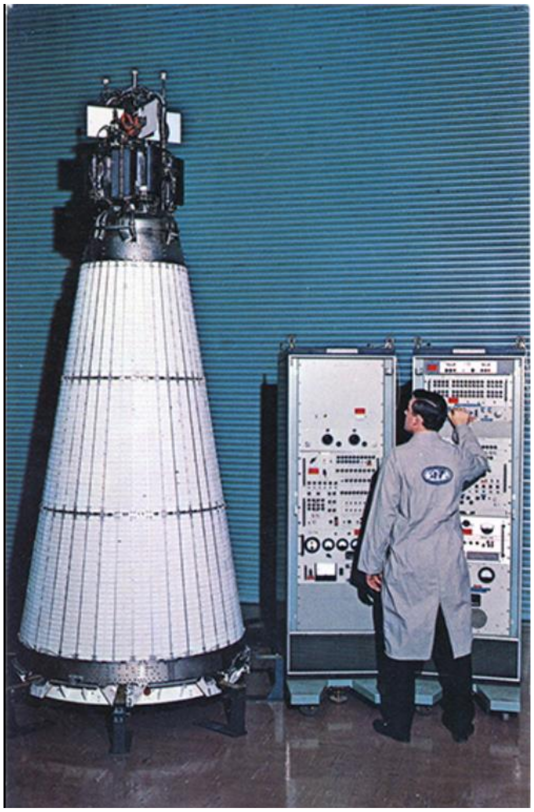

Figure 5: SNAP-10A with its nuclear reactor at the top (Credit: Nuclear Institute)

*Nuclear Propulsion*: There are two types of nuclear propulsion: NEP and nuclear thermal propulsion (NTP). NEP converts heat from the fission reaction to electrical power, identical to small-scale nuclear reactors, but uses that electric power to produce thrust through the acceleration of an ionized propellant.[91] In other words, for very little mass, NEP could provide very efficient propulsion for spacecraft, particularly those towards deep space further away from the sun.

Besides the previously discussed early phases of testing of NEP technologies with TOPAZ-II and the SNAP programs, NASA and DOE initiated the Jupiter Icy Moons Orbiter (JIMO)/Prometheus in 2003. JIMO/Prometheus attempted to develop an NEP

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Eljay B. Bowron, "TOPAZ II Space Nuclear Power Program - Management, Funding, and Contracting Problems" (Government Accountability Office, December 1, 1997), 2, https://www.gao.gov/assets/osi-98-3r.pdf.[87] {Citation}

[88] Bennet, "First Flights: Nuclear Power to Advance Space Exploration," 2, 8.

[89] Ibid., 9.

[90] National Academies of Sciences, Engineering, and Medicine, "Space Nuclear Propulsion for Human Mars Exploration," 37.

[91] Ibid., 35.

spacecraft to explore Jupiter and several of its moons.[92] However, despite technological advancements in dynamic energy conversion, heat rejection, and related electric propulsion innovations, the program was terminated in 2005 after NASA “reevaluated its budgetary priorities.”[93] Further, NEP is promising but intermittent funding has severely hindered any advancement in its technology readiness level since 2005.[94] Nevertheless, ongoing technology advancements related to solar electric propulsion, such as that demonstrated by ESA’s SMART-1, serve as a technological foundation for NEP to advance in the future.

NTP combines technologies from both nuclear reactors and chemical propulsion. NTP generates heat from a fission reaction like NEP does, but it heats the propellent (liquid hydrogen) that is pumped into the nuclear reactor and subsequently accelerates it out of the nozzle, generating thrust.[95] The earliest and most successful program to date was called Project Rover and its Nuclear Engine for Rocket Vehicle Applications (NERVA). From 1955 to 1973, the program successively built and tested 22 reactors that iteratively improved the technology from each test.[96] One test of a reactor revealed structural vibration issues that took two subsequent reactors in order to isolate the problem and apply a technological solution.[97] Although the entire program conducted only ground-based tests, it demonstrated a proof of concept for NTP technology that has yet been advanced since its cancellation in 1973.[98] After costing approximately $1.4 billion USD (roughly over $8 billion in today’s USD), U.S. President Nixon terminated the program, likely for similar reasons that the SNAP-10A had been cancelled.[99]

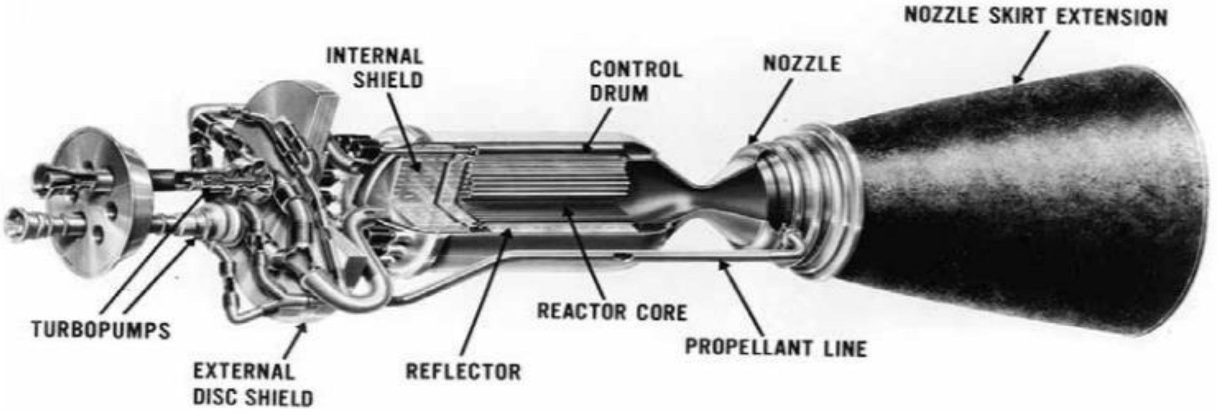

Figure 6: Explanatory drawing of the NERVA nuclear rocket engine (Credits: NASA and Nuclear Institute)

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[92] Ibid., 38.
[93] Ibid.
[94] Ibid., 63.
[95] Ibid., 12.
[96] Ibid., 14.
[97] National Academies of Sciences, Engineering, and Medicine, “Space Nuclear Propulsion for Human Mars Exploration” (Washington, DC: The National Academies Press, 2021), 15, https://www.nap.edu/catalog/25977/space-nuclear-propulsion-for-human-mars-exploration.
[98] Ibid., 18.
[99] R.A. Haslett, “Space Nuclear Thermal Propulsion Program Final Report” (Bethpage, NY: Grumman Aerospace Corporation, May 1995), 3–7, https://apps.dtic.mil/dtic/tr/fulltext/u2/a305996.pdf.

NTP technology gained some renewed interest a little over a decade later as part of the Strategic Defensive Initiative (SDI). This was called the Space Nuclear Thermal Propulsion (SNTP) program and it made some developments on fuel, safety, and materials[100] An important success of the SNTP program was the testing of mechanical and thermal properties of carbon-carbon material and carbide coatings at extremely high temperatures for key components such as nozzles and turbines.[101] Like its predecessors, the program slowed in the 1992 and was eventually terminated in January 1994 after expending roughly $200 million USD (roughly over $350 million in today's USD) due to changing national priorities, changing security requirements, and domestic economic pressures.[102]

| **Specific Impulse ($I_{sp}$) of Chemical and Nuclear Thermal Propulsion*** | | | |
|---|---|---|---|
| | Chemical Propulsion | | Nuclear Thermal Propulsion |
| | Kerosene or Hydrazine | Liquid-Hydrogen | |
| $I_{sp}$ | 200-300s | 300-400s | 800-1000s** |
| *Estimates only; $I_{sp}$ varies depending on oxidizers and conditions | | | |
| **Estimate based on ground-tests only | | | |

Figure 7: Chart showing the potential for NTP compared to chemical propulsion.

*Radioisotope Power Systems:* Unlike the small-scale nuclear reactors that rely on intentional fission reactions, radioisotope power systems (RPS) rely on the natural decay of a radioactive element such as Plutonium (238Pu). This decaying process provides heat which is then converted to be used as energy and/or keep it at its optimal functioning temperature. RPS generally consists of the same three basic elements: the radioisotope heat source that produces thermal power; the converter that transforms that thermal power into electrical power; and the heat rejection radiator.[103]

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[100] National Academies of Sciences, Engineering, and Medicine, "Space Nuclear Propulsion for Human Mars Exploration," 18.

[101] Haslett, "Space Nuclear Thermal Propulsion Program Final Report," 4-87-4–89.

[102] Ibid., 1–1.

[103] Robert L. Cataldo and Gary L. Bennet, "U.S. Space Radioisotope Power Systems and Applications: Past, Present, and Future" (NASA Glenn Research Center, July 2012), 1.

