Testimony of
Ralph L. McNutt, Jr., Ph.D.
Chief Scientist for Space Science
Space Exploration Sector
The Johns Hopkins University Applied Physics Laboratory

Before the
Subcommittee on Space
for the
Committee on Science, Space, and Technology
U.S. House of Representatives

October 4, 2017
"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

> *We shall not cease from exploration*
> *And the end of all of our exploring*
> *Will be to arrive where we started*
> *And know the place for the first time.*
>
> *- T.S. Eliot (1942)*

Introduction

The world changed 60 years ago today when the Soviet Union launched the artificial satellite Sputnik I into Earth orbit. While plans had been announced in the United States to launch such an object as part of the International Geophysical Year (IGY) of 1957, Sputnik caught the United States off guard. A 23-inch diameter sphere weighing just over 184 lbs (83.6 kg), much of Sputnik's weight was made up of 112 lbs. (51 kg) of three silver-zinc batteries, which regulated the temperature and powered the radio transmitter. The battery power lasted for 22 days and the satellite itself for 3 months before reentering the Earth's atmosphere.

Although it is commonplace now for most satellites to be powered – and very efficiently so – with solar arrays, this was not always the case. The first American satellite, Explorer I, launched at the end of January 1958 was also battery powered. Vanguard I, the fourth artificial satellite, a 6.4-inch diameter sphere weighing 3.2 lbs. was powered by six solar cells producing a watt of electricity, which allowed one of the transmitters to operate until 1964 (a separate transmitter was powered by a battery until 1958). Vanguard remains as the oldest spacecraft still in Earth orbit.

Providing power to satellites was an ongoing technical challenge. Batteries were reliable, but were also heavy and had limited lifetimes. Solar cells showed promise, but were subject to radiation damage in space that also limited their lifetimes. The use of nuclear power supplies for spacecraft, both in the form of radioisotope supplies and fission reactors was a subject of significant study. Such supplies offered lifetimes far in excess of the lifetime that could be expected from the electronics and other subsystems on satellites as well as total independence from both orientation of the spacecraft with respect to the Sun and the radiation environment of space.

The Atomic Energy Commission (AEC), beginning in 1951 and following RAND Corporation studies on the topic from the later 1940's, initiated what became the Systems Nuclear Auxiliary Power (SNAP) program. Following a great deal of development work, the first power unit was tested on the Navy's Transit 4A communications satellite, which was launched on June 29, 1961. The 175-lb satellite (slightly lighter than Sputnik I) was powered mostly by solar cells tied to nickel-cadmium batteries. However, the spacecraft also carried a ~4.5-lb SNAP 3B7 power supply, about 5.5 inches long and 4.5 inches in diameter, producing 2.7 watts of electricity from the heat provided by the radioactive decay of ~7 ounces (~200 grams) of the rare, human-produced isotope plutonium-238 (Pu-238).

Since those early years, many other isotopes have been proposed, produced, investigated, and tested. For spacecraft applications and reasons of moderate power combined with long lifetime, safety in handling, assembly and mounting in spacecraft, and relative ease of production, Pu-238 in the chemical form of plutonium dioxide has always been the best technical choice. While it is radioactive and must be handled with care, and while is it certainly not "cheap" to produce – and never has been – nonetheless it has consistently been, and continues to be, the best choice due to reasons of physics and chemistry that any technologies are subject to.

The Next Steps Taken

While solar arrays have vastly improved with time, both with respect to their efficiency in converting sunlight into electricity and in their tolerance to radiation damage in space, they remain limited in power output by the amount of sunlight available to them. Given the decrease of sunlight intensity with distance from the Sun (the "inverse-square law"), it had already become clear to NASA in the late 1960s that Radioisotope Power Systems (RPS) would be enabling for spacecraft trips past the asteroid belt to Jupiter and beyond. This led to the test of two SNAP 19 units on the Nimbus III satellite in 1969, qualifying them for use on Pioneer 10 and Pioneer 11, the first spacecraft to Jupiter and then to Jupiter and Saturn, respectively.

Such systems proved to be vital for applications closer to the Sun as well in applications for which large solar arrays were out of the question due to other engineering limitations. SNAP 27 systems were used to power the Apollo Lunar Surface Experiments Packages (ALSEPs) left on the lunar surface during the Apollo 12, 14, 15, 16, and 17 missions, and modified SNAP 19s enable the Viking 1 and 2 stations on the surface of Mars.

