Identifying and Mitigating Barriers to the Adoption of Dynamic Radioisotope Power Systems for Space Flight

E. Scott Brummel
Humans and Autonomy Lab
Duke University
304 Research Dr,
Durham, NC 27708
419-708-4569
Sab126@duke.edu

Paul Ostdiek
Applied Physics Laboratory/
Johns Hopkins University
11100 Johns Hopkins Rd.
Laurel, MD 20723
443-778-1458
Paul.Ostdiek@jhuapl.edu

Dave Woerner
Jet Propulsion Laboratory/Caltech,
4800 Oak Grove Dr,
Pasadena, CA 91011
818-354-4321
david.f.woerner@jpl.nasa.gov

Kenneth Hibbard
Applied Physics Laboratory/
Johns Hopkins University
11100 Johns Hopkins Rd.
Laurel, MD 20723
443-778-1458
Kenneth.Hibbard@jhuapl.edu

Ellen Stofan
National Air and Space Museum
Independence Ave at 6th St, SW
Washington, DC 20560
202-633-2214
ellen.stofan@jhuapl.edu

June Zakrajsek
NASA Glenn Research Center
21000 Brookpark Rd,
Cleveland, OH 44135
216-433-4000
june.f.zakrajsek@nasa.gov

Mary L. Cummings
Humans and Autonomy Lab
Duke University
304 Research Dr,
Durham, NC 27708
919-660-5306
mary.cummings@duke.edu

Abstract - **Given increasing complexity of many safety-critical systems, many organizations like NASA need to identify when, where, and how inappropriate perceptions of risk and anchoring of trust affect technology development and acceptance, primarily from the perspective of engineers and related management. Using the adoption of Dynamic Radioisotope Power Systems (RPS) for space exploration as a backdrop, we define and explain factors that contribute to inappropriate risk perception of various stakeholders. Three case studies (Mars Science Laboratory, Parker Solar Probe, and Titan Mare Explorer) demonstrate how NASA considered Dynamic RPS but decided against the new technology for less efficient alternatives of solar power and solid-state RPS. In the case of Dynamic RPS, increased design complexity that differs from previous successful solid-state power systems flown on the Voyager probes and Cassini spacecraft is one contributing factor, but not the only one. Problems with system performance and incorrect technology readiness labeling of Dynamic RPS technology led to an increased perception of distrust in Dynamic RPS for future missions. We also find that the perception of risk for Dynamic RPS future development is exacerbated by on-going organizational challenges requiring multi-agency collaboration and coordination. Difficulties in setting realistic expectations for the new technology as well as maintaining coherent roles and responsibilities among the disparate teams involved challenged the technology's credibility and confidence of mission planners. Further, the lack of an independent technology readiness assessment process and a lack of transparency into ongoing technical problems also constrained mission planners from gaining critical information about the technology's reliability. Though technology development budgets and schedules are often constrained due to sociotechnical and political reasons, technology development teams that address the challenges identified here could allow them to mitigate the sources of inappropriate trust that are within their control.**

TABLE OF CONTENTS

978-1-5386-2014-4/18/$31.00 ©2018 IEEE

1. INTRODUCTION

Operators of complex systems, particularly safety-critical ones like those in command and control settings often distrust new technologies which can negatively affect mission outcomes since systems are not utilized to their full capacity [1–3]. This problem is only expected to get worse as more opaque technologies like those enabled with artificial intelligence are inserted into these systems. To address these issues, significant research is underway to better understand the core cognitive elements of trust and risk perception for such systems, as well as to develop models and design interventions for appropriately anchoring trust [4–9].

While this previous research addresses a clear operational need, a limitation of these efforts is the focus on operators and managers of real (or near-) time systems. Of interest to many organizations like NASA is the need to identify when, where, and how perceptions of risk and anchoring of trust, both too much and too little, affect technology development and acceptance, primarily from the perspective of engineers and related management. Despite the significant research that is currently underway to mitigate inappropriate trust and risk perception for operators of complex systems, very little research is occurring to assess, describe, model, or develop risk mitigation strategies for engineers developing or applying new technologies.

In this paper we attempt to minimize this gap by defining and explaining factors contributing to inappropriate risk perception and resulting barriers for the adoption of Dynamic Radioisotope Power Systems (DRPS) for space exploration and offer up possible mitigations to these barriers. While solar power is a common and reliable means of providing electricity for most of NASA's space missions, many potential space science opportunities exist in environments without sufficient sunlight for solar powered space flight. For example, because Saturn is about ten times farther from the Sun than Earth, the available sunlight to produce electricity for space operations is only one hundredth of that on Earth.