Innovations in RPS design and materials have iteratively improved efficiencies and increased safety measures.[104] Specifically, over the span of the past 30-40 years, “the power produced by a space Radioisotope Thermoelectric Generator (RTG) has increased over one-hundredfold” as seen in Figure 8 without any catastrophic issues.[105]

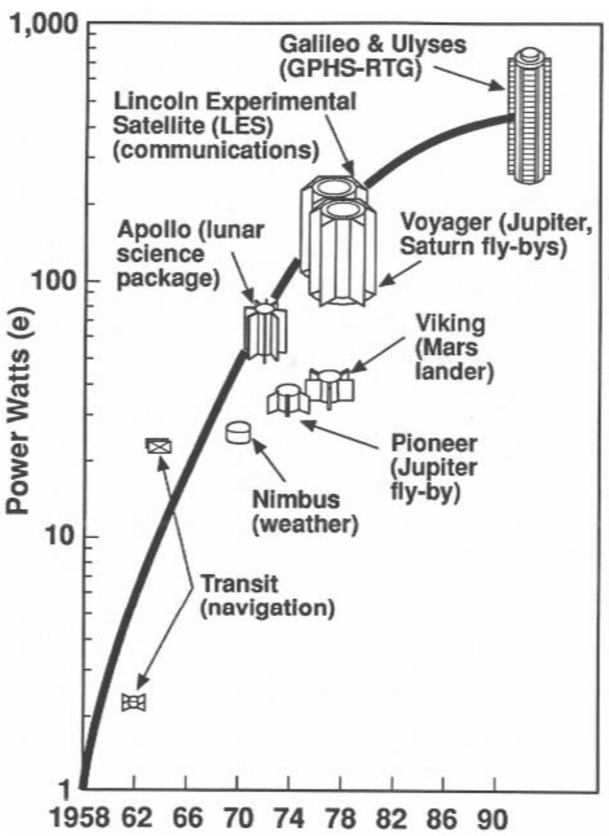

Figure 8: Progress in RTG Development. Not included is the MMRTG which produces 110 power watts. (Credits: NASA and Rockwell)

Figure 9: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) powering the Perseverance. Rover (Credit: DOE)

Variations of RTGs and Radioisotope Heater Units (RHUs) have been used for hundreds of space applications since 1961 by the United States and the Soviet Union.[106] The most recent and notable example is the ongoing NASA Mars 2020 Mission that employs the Perseverance Rover. The Perseverance Rover uses a similar Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) that its predecessor, the Curiosity Rover used, to generate electricity for its energy requirements without any moving parts.[107] The MMRTG is designed and built by the DoE and is a product of decades of RPS research, development, experimentation, testing, and space mission feedback.[108]

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[104] Ibid., 4–20.

[105] Ibid., 12.

[106] Gary L. Bennett, “Radioisotope Power: Historical Review,” *Earth Systems and Environmental Sciences*, January 2021. Specifically, the United States has flown 42 RTGs.

[107] “Mars 2020/Perseverance” (NASA Mars Exploration Program, March 2020), https://mars.nasa.gov/files/mars2020/Mars2020_Fact_Sheet.pdf; “Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)” (NASA, May 2020), https://mars.nasa.gov/internal_resources/788/.

[108] Cataldo and Bennet, “U.S. Space Radioisotope Power Systems and Applications: Past, Present, and Future,” 13–16.

Critical to the design of the MMRTG are the integration of innovative applications of material technologies in different components. Materials used for thermal insulation help regulate heat dissipation, materials used for thermoelectric couples increased the efficiency of the conversion of thermal energy, and the general purpose heat source (GPHS) is protected by sleeves of rugged carbon-bonded carbon fiber.[109] In addition, the plutonium is combined with ceramic and encapsulated with iridium that both serve to contain the radioactive fuel should a crash occur.[110] This is a clear example of how the technological innovations have not only made the use of nuclear power more efficient but also safer. These material technologies enable the MMRTG to safely and reliably operate in both the vacuum of space and on planets and along with its flexible and modular design, allows it to have a wide range of space mission applications.[111] Further, the MMRTG illustrates how a nuclear power source can provide continuous power without the need for the additional mass and volume of large solar arrays and heavy batteries.[112]

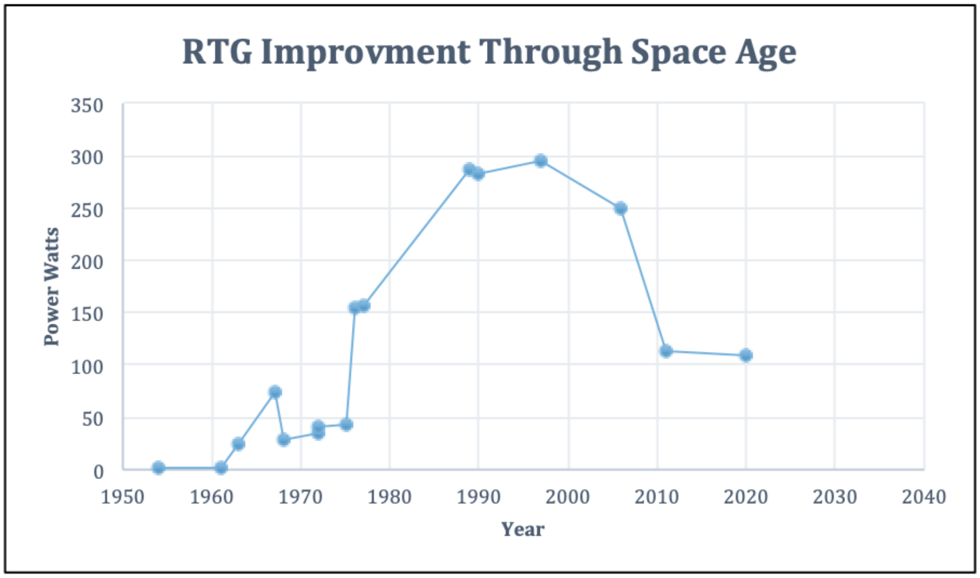

Figure 6: Progress in radioisotope thermal generator (RTG) development. Note that despite the decrease in performance of the MMRTG, it decreased weight by 15 Kg to meet mission requirements. (Credits: NASA and Rockwell)

### *4. Space Batteries*

As discussed in the case study, batteries are essential capabilities that fill the energy supply gaps of photovoltaics and nuclear energy and their inherent limitations. In other words, when photovoltaic systems are in Earth's shadow or covered in Martian dust, it is batteries that supply the necessary energy requirements. When the RTS only provides a

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[109] "Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)."

[110] Ibid.; Meghan Bartels, "Why NASA's Mars Rover Perseverance Will Use Nuclear Power to Keep Itself Warm," *Space*, July 2020, https://www.space.com/mars-rover-perseverance-nuclear-power-source-explained.html#xenforo-comments-32615.

[111] Cataldo and Bennet, "U.S. Space Radioisotope Power Systems and Applications: Past, Present, and Future," 13–14.

[112] Ibid., 21.

limited amount of energy insufficient for a particular activity, its batteries that can provide the excess energy required. An analysis of battery innovations and technologies illustrates how the iterative advancements made in battery technology enabled and enhanced space missions throughout the space age and continue to do so today and into the future. Without batteries and their iterative innovative technological improvements, many space endeavors would have been impossible to achieve.

Throughout most of the space age, no one type of battery design has proven suitable for all the varying space applications that have emerged. Although most battery concepts were innovated outside the realm of accomplishing something in space, those battery concepts still had to be redesigned to meet the challenges of operating in space. Thus, many batteries used in space are fundamentally designed differently from their terrestrial counterparts and have proven to be one of the safest and most reliable components of spacecraft or satellite. Even then, batteries have an extensive history throughout the space age of being iteratively improved to meet space mission requirements. The challenges of space have required the continuing research and development of batteries and their cells, resulting in longer shelf and cycle life, improved seals and separators, impact resistance, charge controls, weight and size, materials, electrodes and more.[113] Batteries are critical because they store excess energy from energy systems (whether photovoltaic, nuclear, or otherwise) during periods of charging and provide that excess energy during periods of discharging when solar arrays are in the dark or if extra energy is needed to perform a function. This case study will explore only a few of the most significant batteries and their iterative innovations and the types of missions made possible by them.

*Silver-Zinc Batteries*: The first three batteries in orbit around Earth happened to be sealed inside the first satellite in space, *Sputnik 1* in 1957.[114] These were silver-zinc (Ag-Zn) batteries and were later used on *Sputnik II* and on Yuri Gagarin's *Vostok* in 1961.[115] Despite the invention of a silver-zinc battery in 1800 by Italian physicist Alessandro Volta and later improved significantly in the 1920s by French professor Henri André, it was Russian scientist Vladimir Bagotsky who pioneered the research and development necessary to iteratively innovate the

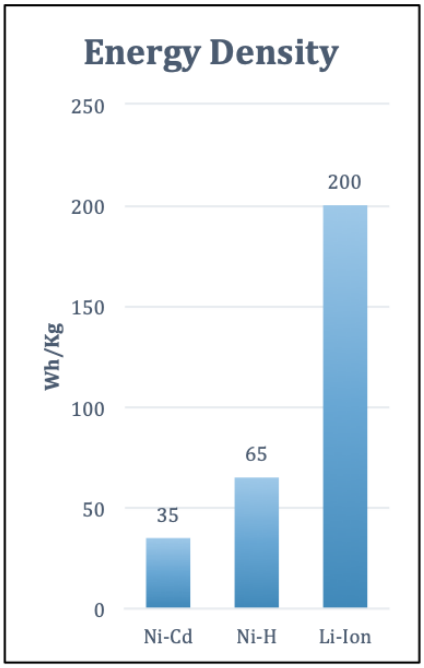

Figure 6: Progress of energy density in multi-rechargeable space battery technologies. Note that Ag-Zn batteries were not reliable for recharging until the 21st century.