The twin Voyager 1 and 2 spacecraft followed Pioneer 10 and 11 out of the solar system, employing the Multi-Hundred Watt (MHW) RPSs developed by the U.S. Air Force for the communications satellites Lincoln Experimental Satellite (LES) 8 and 9.

With the then-upcoming Ulysses mission – joint between NASA and the European Space Agency (ESA) – a standardized "building block" for the RPSs, a General Purpose Heat Source (GPHS) was developed to ensure safety standards and cost efficiencies could be more easily realized for future missions. The GPHS modules combined with silicon-germanium converters enabled the Ulysses mission (one unit; with ESA and in an orbit near perpendicular to the orbital plane of the Earth and most of the planets), Galileo (two units; orbital mission to Jupiter), Cassini (three units; orbital mission to Saturn, just ended 15 September 2017), and New Horizons (one unit; had been a flight spare for the other missions; fly through the Pluto system on July 14, 2015 and now en route to the Kuiper Belt Object (KBO) "(486958) 2014 MU_{69}" on January 1, 2019).

None of these missions would have been possible without these RPS power supplies employed on them.

Cassini at Saturn

Describing all of the Cassini results from Saturn is an ongoing process. As the data returned from Cassini continue to be mined, there will be more and more new results. Taking a very broad-brush approach one can summarized some of the findings from the Cassini Huygens mission (*Ten Notable Findings from Cassini Huygens* by JoAnna Wendel, Earth and Space Science News, Vol. 98, No. 9, September 2017) as:

1. Cassini Revealed Enceladus's Potentially Habitable Internal Ocean
2. Huygens Showed Us Titan, a Possibly Primordial Earthlike World
3. Cassini Changed How We Think of "Habitability"
4. Cassini Found Enceladus Ocean Material in the E Ring
5. Cassini Unlocked Mysteries of Saturn's Hexagon
6. Cassini Showed Us One of Saturn's Huge, Infrequent Storms...
7. ...And That Storm Helped Cassini Detect Atmospheric Water
8. Cassini Dazzled Scientists with Saturn's Color-Changing Atmosphere
9. Cassini Spied Saturn's Rings Acting Like a Seismometer
10. Cassini Showed Us Saturn's Other Dynamic Moons

Cassini spent 13 years in orbit about the ringed-planet Saturn (2004 to 2017), acquired 435,000 images, and generated 3,948 scientific papers with 750 of these published in 6 journals of the American Geophysical Union (from Mike Liemohn, Editor-in-Chief, Journal of Geophysical Research: Space Physics).

At Saturn Orbit Insertion (SOI) on 1 July 20014, the three GPHS Radioisotope Thermoelectic Generators (RTGs) provided 744 watts for electricity to run the spacecraft from ~54 pounds of plutonium-238 (a smaller weight than that of the total plutonium dioxide mass in the generator housings).

New Horizons at Pluto

After a journey of 9.5 years (January 19, 2006 to July 14, 2015), the New Horizons spacecraft revealed the Pluto system: Pluto itself, its large moon Charon, and four more satellites (Nix, Hydra, Kerberos, and Styx). Pluto and Charon are entirely different worlds with different and unique landforms and surface compositions. Pluto itself has glaciers of frozen nitrogen, mountains of water ice, a surface that changes with, rather than being frozen by, time. The entire landscape merges with layers of haze and a tenuous atmosphere, reaching outward from the surface itself, showing the Kuiper Belt to be populated with anything but boring balls of ice, rather with distinct systems with personalities of their own.

No Guaranteed Future for RPS

Against the backdrop of the Cassini mission operations at Saturn and the successful flyby of the Jupiter system by New Horizons in the first half of 2007, it had become clear that there would be potential issues for any future missions that required RPSs. With the wind-down of the Cold War and fewer non-NASA users of Pu-238 in the U.S., supplies were more and more focused on purchases of the material from Russia. At the time of the RPS Provisioning Report (aka the "Casani report" of May 8, 2001), a restart of domestic Pu-238 production was still being discussed (it had been shut down when the Savannah River K-reactor was taken off line in 1988), and DOE had issued a record of decision (ROD) to proceed.