Non-solar solutions have the ability to overcome these power limitations and fill critical mission gaps in space exploration [10]. US government has relied on static RPS to generate energy through the use of Radioisotope Thermoelectric Generators (RTGs) that rely on thermoelectric couples. These solid-state devices produce electricity by converting heat from decaying plutonium flowing through semiconductors and into the much lower temperature of space. Such technology was also used for the more recent Mars Curiosity rover missions. However, as will be discussed in more detail in later sections, these solid-state RPS systems are relatively inefficient and the plutonium fuel is costly to produce, store, and process. DRPS, such as Stirling-based RPS, are more efficient, promising a slower rate of consumption of plutonium fuel. NASA has struggled to field such systems and risk perception likely plays an important role, which will be elucidated here.

2. RADIOISOTOPE POWER SYSTEMS

To facilitate the production and development of Radioisotope Power Systems (RPS) systems for NASA space missions, the NASA Glenn Research Center (GRC) hosts the RPS Program Office with funding provided by NASA's Science Mission Directorate's Planetary Science Division. While GRC leads RPS-related programs, the Department of Energy (DOE) is required by the Atomic Energy Act of 1954 to design, manufacture, and fuel RPS including Dynamic-RPS. Working in conjunction with GRC and DOE, the Johns Hopkins University Applied Physics Laboratory (APL), Goodard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL) also assist with ongoing RPS and DRPS development.

In the mid-1990s, NASA and DOE began investing in the development of the more fuel-efficient, multi-mission capable RTGs and Stirling-RPS systems. Unlike earlier solid-state systems, Stirling-RPS use compression and expansion of a working fluid or gas (such as helium) via heat addition from the decay of Pu-238 to move a turbine or piston to drive an alternator that produces electricity.

Static RPS (i.e. RTGs) typically convert energy at five to seven percent efficiency, but a Stirling-RPS could achieve nearly four times the efficiency. Increased efficiency has been a concern as Pu-238 production stopped in 1988 when the DOE shuttered the Savannah River Site reactor [11-12]. To maintain it's capability for RPS-enabled flight, NASA began funding the DOE to restart Pu-238 production in 2011.

DRPS development and use would seem an obvious choice for various NASA missions. Figure 1 illustrates the relative use-areas of NASA's available power systems. To the extent that Pu-238 availability or cost of production is a factor in picking an RPS for spaceflight, the efficiency of DRPS compared to solid-state RPS suggests increased DRPS use. In fact, the benefits of Stirling-RPS were recognized by the National Research Council's (NRC) findings in 2006 that 21 of the envisioned missions for the coming decade would be significantly enhanced by RPS [10]. However, in the decade since the NRC's prediction of RPS space flight missions, only 4 of the RPS-enabled missions envisioned by NASA continued to consider RPS as a possible power source and none include DRPS [10].

Two Discovery-class missions (TiME and CHopper) were formally incentivized by NASA to carry Stirling-RPS, indicating that DPRS missions were endorsed at the highest levels of NASA. However, none of these Stirling-RPS-planned missions were approved for flight following NASA's independent risk assessments and mission selection. The Discovery missions were not selected past the initial Phase A studies and two flagship missions were later converted from Stirling-RPS to solar. To date, no Stirling nor DRPS system has flown in space nor are either in development for use in space, though this technology's development is still being funded.

The failure at integrating Stirling-RPS into space flight is just one example of the failure to impliment new technology that occurs in high-tech companies around the country. In otherwords, such failures can, in part, be understood as high expectations blind to harsh realities. Engineers experienced with such failures and dashed expectations can be resistant to change. Engineers comfortable with current technology can also be resistant to change, even in the face of empirical evidence [18]. Despite the desire to be objective in the face of data, engineers can be subject to their own decision biases and irrational reasoning processes [19]. Any hope for the successful implementation of Striling or other DRPS or any newly minted technology depends on successfully overcoming both the technical, social, and psychological barriers to development and adoption.

In this next section, three examples of abandoned Dynamic-RPS applications, specifically Stirling-RPS, are highlighted to aid in this analysis of the difficulties of adopting DRPS for space exploration. Following the case studies, we explain the origins and justifications for NASA's interest in and evolution of DRPS as well the specific developments leading up and possibly contributing to the failed attempts of DRPS adoption. We conclude with an analysis of barriers to the technology's adoption and a discussion of possible mitigations of these barriers.