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[113] Paul Bauer, "Batteries for Space Power Systems" (Redondo Beach, CA: NASA, 1968), v.
[114] Alexander M. Skundin and Galina A. Tsirlina, "V. S. Bagotsky's Contribution to Modern Electrochemistry," *Journal of Solid State Electrochemistry*, no. 18 (April 25, 2014): 1151.
[115] Ibid.

technology necessary to make Ag-Zn batteries space qualified.[116]

Ag-Zn batteries have high specific energy (efficiency), making them suitable for launch weight requirements as well as ensuring enough energy would be available to a spacecraft to perform its mission once in space.[117] Because of these properties, NASA coincidently sought to utilize Ag-Zn batteries for many of its early programs.[118] Ag-Zn batteries were used for many launch vehicles/systems, the Ranger 3, Mariner 2, lunar rovers, the Apollo Command Module, and even powered the lunar drill and the life-support equipment on the spacesuits used during Extra-Vehicular Activities (EVA).[119] A key innovation by NASA was the inclusion of special separators within the battery cells to extend the longevity and cycle life, making many of the batteries used tailor-made for space applications.[120]

However, their inherent limitations became evident during NASA’s early space programs, specifically Apollo. Ag-Zn batteries had great energy density but they had an incredibly short cycle life, meaning that the rechargeable variants could only be recharged a limited number of times.[121] The other barrier was the relative high cost associated to using silver, which limited it to mostly government-based programs (Ag-Zn batteries continue to be used for some military applications). Despite the more limited scope of Ag-Zn battery technology in space today, the advances in the technology throughout the Apollo era by NASA ended up enabling a successful commercial spin-off by ZPower that has since advanced NASA’s research efforts into viable commercial products.[122]

*Nickel-Cadmium Batteries*: While Ag-Zn batteries, and in some instances the similar silver-cadmium batteries, were used for relatively short-term space applications, nickel-cadmium (Ni-Cd) batteries could fulfill longer-term space applications because their properties and design enabled significantly more charging/discharging (recharge) cycles without significant and immediate degradation in performance.

The Ni-Cd battery was first patented in 1899 by Swedish chemist Waldemar Junger and was shortly followed by U.S. inventor Thomas Edison who patented (in Britain) a

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[116] David Linden and Thomas B. Reddy, *Handbook of Batteries*, 3rd Edition (New York, NY: McGraw-Hill, 2002), 33.1; Electrochemical Society, “Vladimir Sergeevich Bagotsky: Scientist and Teacher” (The Electrochemical Society Interface, Spring 2013), 29, https://www.electrochem.org/dl/interface/spr/spr13/spr13_p028_031.pdf. Henri André also developed the first rechargeable version of a silver-zinc battery in 1941.
[117] Linden and Reddy, *Handbook of Batteries*, 33.1. Specific energy is synonymous with energy density and is defined as the amount of energy per unit mass. In other words, the size to power ratio.
[118] Bauer, “Batteries for Space Power Systems,” 2.
[119] Linden and Reddy, *Handbook of Batteries*, 33.26; Gerald Halpert, Harvey Frank, and Subbarao Surampudi, “Batteries and Fuel Cells in Space” (Electrochemical Society Interface, Fall 1999), 26, https://www.electrochem.org/dl/interface/fal/fal99/IF8-99-Pages25-30.pdf.
[120] Bauer, “Batteries for Space Power Systems,” 4.
[121] Linden and Reddy, *Handbook of Batteries*, 33.2.
[122] Mike DiCicco, “NASA Research Helps Take Silver-Zinc Batteries from Idea to the Shelf,” *NASA*, December 1, 2016, https://www.nasa.gov/directorates/spacetech/spinoff/feature/Silver-Zinc_Batteries.

different design in 1901.[123] Ni-Cd batteries would be iteratively improved over time and its resulting long cycle life and overcharge capability made it suitable for many space applications.

The existing Ni-Cd battery technology used commercially in the early 1960s proved to be insufficient to meet all the requirements needed to ensure effective operations in space.[124] There were concerns with heating that required appropriate design interface with thermal-control systems; production characteristics were not uniform or consistent; and the cells leaked, requiring a high-integrity hermetic seal.[125] The advent of the hermetically sealed Ni-Cd battery increased the tolerance for overcharge, improved life cycle and longevity, and led to more compact designs.[126]

Ni-Cd batteries became one of the early standard space batteries in the 1960s, particularly for satellites.[127] Examples of just a few of the spacecraft that used nickel-cadmium batteries were the Ariel I;[128] Syncom-2 and 3;[129] and the Viking Landers and Orbiters.[130] In several instances, Ni-Cd batteries proved to be the most effective battery for long duration space applications, but not at first. Many other space systems using Ni-Cd batteries experienced degradation in battery performance over time, requiring innovative design changes and even battery management techniques to maximize longevity and cycle life.[131]

Using Intelsat communication satellites as an example, the improvement in Ni-Cd battery technology is evident. The first generations of Intelsat satellites (I-IVF) from 1965 to 1975 all used Ni-Cd batteries but routinely fell short of their expected mission life of seven years.[132] The degradation of the Ni-Cd batteries progressed faster than expected leaving an insufficient amount of power that was needed to operate the satellites at full capacity.[133] The improved Ni-Cd batteries (and battery management techniques) used in subsequent Intelsat satellite generations (IVA-V) from 1976-1982 proved a significant

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[123] Paul Bauer, “Batteries for Space Power Systems” (Redondo Beach, CA: NASA, 1968), 69.
[124] D.C. Bomberger and L.F. Moose, “Nickel-Cadmium Cells for the Spacecraft Battery” (NASA Astrophysics Data System, January 1963), 1687–88, http://adsabs.harvard.edu/pdf/1963NASSP..32.1687B.
[125] Ibid., 1688; Bauer, “Batteries for Space Power Systems,” 112.
[126] Bauer, “Batteries for Space Power Systems,” 70.
[127] Ali Sayigh and Andrew J. Cruden, eds., *Comprehensive Renewable Energy*, vol. Fuel Cells and Hydrogen Technology (Amsterdam, Netherlands: Elsevier, 2012), 40.
[128] John Paulkovich, “Solar Array Regulators of Explorer Satellites and Ariel I” (Greenbelt, MD: NASA Goddard Space Flight Center, n.d.), 2.
[129] R.J. Darcey, “Syncom 2,” *NASA Space Science Data Coordinated Archive*, accessed April 7, 2021, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1963-031A.
[130] Jet Propulsion Laboratory, “Viking Mission to Mars” (Pasadena, CA: NASA Jet Propulsion Laboratory, 1988), https://mars.nasa.gov/internal_resources/828/.
[131] Gopalakrishna Rao et al., “Nickel Cadmium Battery Operations and Performance” (Greenbelt, MD: NASA Goddard Space Flight Center, November 1994), 399–401, 408.
[132] Donald H. Martin, “Communication Satellites: 1958-1992” (El Segundo, CA: The Aerospace Corporation, December 1991), 47–56.
[133] D. Cooper and A. Ozkul, “Comparative Performance of Intelsat V Nickel Hydrogen and Nickel Cadmium Batteries” (Washington, D.C.: International Telecommunications Satellite Organization, Fall 1983), 540.

increase in longevity and cycle life, extending the lifespan of many of those satellites to as long as 18 years.

In a similar case of iterative improvements for a more recent satellite system, the GPS Block IIR/IIR-M series of satellites were projected to be primarily limited by the Ni-Cd battery technology used. However, updated stringent battery and power management techniques were employed to change this dynamic and extend the expected seven-to-eight years lifespan of the Block IIR/IIR-M satellites to well over ten years.[134] 15 of the 20 GPS Block IIR/IIR-M satellites that were launched between the years 1997 and 2009 remain in operation as of the writing of this paper, some lasting over 15 years so far.[135]

*Nickel-Hydrogen Batteries*: While Ni-Cd batteries were innovated before the space age and then subsequently improved iteratively to meet the specific requirements for space missions, nickel-hydrogen (Ni-H) batteries were invented during the space age and developed specifically for space applications. Three Russian inventors, Boris Tsenter, Vyacheslav Sergeev, and Alexandr Kloss, designed a Ni-H battery in 1971 that was later patented in the United States in 1972.[136] However, this Ni-H technology was also being developed in the United States in the late 1960s by COMSAT and Tyco Laboratories under sponsorship of Intelsat who were incentivized to improve spacecraft battery designs and performance. In an effort to extend the life of long-term space missions, particularly Geosynchronous Orbit (GEO) applications, they innovated hermetically sealed Ni-H cells in 1970.[137] Hughes Aircraft Company under the sponsorship of Wright Patterson Air Force Base was also researching and developing Ni-H cells at

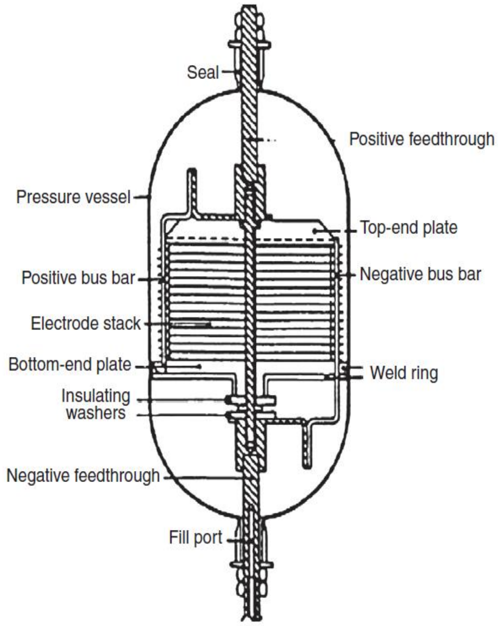

Figure 12: Design of the NTS-2 nickel–hydrogen cell (Credit: NASA)

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[134] Inside GNSS, “Change in GPS IIR/IIR-M Satellite Battery Charging Will Extend Mission Life,” *InsideGNSS*, February 28, 2014, https://insidegnss.com/change-in-gps-iir-iir-m-satellite-battery-charging-will-extend-mission-life/.