With a variety of upcoming requirements from NASA for (1) a 2007 Mars Smart Lander (MSL), (2) Europa Orbiter (EO), (3) Pluto Kuiper Belt (PKB), (4) Solar Probe (SP), and (5) a 2011 Mars Sample Return (MSR) mission, plans were made to develop a dynamic, Stirling RPS and a "new RTG" as a backup. The Stirling converter promised far greater conversion efficiency than existing static, thermoelectric converters, which would help take some of the pressure off of the Pu-238 supply but was seen as offering developmental and consequent programmatic risk. Hence the new RTG was designed to serve as a backup to the Stirling unit in order to alleviate such programmatic risks, if development problems arose. This middle ground eliminated both the risk of an all-Stirling program and the continued high-use rate of Pu-238 in an all-RTG program – the driver was viewed to be the provision of a Stirling system to the MSL mission in time for a 2007 launch.

With the 9/11 attacks in the United States, security for production of Pu-238 and assembly of the RPSs came under renewed scrutiny. One consequence was the removal of the Mound facility in Miamisburg, Ohio to a new facility in Idaho in the midst of the fueling campaign for the GPHS-RTG for New Horizons. The Stirling program suffered technical performance issues and the "new RTG" that was the "backup" now became the primary item. In order to operate in both an atmosphere (on the surface of Mars) and in the vacuum of space, a decision was made to go back to the conductive converter technology that had been used in the SNAP 19 units, in effect abandoning the more efficient and longer-lived, silicon-germanium technology that could operate only in a hard vacuum. The unit was christened the "Multi-Mission RTG" or MMRTG.

MSL, now the Mars Surface Lander, was already slipping to a 2009 launch date (and eventually to a 2011 launch date as the "Curiosity" rover). Mars Sample Return was, in turn, moved even further "to the right," i.e., to a later launch date. Europa Orbiter was cancelled, Pluto Kuiper Belt became the competitive procurement won by the New Horizons team, with the promise of a GPHS-RTG in the form of the Cassini "flight spare," and Solar Probe was reformulated as "Solar Probe Plus" (now Parker Solar Probe) to eliminate its need for an RTG. An Advanced Stirling Radioisotope Generator (ASRG) project was begun, picking up from the Stirling unit originally advocated as the prime development by the RPS Provisioning Team in 2001.

At this time (2008), the Radioisotope Power Systems Committee was stood up by the National Research Council to assess the situation. That committee made 13 findings, 3 recommendations, and 2 high-priority recommendations. While most of the recommendations reiterated many aspects of the then-current situation, the final one was one of the most significant, reflecting upon the lack of progress since the Provisioning report of 2001:

> **FINDING. Flight Readiness.** NASA does not have a broadly accepted set of requirements and processes for demonstrating that new technology is flight ready and for committing to its use.

The recommendations addressed the MMRTG, Flight Readiness criteria, and the provision of a guiding Technology Plan. The first required monies for maintaining the MMRTG as something that could be used while other approaches continued to be investigated and developed. The Committee found the other two recommendations as vital for providing overall programmatic guidance, while realizing that neither would be easy to implement:

> **RECOMMENDATION. Flight Readiness.** The RPS program and mission planners should jointly develop a set of flight-readiness requirements for RPSs in general and Advanced Stirling Radioisotope Generators in particular, as well as a plan and a timetable for meeting the requirements.
>
> **RECOMMENDATION. Technology Plan.** NASA should develop and implement a comprehensive RPS technology plan that meets NASA's mission requirements for RPSs while minimizing NASA's demand for 238Pu. This plan should include, for example:
> - A prioritized set of program goals.
> - A prioritized list of technologies.
> - A list of critical facilities and skills.

- A plan for documenting and archiving the knowledge base.
- A plan for maturing technology in key areas, such as reliability, power, power degradation, electrical interfaces between the RPS and the spacecraft, thermal interfaces, and verification and validation.
- A plan for assessing and mitigating technical and schedule risk.

The two high-priority recommendations were listed as such to try to stem what the Committee viewed at the time (2009) as negative trends, which, if left to go for too long, might be irreversible:

> **HIGH-PRIORITY RECOMMENDATION. Plutonium-238 Production**. The fiscal year 2010 federal budget should fund the Department of Energy (DOE) to reestablish production of 238Pu.
>
> - As soon as possible, the DOE and the Office of Management and Budget should request—and Congress should provide—adequate funds to produce 5 kg of 238Pu per year.
> - NASA should issue annual letters to the DOE defining the future demand for 238Pu.