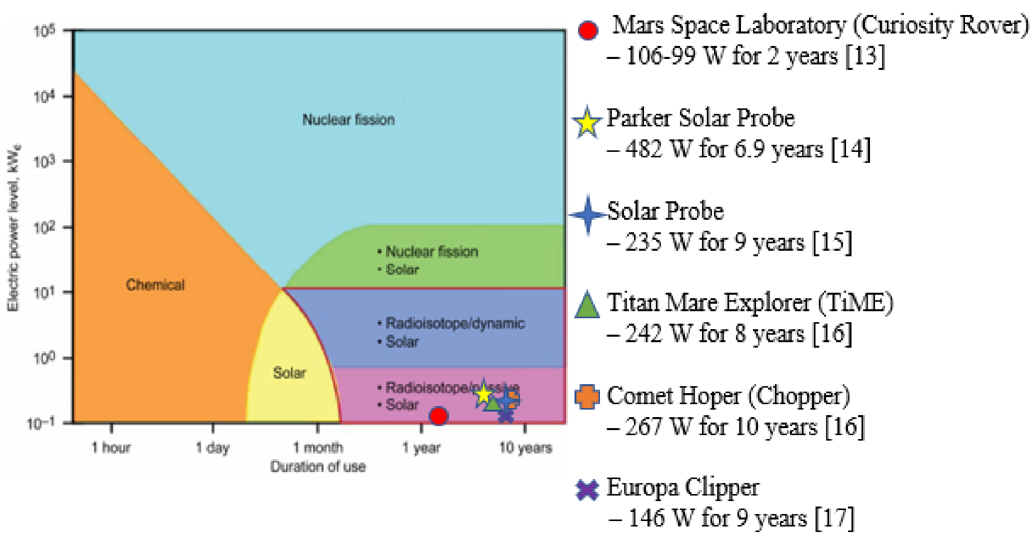

Figure 1. Relative use areas of NASA's available power systems [10].

Case Study: Mars Science Laboratory Mission

The goals of MSL are to discover whether Mar is and or was habitable for life and to lay the foundations for potential future manned missions to the planet [20]. While several earlier NASA surface missions on Mars (Pathfinder, Spirit, and Opportunity) were solar powered, the NRC's 2003 "New Frontiers in the Solar System" decadal study called for a much larger directed and flagship mission to Mars including a rover capable of conducting more sophisticated, longer-lasting, and power-intensive surface observations. Specifically, the NRC study argued that the development and implementation of an advanced RPS would be needed to overcome the science-limiting effects of Martian's dusty, cold, and variable-sunlit surface faced in previous rover missions [21]. NASA successfully launched the Mars Science Laboratory (MSL), which landed the RPS-enabled rover, Curiosity, in August of 2012.

Two power sources were considered for this mission, the 110W Stirling Radioisotope Generator (SRG-110, a Stirling-RPS) and the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG, a solid-state RPS that also generated

110 W.) Initiated by the DOE at the same time as the SRG-110, the MMRTG is a RPS generator designed for multiple mission types as it can provide power in space and on airy bodies such as Mars and Titan. The MMRTG was introduced as an improvement because of its capability to provide power in both vacuum-space and surface missions like MSL, but also future proposed missions throughout the solar system while maintaining the approximate power-conversion efficiency of earlier RPS systems [21–25].

Interestingly, at the time neither the MMRTG or Stirling-RPS were flight-proven technologies. However, proponents of the MMRTG claimed “heritage” by relying on similar thermoelectric couple designs and materials from the earlier Systems for Nuclear Auxiliary Power 19 (SNAP-19) generators flown on the Viking lander and Pioneer missions [22]. While this designation of heritage is not theoretically applied in favor or against a technology until after a mission’s first key decision gate, heritage, or applicability of past designs, hardware, and software to the present one, helps mission planners and assessors determine a mission’s anticipated risks, costs, and schedule [26].

At the time of consideration, the SRG-110 RPS was believed to provide a similar amount of power using four times less plutonium mass, approximately 6 kg, than an MMRTG.. However, despite these advantages, the SRG-110 reportedly lacked lifetime qualification for its convertors [27] and was not as robust against externally-applied dynamic loads as the MMRTG, which was critical for the difficult hard landing that was planned for the MSL [27]. Further, some have advocated for flying a redundant generator for risk mitigation due to a lack of heritage and that would mean the SRG-110’s mass advantage would be lost and MSL would suffer a significant penalty. However, whether the redundant use of DRPS is needed has been a matter of debate [27]. Ultimately the MMRTG was selected over the SRG-110 RPS for its better mission fit in 2004, with the mission’s successful launch following in November 2011.