[135] GPS.gov, “GPS Space Segment,” *GPS: The Global Positioning System*, March 16, 2021, https://www.gps.gov/systems/gps/space/.

[136] Boris Ioselevich Tsenter, Vyacheslav Mikhailovich Sergeev, and Alexandr Ilich Kloss, Hermetically Sealed Nickel-Hydrogen Storage Cell, United States Patent Office 3669744 (Leningrad, filed February 25, 1971, and issued June 13, 1972).

[137] J.D. Dunlop and J.F. Stockel, “Nickel Hydrogen Battery Technology-Development and Status,” *Journal of Energy* 6, no. 1 (January 1982): 28; John J. Smithrick and Patricia M. O’Donnell, “A Review of Nickel Hydrogen Battery Technology” (Cleveland, OH: NASA Lewis Research Center, July 1995), 1.

the same time but with a focus on extending life cycle for Low Earth Orbit (LEO) applications.[138]

After several years of development, experimentation, and testing, the first Ni-H battery on a satellite was launched on the U.S. Navy Navigation Technology Satellite (NTS-2) in 1977.[139] Following the success of Ni-H batteries on the NTS-2 flight and the continued success of experimentation and testing, the batteries proved to be the best suited battery option over Ni-Cd for long-term space missions, especially for commercial satellites in GEO.[140]

Ni-H battery technology itself was a hybrid battery that combined battery cell technology from Ni-Cd batteries with the black hydrogen electrodes technology from hydrogen-oxygen fuel cells.[141] Despite the success of well-managed Ni-Cd batteries in many cases, Ni-H batteries promised several advantages beyond just a slightly improved lifespan.

First, as part of its design, the hydrogen gas replaced the cadmium (metal) electrodes that resulted in significant weight savings of the battery design compared to nickel-cadmium.[142] Accordingly, the specific energy (the efficiency) of the battery was almost twice that of Ni-Cd. The improved specific energy meant that they could store much more energy than Ni-H at the same weight.[143] This was critical to communications satellites that were rapidly growing in size and weight while also significantly increasing energy needs. For example, the Intelsat-III series satellites were just 330 pounds and used 160 watts of energy but the later Intelsat-V series satellites were 2280 pounds and used 1800 watts of power.[144] Reducing battery weight while maintaining or slightly increasing energy availability made the satellites much more efficient in design. The switch to Ni-H from Ni-Cd batteries was necessitated by the demand for increased payload capability that required higher capacity and more energy dense energy-storage subsystems.[145]

Second, the depth of discharge was greater for Ni-H batteries compared to Ni-Cd (70-80% versus 50%), meaning that more of the energy stored in the Ni-H battery (up to

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[138] Smithrick and O'Donnell, "A Review of Nickel Hydrogen Battery Technology," 1.
[139] Sayigh and Cruden, *Comprehensive Renewable Energy*, Fuel Cells and Hydrogen Technology:41.
[140] Dunlop and Stockel, "Nickel Hydrogen Battery Technology-Development and Status," 28.
[141] Ibid.
[142] Y. Borthomieu et al., "40 Years Space Battery Lessons Learned," in *8th European Space Power Conference*, vol. 661 (Germany: European Space Agency, 2008), 4.
[143] Sayigh and Cruden, *Comprehensive Renewable Energy*, Fuel Cells and Hydrogen Technology:40; The NASA History Office, "Astronautics and Aeronautics, 1978: A Chronology" (Washington D.C.: NASA, 1986), 56; Susan Hendrix, "Hubble Space Telescope Servicing Mission 4 Batteries: NASA Facts" (Goddard Space Flight Center, NASA, November 2009), 2, https://www.nasa.gov/pdf/252457main_FS_Batteries.pdf.
[144] Donald H. Martin, "Communication Satellites: 1958-1992" (El Segundo, CA: The Aerospace Corporation, December 1991), 47–50.
[145] Lawrence H. Thaller and Albert H. Zimmerman, "Overview of the Design, Development, and Application of Nickel-Hydrogen Batteries" (El Segundo, CA: NASA Glenn Research Center and The Aerospace Corporation, June 2003), 1.

80%) could be discharged without degrading the battery.[146] As a result, Ni-H batteries could have extended longevity and longer cycle life which was more ideal for any long duration space missions.[147] This also meant that Ni-H batteries were more robust and resilient, as they could not only execute deeper discharging compared to Ni-Cd batteries, but could better tolerate any overcharging.[148] As Ni-H batteries were further researched and developed and gained operational feedback from satellite missions, the technology would be iteratively improved just like Ni-Cd had been. As battery technology advanced, Ni-H battery improvements would offer many more choices and options than the nickel-cadmium technology that it would largely displace.[149]

Ni-H batteries would become the battery of choice over Ni-Cd for GEO satellites beginning in the 1980s that by 1995, over 60 of the satellites in GEO used Ni-H batteries.[150] Then, by 2008, more than 300 GEO satellites had launched with Ni-H batteries aboard.[151] Intelsat's fifth and sixth generation satellites were some of the first communications satellites to use Ni-H batteries. Most of these satellites lasted over 15 years and some of them lasted up to twenty years. Another success that followed in the late 1990s were the Iridium satellites launched from 1997 to 2002. As of 2019, many of those satellites had lasted over 21 years (others close to 20 or so years) without a single nickel-hydrogen battery failure.[152] Additionally, even as the constellation's use grew significantly over its lifespan, the batteries proved to handle the increased electrical consumption, accumulating over 1500 years (13.1 million hours) of failure free performance.[153] Whereas the Hubble Space Telescope's nickel-hydrogen batteries degraded at 2.24% per year, the Iridium nickel-hydrogen batteries only degraded at 1.52% per year.[154]

For a MEO satellite example, the 1w GPS Block IIF satellites launched from 2010 to 2016 were integrated with the most advanced nickel-hydrogen batteries provided by EaglePicher with a design life of 12 years, but given the reputation of nickel-hydrogen batteries, these satellites will likely last decades, limited only by the other operational components.[155] However, a satellite program using nickel-hydrogen batteries like GPS

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[146] Borthomieu et al., "40 Years Space Battery Lessons Learned," 4.
[147] Sayigh and Cruden, *Comprehensive Renewable Energy*, Fuel Cells and Hydrogen Technology:40.
[148] Arvind Kumar Balan and Kay Muller, "Operational Experience with Nickel Hydrogen and Lithium-Ion Batteries" (American Institute of Aeronautics and Astronautics, 2015), 1; Thaller and Zimmerman, "Overview of the Design, Development, and Application of Nickel-Hydrogen Batteries," 1.
[149] Thaller and Zimmerman, "Overview of the Design, Development, and Application of Nickel-Hydrogen Batteries," 1.
[150] Smithrick and O'Donnell, "A Review of Nickel Hydrogen Battery Technology," 1, 4.
[151] Borthomieu et al., "40 Years Space Battery Lessons Learned," 4.
[152] Mark R. Toft, "Retiring Undefeated: Iridium Nickel-Hydrogen Satellite Batteries (1997-2018)" (Iridium, November 29, 2018), https://www.nasa.gov/sites/default/files/atoms/files/ret_undef_iridium_nih2_sat_batt_mtoft.pdf.
[153] Ibid.
[154] Ibid.
[155] Howard, "EaglePicher Nickel-Hydrogen Batteries Power PS IIF SV-1 Global Positioning Satellite."

Block IIF did during this past decade has become a rare occurrence following the emergence of lithium-ion batteries.

In 1984 a NASA researcher at Lewis Research Center, John J. Smithrick, patented an improved Ni-H cell design.[156] This innovative design led to a breakthrough that improved cycle life and cell performance, reduced weight and volume, and further reduced probability of cell failure.[157] This iterative technological improvement of the Ni-H battery design proved critical to enabling two of the most prestigious and awe-inspiring spacecraft known to the world: the Hubble Space Telescope and the International Space Station (ISS).