> **HIGH-PRIORITY RECOMMENDATION. ASRG Development.** NASA and the Department of Energy (DOE) should complete the development of the Advanced Stirling Radioisotope Generator (ARSG) with all deliberate speed, with the goal of demonstrating that ASRGs are a viable option for the Outer Planets Flagship 1 mission. As part of this effort, NASA and the DOE should put final design ASRGs on life test as soon as possible (to demonstrate reliability on the ground) and pursue an early opportunity for operating an ASRG in space (e.g., on Discovery 12).

The first high-priority recommendation has been acted upon, and the first new material has been produced at the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). An updated need for plutonium-238 is included in *Vision and Voyages*, the Planetary decadal survey document, published in 2011. Table 9.5 in that document compares the stated NASA needs as of April 29, 2008 and March 25, 2010. The projected needs decreased with the termination of the Constellation program and its associated pressurized rovers for human use on the lunar surface. Negotiations between NASA and DOE have continued to try to strike the right balance for the production rate, but (to the best of my knowledge) no further requirements letters have changed hands at these two agencies, or, if they have, they have not been easily, publicly accessible.

Subsequent to the issuance of the 2009 RPS report, responsibility for maintenance of the production infrastructure of Pu-238 fuel for the RPSs was transferred to NASA from DOE. An assessment was made of the true cost impacts, and a final report was transmitted from NASA to the Office of Management and Budget (OMB) in the Fall of 2013. I was a member of that study team; to the best of my knowledge, that report has never been made public.

The second high-priority recommendation had also been followed, but technical progress lagged. The need for ASRGs for future missions was reiterated in the *Vision and Voyages* document; however, with costs mounting and technical difficulties continuing, that particular program was cancelled by NASA late in calendar year 2013. There do continue to be ongoing developmental efforts in looking at Stirling technology for RPS converters, however.

It is worth noting that converter technologies for RPSs have long remained technically difficult, expensive, and elusive. The Galileo spacecraft was to originally have used a Selenide Isotope Generator (SIG), which effort was finally stopped due to technical problems and replaced by the GPHS-RTG. Similarly, the use of the alkali-metal thermal to electric converter (AMTEC) for spacecraft use was initially funded as part of NASA's X-2000 technology development program. Technical problems led to its abandonment in the early 2000's with the moves to the Stirling converter and MMRTG as advocated in the 2001 provisioning study.

Overall, a lesson, which should be learned and acknowledged as such, is that while the various converter technologies discussed over the years have shown promise, the actual development of these techniques into usable flight hardware has proven to be a very, very difficult task. This is perhaps best reflected in the fact that no other country in the world to date has developed, much yet used, comparable power systems for deep space use.

Current Status and Perceived Needs

An examination of the *Vision and Voyages* survey reveals that the view of the scientific space community is that the need for such RPS supplies has not gone away. While developments with the solar arrays have now pushed the technology into use in the Jupiter system (notably on the current Juno mission, and the future ESA JUpiter ICy moons Explorer (JUICE) mission and the NASA Europa Clipper mission), such developments have had their own challenges. The notable difficulty was with the low-intensity, low-temperature (LILT) effect that makes for less efficiency (than would have been ascribed to the simple decrease in solar intensity with distance to the Sun alone).

Future missions to the outer solar system, e.g., a return in-depth study of Saturn's moon Titan or to the Icy Giant worlds of Uranus and Neptune and/or Neptune's large moon Triton (perhaps a captured KBO), will all be hard pressed to be flyable without an RPS. As with the MMRTG on Curiosity and Mars 2020 (now being built), other pieces of a successful Mars Sample Return campaign will likely need an RPS. Similarly, future landers on Mercury or landers with rovers into the permanently shadowed regions of the Moon will be problematic without RPSs. Any mission to other large KBOs such as Quaoar, Makemake, Haumea, or others or an Interstellar Probe mission to the far reaches of the interstellar medium beyond, well past the reach of Voyagers 1 and 2, will also have the same needs. These needs will require the capabilities of the long-lived, high-efficiency systems possessed by the MHW and GPHS-RTG systems with their silicon-germanium converters, a capability which we no longer possess (Pioneer 10 and 11, with converters similar to those used in the MMRTGs, finally succumbed to the decay of their power supply outputs. Voyager 1 and 2, now at their 40-year marks, will not outlast the 2020s, and, if supported for operations until then, New Horizons will not outlast the 2030s; even the Pu-238 fueled RPS generators based upon silicon-germanium converter technology will not last forever; even longer-lived supplies are another story).