Case Study: Solar Probe

Since 1994, twenty-two heliophysics missions have flown, all solar powered except for the RPS-enabled 1990 Ulysses mission [16], [28–32]. In 2003, the NRC Solar and Space Physics Decadal Study promoted an RPS-enabled Solar Probe mission to come within 1.3M miles of the Sun as the number one priority of large-scale flagship missions. In the NRC study, RPS was praised for its ability to simplify the mission design and make the record-shattering proximity of the mission possible [31–32]. Following the NRC’s 2003 decadal study, the RPS-enabled Solar Probe mission definition team was led by JHU-APL [32-33], although it previously went through many iterations and was orginally led by JPL.

A JHU-APL Solar Probe mission plan was devised in 2005 to bring a payload of in-situ and remote-sensing instruments within 3 solar-radii (approximately 8 times the distance to the Moon) of the Sun [32]. To achieve this proximity, the mission trajectory would require prolonged space flight through Jupiter’s orbit to swing the probe towards the Sun for two fly-bys separated by 5 years [32]. Radiation exposure from Jupiter, extreme temperatures, bombarding dust particles, and coronal lightening throughout the mission all ruled out the possibility of a solar-powered probe mission, making RPS a requirement [32]. Three MMRTGs were considered for the mission as they were seen as the only viable RPS model available at the time [32]. Production of the General-Purpose Heat Source-RTG, or GPHS-RTG, which supported Ulyssess, Cassini, Hew Horizons and Galileo were no longer available for this mission [34-35].

By 2005, the Science and Technology Definition Team (STDT) for the Solar Probe mission considered the SRG-110, which was theoretically available for a 2014 launch [32–33]. The STDT selected the MMRTG over the SRG-110, however, due to SRG-110’s lack of flight heritage. However, at that time, the MMRTG had started Qualification Unit testing but was not yet scheduled to be flight-test ready until a year later in 2006. Nevertheless, as with the MSL, the team claimed heritage for the MMRTG as a redesign of an earlier RPS model, the SNAP-19, used 30 years earlier in the Viking and Pioneer missions [21], [35]. In 2005, the SRG-110 had over 10,000 hours of duration testing but was a new design altogether with no vacuum, flight, or Qualification Unit testing [36]. Further, contributing to the STDT decision was possible electromagnetic interference of the Solar Probe’s science instruments caused by the alternating current produced by the SRG-110 [21], [31].

By 2007, the overall cost estimates of a RPS-enabled Solar Probe mission had become untennable with NASA’s available funding priorities [38]. Another crucial issue stemmed from concern that DOE would not be able to provide sufficient amounts of Pu-238 for the MMRTGs [11]. Ultimately in 2008, JHU-APL proposed a reduced cost mission instead called Solar Probe+, although the mission was later renamed to Parker Solar Probe (PSP) in honor of astrophysicist Eugene Parker who theorized the existence of solar wind [37–39]. To meet the lower cost and solar power requirements, the probe’s mission trajectory was redesigned to avoid the need for near-Jupiter flight by approaching the Sun within only 8.5 solar radii but with a total of 24 fly-bys. Moreover, the mission trajectory requires a very high launch energy, favoring the lighter solar power system and thus lowering perceived risk [14]. On August 12, 2018, PSP successfully launched per this plan.

Case Study: Titan Mare Explorer

NASA facilitates the creation and execution of its missions through either a directed or competed process. Directed flagship missions, like MSL and PSP, are typically designated as high-priority research opportunities and are designed by teams selected by NASA. Competed missions, like the proposed Titan Mare Explorer (TiME), address science priorities in the Decadal Studies and selected through a competitive peer-reviewed process facilitated by NASA. Manifested through an Announcement of Opportunity (AO) process by programs like Discovery and New Frontiers, competed missions are also typically smaller in scope and cost, and designed and operated in conjunction with other agencies and non-NASA facilities.

Just prior to the 2010 Discovery-12 AO, after the Cassini/Huygens discovery of Titan's lakes and seas in 2007, major questions emerged about the origin, chemistry, and weather patterns on Saturn's largest moon [40]. Further spurred on by the NRC's 2003 "New Frontiers in the Solar System" encouraged development of a mission to Titan and NASA Science Mission Directorate's 2007 "Discovery and Scout Mission Capabilities Expansion Study" (DSMCE), a Titan Mission was identified as one of nine possible Stirling RPS-enabled space missions. JHU-APL then proposed TiME, a Stirling RPS-enabled mission in response to the 2010 Discovery-12 AO [40–42].