Figure 13: Hubble replacement nickel-hydrogen battery module with the lid removed. Each module weighs 460 pounds and measures 36 inches long, 32 inches wide, and 11 inches high (Credit: NASA)

The design of the Hubble Space Telescope and the ISS in LEO would greatly benefit from the advantages provided by Ni-H batteries. The Hubble Space Telescope was launched in April of 1990 and did not need to replace its Ni-H batteries for 19 years until May of 2009.[158] When launched, the Ni-H batteries were very safely rated at just five years of design life, meaning that the batteries lasted 14 years longer than engineers anticipated.[159] As the first LEO satellite to use Ni-H batteries, it paved the way for numerous LEO

Figure 14: NASA astronaut Andrew Morgan works while tethered on the Port 6 truss segment of the ISS to replace older hydrogen-nickel batteries with the new lithium-ion batteries (Credit: NASA)

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[156] John. J. Smithrick, Oxygen Recombination in Individual Pressure Vessel Nickel-Hydrogen Batteries, United States Patent Office 4584249 (Washington D.C., filed June 27, 1984, and issued April 22, 1986).
[157] Smithrick and O'Donnell, "A Review of Nickel Hydrogen Battery Technology," 1–2.
[158] Dennis Overbye, "Astronauts Work on Replacing Hubble's Gyroscopes," *The New York Times*, May 15, 2009, https://www.nytimes.com/2009/05/16/science/space/16hubble.html.
[159] Hendrix, "Hubble Space Telescope Servicing Mission 4 Batteries: NASA Facts," 1.

missions that followed.[160] Even the subsequent replacement batteries were advanced Ni-H batteries that were improved from previous ones with an enhanced design and increased safety.[161]

An identical case can be illustrated by the ISS which had its first set of 12 Ni-H batteries installed in 2003 after being launched in 2000.[162] The remaining 36 batteries (for a total of 48) were installed in subsequent years after they were launched in 2004 and 2005.[163] With only an operational design life of 6.5 years, these batteries once again far exceeded expectations and were not replaced until a series of spacewalks were conducted from 2017 to 2021 to replace them, meaning each of the batteries lasted about 14 years.[164] Although the Ni-H batteries had aged by 2017, it appears they were more likely replaced as a result of a dictated scheduled program rather than an absolute requirement. After one of the new lithium-ion batteries on the P4 truss failed shortly after installation in March, 2019, the battery was replaced by one of the "old" Ni-H batteries until a replacement lithium-ion (Li-ion) battery could be launched several months later.[165] Given that the Hubble Space Telescope's batteries degraded at roughly 2.24% per year, the ISS nickel-hydrogen batteries likely degraded at a similar rate, suggesting they could have provided several more years of life.[166]

*Lithium-Ion Batteries:* The replacement of the ISS Ni-H batteries with lithium-ion batteries is indicative of the space industry's transition to Li-ion battery technology. While Li-ion battery technology was initially commercialized for the purposes of portable electronics starting in the early 1990s, the first real industrial application of Li-ion batteries occurred in the space industry.[167] Development of Li-ion batteries for space was led by the European space industry and began in the early 1990s by AEA Technology (funded by the UK Space Agency) and Saft's Defence and Space Division. The first employment of a Li-ion space battery was on the UK's Space Technology Research Vehicle (STRV-1d) launched by an Arianne-5 in November 2000.[168] This was followed-up shortly after by the ESA's Project for On-Board Autonomy - 1 (PROBA-1) and Small Missions for Advanced Research in Technology-1 (SMART-1) that used Li-ion

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[160] Sayigh and Cruden, *Comprehensive Renewable Energy*, Fuel Cells and Hydrogen Technology:45.
[161] Hendrix, "Hubble Space Telescope Servicing Mission 4 Batteries: NASA Facts," 2.
[162] Penni J. Dalton, "International Space Station Nickel-Hydrogen Batteries Approached 3-Year On-Orbit Mark" (NASA, Glenn Research Center, September 7, 2013), 2, https://ntrs.nasa.gov/citations/20050215412.
[163] Hendrix, "Hubble Space Telescope Servicing Mission 4 Batteries: NASA Facts," 2.
[164] Mark Garcia, "Spacewalkers Complete Multi-Year Effort to Upgrade Space Station Batteries," *NASA*, February 2, 2021, https://www.nasa.gov/feature/spacewalkers-complete-multi-year-effort-to-upgrade-space-station-batteries.
[165] Derek Richardson, "NASA Astronauts Finish ISS Battery Upgrades, Replace Cameras," Spaceflight Insider, (February 1, 2021), https://www.spaceflightinsider.com/missions/iss/nasa-astronauts-finish-iss-battery-upgrades-replace-cameras/.
[166] Mark R. Toft, "Retiring Undefeated: Iridium Nickel-Hydrogen Satellite Batteries (1997-2018)" (Iridium, November 29, 2018), https://www.nasa.gov/sites/default/files/atoms/files/ret_undef_iridium_nih2_sat_batt_mtoft.pdf.
[167] Yannick Borthomieu, "Chapter 14: Satellite Lithium-Ion Batteries," in *Lithium-Ion Batteries: Advances and Applications* (Elsevier, 2014), 318.
[168] Ibid., 328.

batteries, the latter of which used Saft's initial Li-ion battery technology.[169] Despite its two year design life, PROBA-1 continues to operate and it will be doing so for 20 years if it continues to do so by October 2021.

Li-ion batteries provide significantly better specific energy, lower self-discharge rates, low thermal dissipation, and higher coulombic efficiency compared to Ni-H batteries.[170] Unlike Ni-H batteries that were primarily an aerospace battery design with little commercial marketability (until some recent interest in terrestrial energy storage concepts), Li-ion battery technology continues to be more heavily funded and thus, more rapidly developed because of their commercial applicability. As a result, Li-ion battery technology has more rapidly displaced and supplanted most other space-related batteries.[171] Further, given that R&D for Li-ion battery technology spans across multiple industries, unlike Ni-H battery technology, the space industry is likely to continue benefiting from cross-industry advancements and innovations.[172] Li-ion batteries are uniquely customizable to meet the energy requirements and weight of a specific satellite design or for a specific space application.[173] In fact, distinctively designed Li-ion batteries play a critical role in the Mars Perseverance Rover and the Ingenuity helicopter.

Although the MMRTG for the Perseverance provides safe, reliable, and continuous energy, the 110 watts it produces is often insufficient for many of the Perseverance's activities. The Perseverance's power demands can reach up to 900 watts during some science activities and its two Li-ion batteries supplement the MMRTG in order to meet the increased energy demand.[174] As it resumes normal daily activities, the two custom Li-ion batteries designed specifically for the Mars mission get recharged by the MMRTG and will potentially continue operations for at least 15 years.[175] The Ingenuity helicopter also uses six custom lightweight, highly efficient Li-ion batteries that powers its flight for roughly 90 seconds at 350 watts.[176]

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[169] Borthomieu et al., "40 Years Space Battery Lessons Learned," 7.

[170] Sayigh and Cruden, *Comprehensive Renewable Energy*, Fuel Cells and Hydrogen Technology:42; Borthomieu, "Chapter 14: Satellite Lithium-Ion Batteries," 312.

[171] "Nobel-Winning Lithium-Ion Batteries Powering Space," *European Space Agency*, October 15, 2019, https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Nobel-winning_lithium-ion_batteries_powering_space.

[172] Borthomieu, "Chapter 14: Satellite Lithium-Ion Batteries," 343.

[173] Ibid., 318, 332.

[174] "Mars 2020 Perseverance Launch Press Kit," *NASA Jet Propulsion Lab*, January 2021, https://www.jpl.nasa.gov/news/press_kits/mars_2020/launch/mission/spacecraft/power/.

[175] Pat McGonigle, "From Missouri to Mars: NASA's New Rover Powered by Batteries Made in Show-Me State," *Fox4 News*, February 18, 2021, https://fox4kc.com/news/from-missouri-to-mars-nasas-new-rover-powered-by-batteries-made-in-show-me-state/.

[176] "NASA's Ingenuity Mars Helicopter: The First Attempt at Powered Fligh on Another World," *American Scientist*, February 2021, https://www.americanscientist.org/article/nasas-ingenuity-mars-helicopter#:~:text=Ingenuity%20specs&text=Ingenuity%20stay%20in%20contact%20at,(24%20hours%2040%20minutes).&text=On%20Mars%2C%20the%20helicopter%20weighs,flight%2C%20which%20draws%20350%20watts.

### *5. Looking Ahead*

Li-ion batteries appear to be the state-of-the-art battery technology over the next decade. Any battery technology or new electrochemistry breakthrough that occurs will still take some time to become space qualified.[177] The next decade is likely to see innovations tied to incrementally improving existing energy and battery technologies. For example, carbon fiber material is being experimented/tested in new battery systems to reduce weight of the battery (mass) and simultaneously serve two functions: load-bearing structure support and acting as part of the battery system given its electrical conductivity[178]

Another interesting outlook is that future innovations of energy sources and systems developed in space are likely to have eventual application to terrestrial industries and markets. For example, even though Ni-H batteries were too expensive for exploitation in industries outside of aerospace, new innovation may be changing this. Innovative design changes in Ni-H battery technology that use new and abundant materials to bring the costs down, combined with its broad temperature resilience (i.e., does not need heating or air conditioning), high reliability, long cycle life of up to 30 years and 30,000 cycles, and low-maintenance needs, makes it suitable for large-scale energy storage requirements over existing Li-ion batteries.[179]

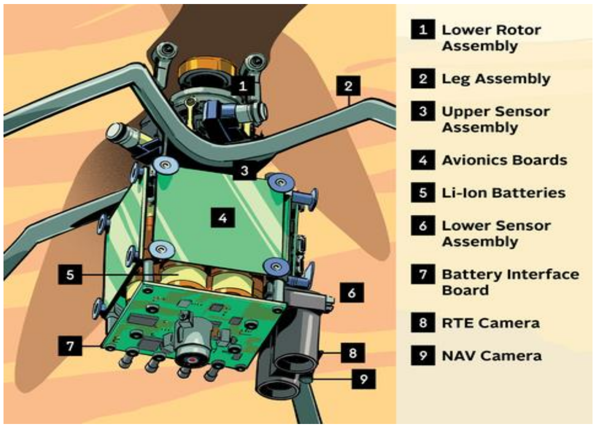

Figure 15: Sketch of the Ingenuity's revealing the six lithium-ion batteries integrated inside lower assembly (Credit: Popular Mechanics)

How the Perseverance Rover and its MMRTG perform may be indicative of the potential for further investment in RPS technologies. Missions like Voyager 1 and 2 continue to demonstrate the utility of RTG for enduring and far-reaching space exploration missions, but for near-Earth, lunar, and Mars endeavors, the optimism for energy sources generally lies in photovoltaics. However, the last few decades of Mars exploration have illustrated the risks of solar panel use in such a dusty environment. The Spirit and Opportunity Rovers illustrated the significant amounts of dust that would build-up and cover the solar panels, significantly reducing the efficiency. It would seem risky for future expensive space endeavors to rely solely on photovoltaics that rely on the unpredictable weather on Mars to produce enough winds to blow the dust off the solar panels on a regular basis.