The Nuclear Power Assessment Study (NPAS) of 2014 to 2015 was conducted with many participants both from the DOE and NASA to examine the objective of discussing "a sustainable strategy and present findings for the provisioning of safe, reliable, and affordable nuclear power systems that enable NASA Science Mission Directorate (SMD) missions and is extensible to Human Exploration and Operations Mission Directorate (HEOMD) needs in the next 20 years." That group of people looked in depth at various future possibilities, again using *Vision and Voyages* as a guide. They came to ten, broad conclusions:

1) NASA will need appropriately sized nuclear power systems to support robotic space missions for the period covered by the decadal surveys currently in force.
2) This need for nuclear power systems is expected to extend for at least one more decade past that covered by the current decadal surveys.
3) Without significant budget increases in mission cost caps, projected, single-mission power requirements are unlikely to exceed ~600 W_e [i.e., watts of electrical power, rather than thermal power].
4) Radioisotope Power Systems (RPS) with projected Pu-238 production rates and current technology may suffice to fulfill currently projected SMD needs.
5) Significantly increased capability in the rate of RPS electrical power available for missions is possible only with increased Pu-238 production rates and/or flight qualification of a dynamic [e.g., Stirling] converter.
6) Converter technologies are independent of the nature of the nuclear heat source.

7) SMD has a continuing requirement to maintain and advance RPS for the next two decades and to plan for increased Pu-238 production rate over time.
8) A space-based fission power system (FPS) could potentially enable higher power SMD missions, but only if the future need arises and sufficient new funds to develop an FPS flight unit are provided.
9) FPS could be used on, but are not currently required for, SMD missions and would present technical challenges.
10) SMD has no current requirements for a mission power system at the 1-kW_e [1,000 watts of electricity] level or higher, and so no current requirement for an FPS exists.

A Road Forward

With a great expenditure of funds (literally billions of inflation-adjusted dollars from the late 1940s forward), effort, and time (over six decades) the United States has developed a technology for powering spacecraft to regions of space not otherwise reachable. The spectacular results from the Cassini mission to Saturn, the New Horizons mission to the Pluto system, and the Curiosity mission carrying out its in-depth investigations of Mars would not have been possible without this means, a means duplicated by no other country or entity on this planet. The road forward remains clouded, not because we do not know the way, but because we do not like its cost. Time and again, we have attempted other roads with the promise of a less-expensive way out, only to run into new technological dead-ends after an additional great expenditure of time and money.

Operating on the edge of the scientifically and technologically possible will never be cheap, yet the realities of resources mean that we must plan prudently as we move ahead. Production of Pu-238 fuel and converters to use it is a complicated undertaking, most efficiently carried out with decades of upfront planning and carefully planned stewardship of the required infrastructure. The spacecraft missions that make use of these materials come and go on much shorter times scales, with starts and stops, and turns and twist that resist the type of planning needed to produce the power supplies. This dichotomy has led to the continuing managements challenges between the DOE and NASA, which has become even more difficult as NASA has emerged as the "primary customer" for RPS.

This activity is one that requires active joint management by both the DOE and NASA. The years following the original 2009 RPS study have shown that formal and public yearly assessments of needs by NASA and DOE can help to maintain a solid operative plan and that a corresponding and regularly updated, public technology plan attached to consensus-based, flight-readiness requirements, all items called for in the 2009 RPS report, could provide beneficial tools for all of the stakeholders in tracking and managing the progress needed in implementing Decadal missions in the future. Such an effort is not trivial, nor should it be. The unfortunate debacle presented by the cancelled ASRG effort is yet another example in the line following the selenide and AMTEC converter dead ends, not of a management failure but of how technically difficult these efforts are. It also helps drive home the point that the GPHS-RTG technology was a technical result that should be seriously reconsidered for reestablishment as the backup to missions that do not need to operate in an atmosphere, yet cannot be carried out without RPS power. At the same time, the MMRTG remains vital for the exploration of Mars and the search for life there. Perhaps the lesson is that despite our best attempts, there is no "one size fits all" RPS converter technology, nor is there one on the horizon.