*Nuclear propulsion*. NEP and NTP are likely critical technologies necessary for any future human exploration of the solar system beyond the moon. To illustrate the

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[177] Barde, "1989 - 2019: Three Decades of Power Systems Evolution Through the Prism of ESPC," 4.

[178] "State-of-the-Art: Small Spacecraft Technology," 40.

[179] Aaron Larson, "Battery Technology Used in Outer Space Could Be a Gamechanger on Earth," *Power Magazine*, March 4, 2021, https://www.powermag.com/battery-technology-used-in-outer-space-could-be-a-gamechanger-on-earth/.

improvement of NTP over traditional chemical propulsion to reach Mars for example, one merely has to look at one datapoint, the specific impulse. Specific impulse, defined in seconds, indicates how much thrust is obtained by the propellant and a higher number means greater efficiency. A typical chemical rocket delivers a specific impulse ranging from 175 to 300 seconds. The most efficient chemical propellant used is liquid hydrogen, which has been used since 1962 when it powered the upper stage of an Atlas-Centaur rocket. Liquid hydrogen generates a specific impulse between 300-400 seconds under ideal conditions.[180] On the other hand, the NERVA tests demonstrated that NTP could produce a specific impulse of over 900 seconds and in the ground test that most accurately emulated actual space flight, still achieved over 700 seconds.[181] In other words, NTP technology from the 1960s could cut the travel time to Mars by more than half compared to state-of-the-art chemical propulsion systems – though unproven in actual space flight.

Over the past few years there has been renewed interests in nuclear propulsion technologies as the limitations of existing chemical propulsion technology become painfully apparent. It may also shock many readers that much of the nuclear propulsion technology is on the shelf waiting to be advanced. NASA, in coordination with the DOE, have recognized the utility of NEP and NTP for Mars missions and beyond and are making renewed efforts towards developing, testing, and maturing these two propulsion options.[182] The challenges of achieving nuclear propulsion are similar to the previous material and energy technology challenges previously faced. The technological challenges will require innovative and incremental improvements that apply technologies from multiple sectors. Shielding material innovations will be critical to ensure the safe operation of nuclear propulsion that contain and prevent the leaking of any radioactive materials and prevent harmful radiation damage to other spacecraft components or even on-board astronauts. In addition, material innovations capable of tolerating the extreme temperatures from the nuclear reactions in the engine would be needed as well.

Recognizing the benefits and applications of RPS technologies and their proven effectiveness and reliability, renewed interest has emerged in recent years for a number of reasons. The European Space Agency (ESA) has increased interest in deep space missions, Mars sample return missions, and more recently, participation in the lunar Gateway and Artemis programs.[183] As a result, the ESA initiated the ESA RPS Program in 2010 that iteratively develops RPS technologies to enable and enhance future space science and exploration missions.[184] While the United States has a long history in RPS R&D, the Perseverance and Curiosity Rovers are the only two U.S. civil space missions

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[180] Robert A. Braeunig, “Rocket Propellants,” *Rocket & Space Technology*, 2008, http://www.braeunig.us/space/propel.htm#:~:text=Liquid%20hydrogen%20delivers%20a%20specific,engines%20of%20the%20Space%20Shuttle.

[181] National Academies of Sciences, Engineering, and Medicine, “Space Nuclear Propulsion for Human Mars Exploration,” 15–16.

[182] Clare Skelly, *NASA*, February 12, 2021, https://www.nasa.gov/directorates/spacetech/nuclear-propulsion-could-help-get-humans-to-mars-faster.

[183] Richard M. Ambrosi et al., “European Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs) for Space Science and Exploration,” *Space Science Review* 215, no. 55 (2019): 2–3.

[184] Ibid., 3.

that have used RPS technology over the past decade.[185] However, in 2019, the United States updated executive space policy guidelines in an effort to reduce barriers in exploiting RPS technologies for space mission applications.[186] The next planned use of RPS by NASA is the Dragonfly mission which will send an MMRTG-powered flying quadcopter to Saturn's moon, Titan, in 2026.[187]

### B. Digital Technology

> *NASA alone was not responsible for the microelectronics revolution that was centered in and around Silicon Valley beginning in the early 1960s. Its role in innovation was nevertheless critical.*[188]

The history of the early computers is closely associated with the early history of human spaceflight. Borrowing from the legacy of aeronautical technologies, space systems gradually employed computerized systems to assist with various tasks. In particular, navigation and guidance computerized systems developed for the U.S. Air Force for fighter jet planes and rockets found use in the newly developing field of space exploration. The key difference between the two applications remained the presence of a human in the loop. A vivid debate between proponents of robotic versus human space missions originates from the early stages of space exploration and continues today. Project "Apollo exemplified broad changes in human-machine relationships", even though it did not directly cause these changes.[189] This case study uses the Apollo program as the starting point for the use of computers, microchips, and automation in space exploration.

Following a discussion of the innovatively complex Apollo navigation and positioning computer, the report addresses some other notable computer-driven innovations in spaceflight history. In the decades following the Apollo program, NASA engineering practices were changed by the emergence of computer-based engineering capabilities.[190] At the same time, the new systems were becoming "increasingly complex, difficult to test, and designed to operate at an increasingly high-performance envelope."[191] While computers opened up new possibilities for human spaceflight

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[185] Kaitlyn Johnson, "What Does the Trump Administration's New Memorandum Mean for Nuclear-Powered Space Missions?," *Center for Strategic and International Studies*, August 28, 2019, https://www.csis.org/analysis/what-does-trump-administrations-new-memorandum-mean-nuclear-powered-space-missions.

[186] Ibid.

[187] Stephen Clark, "Plutonium Power Source Installed on NASA's Next Mars Rover," *Spaceflight Now*, July 22, 2020, https://spaceflightnow.com/2020/07/22/plutonium-power-source-installed-on-nasas-next-mars-rover/.

[188] Roger D. Launius, Howard E. McCurdy. "NASA SPACEFLIGHT: A History of Innovation," 2018, Palgrave Studies in the History of Science and Technology ISBN 978-3-319-60112-0) https://doi.org/10.1007/978-3-319-60113-7, hereafter "NASA SPACEFLIGHT"

[189] David A. Mindell. "Digital Apollo: Human and Machine in Spaceflight (Cambridge, MA: MIT Press, 2008)", hereafter "Digital Apollo"

[190] Steven J. Dick, Roger D. Launius. "Critical Issues in the History of Spaceflight" 2006, National Aeronautics and Space Administration Office of External Relations History Division, Washington, DC, NASA SP-2006-4702, hereafter "Critical Issues in the History of Spaceflight"

[191] Ibid.

technologies, they also forced aerospace engineers to quickly adapt to new challenges in the post-Apollo era.

The case study concludes with a discussion of the applications of Artificial Intelligence in space exploration. While the concept of automation dates back far beyond humanity's first steps on the Moon, the space environment created the demand for new innovative ways of making systems more autonomous. NASA's history of robotic probes also included very impressive technological innovations.

### *1. Microchip technology*

The very high costs of accessing space underscored the need for smaller and lighter components of technology systems onboard spacecraft. Only a few years before the 1961 initiation of the Apollo mission, Texas Instruments engineer Jack St. Clair Kilby and Fairchild Semiconductor physicist Robert Norton Noyce filed competing patents for their inventions of the first integrated circuits (IC). Although there was an intellectual property dispute, the both eventually agreed to share credit and cross-license each other's portfolio of patents relating to the IC."[192]

Before the invention of the microchip, conventional electronic circuits were composed of discrete electronic components (resistors, diodes, transistors) that were assembled together with conducting wires. Integrated circuits, commonly known as microchips, are circuits in which all the electronic components are assembled on the surface of a thin semiconductor material, such as silicone.[193]

Integrated circuits have been particularly attractive for spacecraft, mainly because they tend to be notably smaller than traditional electrical circuits, consume less power, increase operational speed, and even promise reduced costs per electronic function.[194]

However, the same characteristics were advantageous for innovations in aircraft and missile technologies, which preceded space systems. By the time NASA sought to integrate microchips into their Apollo spacecraft, the U.S. Department of Defense had been driving the demand for integrated circuits production. Even though the U.S. Air Force was interested in microchips, the computer industry was not yet interested in the disruptive technology.[195] Decades after their invention, integrated circuits proved to be a technology with a wide array of applications in virtually all electronic products, from the Apollo guidance computer to today's smartphone. [196]

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[192] "NASA SPACEFLIGHT"

[193] "Patent Expert Issues: Layout Designs (Topographies) of Integrated Circuits," https://www.wipo.int/patents/en/topics/integrated_circuits.html

[194] Mathematica, INC. "QUANTIFYING THE BENEFITS TO THE NATIONAL ECONOMY FROM SECONDARY APPLICATIONS OF NASA TECHNOLOGY -EXECUTIVE SUMMARY", 1976, Prepared by MATHEMATIC, INC., Princeton, N.J. 08540, for *NASA Headquarters*, hereafter "MATHEMATICA"

[195] "Three Takeaways from Computer Chip Patent Wars", 2016, *Beem* patent law, https://beemlaw.com/three-takeaways-from-computer-chip-patent-wars/

[196] "MATHEMATICA"

### *2. The Apollo Guidance Computer (AGC)*

Due to the great distance to the lunar surface and the constant but limited speed of light, NASA was compelled to produce an increased level of autonomy for the Apollo missions. Furthermore, engineers were concerned with solving the navigation, guidance, and flight control problems that could arise given the distance and time delay in communications with the new spacecraft.[197] To respond to these challenges, the newly developed microelectronic computer was ultimately determined as the best technological solution. The difficulty of designing a new computer for the lunar landing was making this system "robust, reliable, even bulletproof."[198]

Despite an existing working relationship with IBM for the Saturn V rocket computers, NASA opted instead for the MIT Instrumentation Lab as the main contractor for the design, development, and construction of the Apollo guidance and navigation computer's hardware and software systems.[199] The MIT Lab had a partnership with Noyce and Moore's Fairchild Semiconductor to supply the silicon microchips for the AGC.[200] The decision to use silicone microchips was a bold one at the time since the technology had not been yet widely tested.[201] The partnering of NASA with MIT proved useful as a learning experience, as both groups of engineers learned to employ the latest principles of software engineering in real-time applications.[202]

Present-day clichés stating that ‘‘we went to the moon with a computer that was less capable than a pocket calculator,’’ tend to minimize the complexity of the Apollo navigation and landing computer. If we "consider interconnections, reliability, ruggedness, and documentation, the Apollo guidance computer is at least as impressive for its time as the current desktop computers are today. And the Apollo software was an equally intricate ballet of many people’s work and ideas."[203] The fundamental divide we observe today between computer hardware and software was not, however, as clear in the 1960s. In the early stages of computer developments, the software of analog computers was hardwired into the computers' physical structure.

Early computers were not yet developed to host a variety of software applications but were designed to accomplish very specific tasks. One of the great innovations in computing in the 1960s was "timesharing," the idea that many programs would access a computer simultaneously, in real-time as though each had the machine to itself. Timesharing worked by allocating a slice of time to each user or program, and then switching between them many times per second."[204] However, the designers of the

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[197] "Computers in Spaceflight: The NASA Experience", Chapter Two "Computers on Board The Apollo Spacecraft"
[198] "Digital Apollo"
[199] "Computers in Spaceflight: The NASA Experience", Chapter Two, "MIT chose a hardware and software contractor"
[200] Paul Ceruzzi. "Apollo Guidance Computer and the First Silicon Chips," 2015, Smithsonian National Air and Space Museum, https://airandspace.si.edu/stories/editorial/apollo-guidance-computer-and-first-silicon-chips
[201] "Computers in Spaceflight: The NASA Experience", Chapter Two, "MIT chose a hardware and software contractor"
[202] Ibid.
[203] "Digital Apollo"
[204] Ibid.

Apollo computer chose not to adopt this early technological innovation. Instead, they opted for a system that would only perform one task at a time, prioritizing the computer's attention to the most important task at hand. This design had the advantage of ensuring that the entire computing power would be used to run the most important program at a critical time, without diverting resources to operations that could be performed at later stages of the landing process or that were optional.[205]

The AGC was considered fairly compact considering the state of technology at that time.[206] One of the most difficult challenges posed by the miniaturization process was designing the memory requirements for the computer. As mission requirements developed during the years of planning of the Apollo program, the size of the computer's memory module needed to increase proportionally.[207]

> *One reason the designers underestimated the memory requirements was that NASA did not provide them with detailed specifications as to the function of the computer. NASA had established a need for the machine and had determined its general tasks, and MIT received a contract based on only a short, very general requirements statement in the request for band.*[208]

Another challenging aspect of the Apollo mission for the AGC was that the computer had to be resilient enough to withstand failure. Unlike bugs, systemic software failures could not be successfully predicted or completely avoided by design. MIT's solution to keeping the AGC running and functional was to ensure the computer was capable to restart in case of software failure.[209] A unit-logic device was developed as a solution in the following decades, composed of three analog circuit computers instead of one. Thus, if one computer would fail, the other two would 'outvote' the dissonant one, and the system would restart it.[210] Luckily, no AGC ever experienced a hardware failure during a mission. Instead, the computer's robustness saved at least two missions from probable abort.[211]

Opting to automate the landing and navigation systems was not an easy choice in retrospect. Early astronauts were reticent to share control of their spacecraft with digital computers, which they saw as unreliable and prone to failure.[212] In those early days of development, electronics routinely failed. Nevertheless, the AGC was not allowed to fail, proving the reliability of digital electronics in some of the most adverse and unpredictable

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[205] Ibid.

[206] "Computers in Spaceflight: The NASA Experience", Chapter Two "The Apollo guidance computer: Hardware"

[207] "Computers in Spaceflight: The NASA Experience", Chapter Two "The Apollo guidance computer: Hardware"

[208] Ibid.

[209] "Computers in Spaceflight: The NASA Experience", Chapter Two "The Apollo guidance computer: Software"

[210] Paul Ceruzzi. "Apollo Guidance Computer and the First Silicon Chips," 2015, Smithsonian National Air and Space Museum, https://airandspace.si.edu/stories/editorial/apollo-guidance-computer-and-first-silicon-chips

[211] "NASA SPACEFLIGHT"

[212] "Digital Apollo"

environments. The AGC was successfully used on Earth-orbital missions, all lunar landing missions, Skylab missions, and the Apollo-Soyuz project.[213] Furthermore, the use of the lunar computer on an F-8 research aircraft "fly-by-wire," contributed to the later development of the Space Shuttle's fully fly-by-wire system.[214]

The Apollo program was the most ambitious US space effort, both in terms of the costs and the challenges that needed to be overcome. The cost of the AGC was upwards of $10 million[215] was still a small share of the overall budget of Apollo. Nevertheless, it successfully assisted the astronauts in landing on the lunar surface. The AGC involved multiple technological innovations of its time, including microchips, and was not welcomed by all NASA engineers and astronauts due to its disruptive nature. It was only with the passing of time that we look back to the legacy of the Apollo computer and its impact on future computers onboard spacecraft, as well as in the consumer market.

### *3. Space Shuttle Fly by Wire System*

The legacy of the Apollo program extends beyond national pride and projected technological superiority. The large investment in the research and development of the necessary technologies to put the first humans on the Moon needed to yield returns beyond lunar rock samples. NASA and MIT Instrumentation Lab's efforts to digitize aerospace systems using integrated circuits and dedicated software led to an in-house technology transfer in the case of the fly-by-wire system. The Digital Fly-by-Wire (DFBW) is a system composed of multiple computers that instantly analyze a pilot's control inputs and mediates their transmission to the flight control elements. The computers analyze the controls against variables such as the aircraft's speed, weight, and even atmospheric conditions, to produce optimized control signals.[216] The DFBW systems increased safety, reduced the aircraft's weight, and even increased maneuverability .[217]

> *Changes in engineering practice over the 1970s, 1980s, and 1990s meant that engineers in the manned space program were working in the increasingly mediated environment of computer-based engineering whilst working on technological systems that were becoming increasingly complex, difficult to test, and designed to operate at an increasingly high performance envelope.* [218]

The DFBW technology circled back from the F-8 plane into the Space Shuttle prototype Enterprise in 1976, as part of the flight control system (FCS) computer for the orbiter.[219] The FCS was comprised of four computers for guidance, navigation, and control

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[213] "Computers in Spaceflight: The NASA Experience", Chapter Two "Lessons"

[214] Ibid.

[215] "Computers in Spaceflight: The NASA Experience", Chapter Two "Evolution of the hardware: Old technology versus new block I and Block I designs"

[216] Gray Creech. "Digital Fly By Wire: Aircraft Flight Control Comes to Age," 2003, NASA Dryden Flight Research Center, https://www.nasa.gov/vision/earth/improvingflight/fly_by_wire.html

[217] Ibid.

[218] "Critical Issues in the History of Spaceflight"

[219] Gray Creech. "Digital Fly By Wire: Aircraft Flight Control Comes to Age," 2003, NASA Dryden Flight Research Center, https://www.nasa.gov/vision/earth/improvingflight/fly_by_wire.html

algorithms for the entire flight. The complex system performed multiple functions, including flying the Shuttle "as a boost vehicle, as a spacecraft, as a reentry vehicle, and as a conventional aircraft."[220] The Shuttle's large-scale multi-faceted computer was a counterexample of the corollary of Moore's Law suggesting that computers get smaller and lighter with time.[221] The FCS software was comprised of approximately 2 million lines of code, implemented incrementally over 15 years, and which was supported by the work of approximately 275 people.[222] Even though the Space Shuttle was retired by NASA in 2011, digital innovations in spacecraft continued to advance rapidly as private space companies are racing to build a commercial space infrastructure.