As President Kennedy said in unveiling the manned lunar program, as explorers and as Americans, we choose to do things not because they are easy but rather "because they are hard, because that goal will serve to organize and measure the best of our energies and skills, …." These sentiments are no less true of our endeavors in space today.

No one, either at the launch site of Sputnik I in Kazakhstan or in Washington, D.C. learning of that event sixty years ago today would have predicted the incredible results, which we have all now witnessed, to be returned by robotic satellites operating throughout our solar system and along our first faltering steps to the stars. But making a thing look easy does not mean it is easy or that the effort was not worth it. Rather that apparent "easiness" is the reflection of the determination of the woman and men who have made it look so. We can continue on this path with new wonders to be beheld sixty years from now, or we can stop. It is an active choice, and that choice is ours, as we make the history for future generations to look back at. In the end, it really is all about us.

Summary

1. **Introduction**
   Launch of Sputnik 60 years ago
   Vanguard and solar cells
   Batteries – robust but limited lifetime
   SNAP development
   Selection of Pu-238 isotope

2. **The Next Steps Taken**
   Limitations of solar arrays with Sun distance
   SNAP 19 units on Nimbus III satellite to qualify for use on Pioneer 10 and Pioneer 11
   Applications closer to the Sun as well in other applications
   SNAP 27 for ALSEPs - Apollo 12, 14, 15, 16, and 17
   Modified SNAP 19s enabled the Viking 1 and 2 landers
   Voyager 1 and 2 followed Pioneer 10 and 11
   Multi-Hundred Watt (MHW) RPSs developed for LES 8 and 9
   GPHS modules with silicon-germanium converters enabled Ulysses, Galileo, Cassini, New Horizons
   None possible without these RPS power supplies

3. **Cassini at Saturn (graphics)**

4. **New Horizons at Pluto (graphics)**

5. **No Guaranteed Future for RPS**
   Issues for any future missions that required RPSs
   "Casani report" May 8, 2001
   Restart of domestic Pu-238 discussed
   Requirements from NASA: 2007 Mars Smart Lander (MSL), Europa Orbiter (EO), Pluto Kuiper Belt (PKB), Solar Probe, and 2011 Mars Sample Return (MSR) mission
   Stirling RPS and "new RTG" as a backup
   Eliminate risk of an all-Stirling program and continued high-use rate of Pu-238 in an all-RTG
   9/11 attacks - removal of the Mound facility in Miamisburg, Ohio to a new facility in Idaho
   "new RTG" that was the "backup" now became the primary item
   Conductive converter technology used in the SNAP 19 units used for "Multi-Mission RTG" or MMRTG.
   NRC RPS Committee: 13 findings, 3 recommendations, and 2 high-priority recommendations
      RECOMMENDATIONs. Flight Readiness and Technology Plan
      HIGH-PRIORITY. Plutonium-238 Production and ASRG Development
   Projected needs decreased with the termination of the Constellation program
   Responsibility for maintenance of the production infrastructure of Pu-238 transferred to NASA
   Need for ASRGs for future missions reiterated in *Vision and Voyages* document
   Converter technologies for RPSs have long remained technically difficult, expensive, and elusive: Selenide Isotope Generator (SIG) for Galileo, and Alkali-metal thermal to electric converter (AMTEC) for NASA's X-2000 program
   Lesson: development into usable flight hardware has proven to be a very, very difficult task

6. **Current Status and Perceived Needs**
   Scientific space community need for such RPS supplies has not gone away.

Missions to the outer solar system, Mars Sample Return campaign, landers on Mercury, rovers into the permanently shadowed regions of the Moon, missions to large KBOs, and Interstellar Probe also will require long-lived, high-efficiency systems
Voyager 1 and 2, now at their 40-year marks, will not outlast the 2020s
New Horizons will not outlast the 2030s;
The Nuclear Power Assessment Study (NPAS) of 2014 to 2015 reached ten, broad conclusions

7. A Road Forward

U.S. has developed a technology for powering spacecraft to regions of space not otherwise reachable.
Operating on the edge will never be cheap
Requires active joint management by both the DOE and NASA; not trivial, nor should it be.
President Kennedy: "because they are hard, because that goal will serve to organize and measure the best of our energies and skills, …."
Making a thing look easy does not mean it is easy or that the effort was not worth it
The choice is ours, as we make the history for future generations to look back at
It really is all about us.