### *4. Artificial Intelligence*

Artificial Intelligence is currently one of the most discussed general-purpose technologies that promise to revolutionize virtually any digital economic sector, similar to microelectronics in the post-Apollo era. The aerospace sector, historically one at the forefront of emerging technologies, has many potential applications of AI algorithms. Aircraft manufacturer giant Airbus has been using AI to identify patterns in production problems for new systems, reducing the time required to address disruptions.[223]

AI can be broadly described as the varied multitude of algorithms capable of accomplishing tasks that traditionally required human intelligence to complete. Machines become able to carry on complex tasks as a result of a learning process. AI can be broken down into two main categories: expert systems and machine learning. Expert systems refer to algorithms that have advanced along the lines of traditional 20th Century algorithms: sets of meticulously written commands leading to specific outputs (decisions) based on various inputs (data).

The second type of AI system is based on neural networks: algorithms with infrastructure mimicking that of the human brain, with networks of neurons connected in intricate and unique ways. As opposed to expert systems, which required meticulously written instructions from humans, neural networks produce their own instructions, which organically appear as the systems are fed extremely large volumes of data. Within neural networks, machines begin to observe patterns in large collections of numerical data, text documents, pictures, and sounds.

In the example offered above, Airbus is employing neural networks to identify patterns associated with technical failures. But similar systems can also be fed visual geospatial data to determine optimal crop yields, or signal natural disasters, or discover new solar systems from Hubble telescope data.[224] The Mars 2020 mission's Perseverance rover

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[220] Glenn M. Minott, John B. Peller, Kenneth J. Cox. "SPACE SHUTTLE DIGITAL FLIGHT CONTROL SYSTEM," N76-31146

[221] "NASA SPACEFLIGHT"

[222] National Research Council. "Statistical Software Engineering," 1996, Washington, DC, The National Academies Press, https://doi.org/10.17226/5018

[223] OECD. "THE DIGITALISATION OF SCIENCE, TECHNOLOGY AND INNOVATION: KEY DEVELOPMENTS AND POLICIES," 2019, DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INNOVATION COMMITTEE FOR SCIENTIFIC AND TECHNOLOGICAL POLICY

[224] Lonnie Shekhtman. "Nasa NASA Takes a Cue From Silicon Valley to Hatch Artificial Intelligence Technologies", 2019, NASA's Goddard Space Flight Center,

and Ingenuity helicopter both employ AI algorithms that chart the Martian surface in real-time for successful navigation around obstacles and geographical features. NASA developed AI to substitute for the decision-making of mission controllers on Earth since the amount of telecommunications latency between the Earth and Mars makes real time decisions for robotic missions impossible.[225] The previous Spirit and Opportunity rovers were less autonomous, and more dependent on the commands of ground controllers and therefore could do less and incorporated a much higher level of failure risk.[226]

This short summary of major developments in digitization, automation and artificial intelligence highlights the important role of innovation in space exploration. By successive inventions making computer processing faster, chips lighter in weight, and specialized integrated software, space systems were dramatically more capable of fulfilling their missions. However, as with other comprehensive technologies, developing new systems and modifying existing systems, involves many inventions and takes years to perfect and gain acceptance among the human engineers and astronauts. New systems are also very expensive.

## C. Carbon Fiber Composite Materials

The reader can find a very complete history of NASA’s role in the development of advanced composite materials in:

Tenny, Davis, Johnston, Pipes, McGuire, Structural Framework for Flight I: NASA’s Role in Development of Advanced Composite Materials For Aircraft and Space Structures, NASA Langley Research Center, CR-2019-220267 Vo. 1, Contract NNL09AA1Z, April 2019

The following diagram illustrates the development and application of composite materials at NASA from aircraft to space equipment:

**NASA Application of Composites on Flight Vehicles (Source: NASA/CR-2019-220267 Vo. 1)**

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https://www.nasa.gov/feature/goddard/2019/nasa-takes-a-cue-from-silicon-valley-to-hatch-artificial-intelligence-technologies

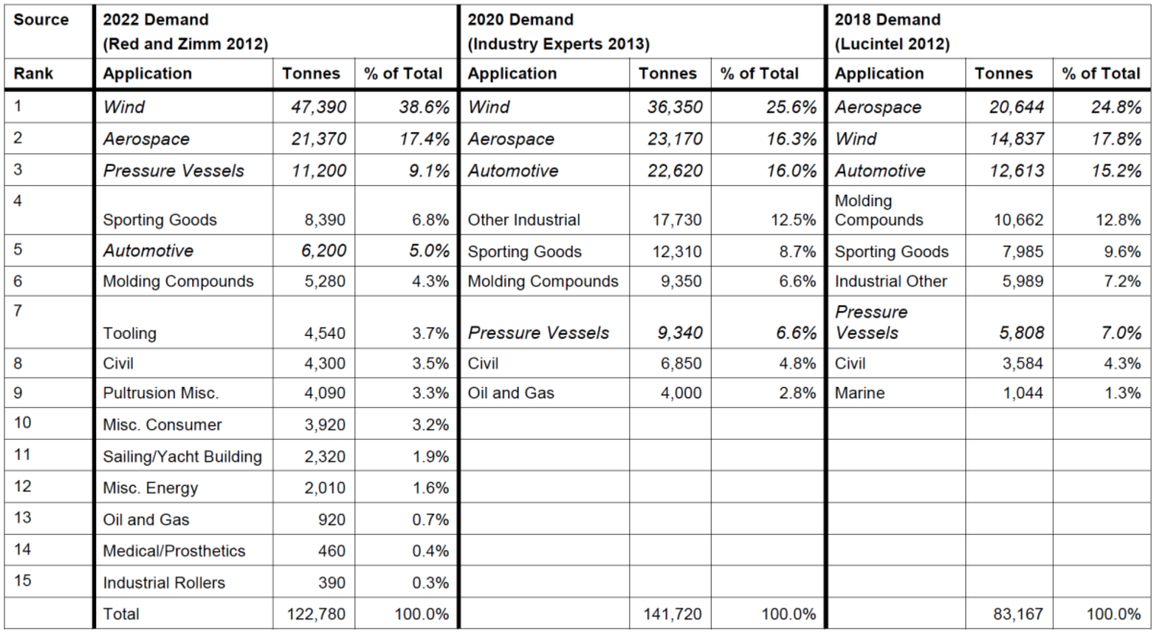
[225] John Bluck. " NASA Develops Robust Artificial Intelligence for Planetary Rovers," 2004, NASA Ames, https://www.nasa.gov/vision/universe/roboticexplorers/robust_artificial_intelligence_jb.html

[226] ibid.

Figure 1

Below is a table showing that almost 10 years ago the demand and industrial use of carbon fiber composites shifted from being primarily aerospace to wind turbines.

## Estimates of Carbon Fiber Demand by Industry (2013)[227]



| Source | 2022 Demand (Red and Zimm 2012) | | | 2020 Demand (Industry Experts 2013) | | | 2018 Demand (Lucintel 2012) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Rank** | **Application** | **Tonnes** | **% of Total** | **Application** | **Tonnes** | **% of Total** | **Application** | **Tonnes** | **% of Total** |
| 1 | *Wind* | *47,390* | *38.6%* | *Wind* | *36,350* | *25.6%* | *Aerospace* | *20,644* | *24.8%* |
| 2 | *Aerospace* | *21,370* | *17.4%* | *Aerospace* | *23,170* | *16.3%* | *Wind* | *14,837* | *17.8%* |
| 3 | *Pressure Vessels* | *11,200* | *9.1%* | *Automotive* | *22,620* | *16.0%* | *Automotive* | *12,613* | *15.2%* |
| 4 | Sporting Goods | 8,390 | 6.8% | Other Industrial | 17,730 | 12.5% | Molding Compounds | 10,662 | 12.8% |
| 5 | *Automotive* | *6,200* | *5.0%* | Sporting Goods | 12,310 | 8.7% | Sporting Goods | 7,985 | 9.6% |
| 6 | Molding Compounds | 5,280 | 4.3% | Molding Compounds | 9,350 | 6.6% | Industrial Other | 5,989 | 7.2% |
| 7 | Tooling | 4,540 | 3.7% | *Pressure Vessels* | *9,340* | *6.6%* | *Pressure Vessels* | *5,808* | *7.0%* |
| 8 | Civil | 4,300 | 3.5% | Civil | 6,850 | 4.8% | Civil | 3,584 | 4.3% |
| 9 | Pultrusion Misc. | 4,090 | 3.3% | Oil and Gas | 4,000 | 2.8% | Marine | 1,044 | 1.3% |
| 10 | Misc. Consumer | 3,920 | 3.2% | | | | | | |
| 11 | Sailing/Yacht Building | 2,320 | 1.9% | | | | | | |
| 12 | Misc. Energy | 2,010 | 1.6% | | | | | | |
| 13 | Oil and Gas | 920 | 0.7% | | | | | | |
| 14 | Medical/Prosthetics | 460 | 0.4% | | | | | | |
| 15 | Industrial Rollers | 390 | 0.3% | | | | | | |
| | Total | 122,780 | 100.0% | | 141,720 | 100.0% | | 83,167 | 100.0% |

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[227] Das, Warren, West, & Schexnayder, Global Carbon Fiber Composites Supply Chain Competitiveness Analysis, CEMAC, Oak Ridge National Laboratory, May 2016