NASA often shapes, constrains, and incentivizes different kinds of mission opportunities considering new NASA priorities, technologies, and practices derived from administration initiatives, congressional concerns, or other management concerns. In the 2010 Discovery-12 Program AO, NASA included an incentive for investigators to test new technologies and enable new science while also reducing mission costs by including up to two government-furnished mission-enabling Advanced Stirling Radioisotope Generators (ASRGs), the successor of the SRG-110 valued at $54M FY 2010, in mission proposals [41].

In 2010, the ASRG qualification unit was still in its preliminary design phase and the Stirling RPS development project had completed its final design review of an ASRG engineering unit. The ASRG design had shown encouraging results as a viable, lighter, and more efficient RPS model that required only a fourth of the Pu-238 as other RPS models. Proposals with an ASRG would receive the power system free of charge but would have to set aside $20M of the $425M allotted for Discovery missions to cover environmental and launch approvals not required of solar-powered missions [41]. As per Federal Acquisition Regulations, ASRG-enabled mission proposal teams would not be able to work or communicate directly with the ASRG development team to protect the integrity of the competitive process [41], [43].

By May 2011, three Discovery mission proposals were selected for Phase A development including JPL's solar-powered InSight mission to Mars, GSFC's ASRG-enabled Wirtanen Comet Hopper (CHopper), and JHU-APL's TiME. Reflecting science priorities laid out in NRC's 2003 Decadal Study, TiME would provide the first direct exploration of an ocean environment beyond Earth by landing in and floating on a large methane-ethane sea on Titan. Scientific instruments aboard TiME would include a mass spectrometer, sonar, meteorological instruments, and imaging cameras. Due to Titan's thick atmosphere resulting in a low solar intensity and the opportunity to simplify landing requirements, RPS was considered over solar power as the possible power source for this mission [16]. Further, because of Titan's low surface temperature, heat from a source like the ASRG must be supplied to maintain mission duration of more than a few hours [16], [44]. If selected, either TiME or CHopper would have been the ASRG's first space flight demonstration. [40]. GSFC's CHopper proposal also included an ASRG.

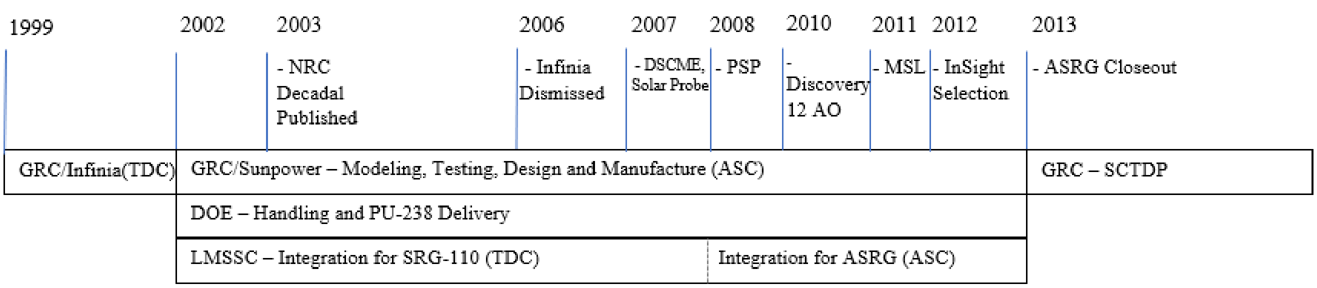

Figure 2: Timeline of development for the TDC and ASC-based SRG models.

After TiME's selection for Phase A development and unbeknownst to the TiME proposal team, the ASRG failed its final design review causing the DOE to restructure its management of further ASRG development [44–46]. That next month, after another detailed review of the TiME, InSight, and CHopper concept studies in 2012, NASA selected the solar powered InSight mission to Mars for the Discovery-12 AO program, which successfully launched in May of 2018.

After review of these three instances in which a Stirling-RPS was considered for space flight but ultimately passed over either for a different power source or different mission altogether, the stated explanations seem to center on a lack of the technology's heritage and mission readiness, as well as constraints placed on mission re-designs. While both the technical and budgetary appropriateness of a technology are essential determining factors in a technology's readiness, the ubiquity of these two explanations glosses over more nuanced but nevertheless fundamental influences determining a technology's adoption for space flight.

We turn now to an assessment of these nuanced influences to the perceived risk and adoption barriers of DRPS to better understand how these influences may affect risk perception and technology adoption. First we review the evolution of DRPS technical origins, progress, and ultimate closure, using the three case studies as a backdrop.

3. DRPS DEVELOPMENT

To better understand these influences, it is important to understand how and why DRPS was developed. As discussed previously, solid-state RTGs convert heat flowing from decaying plutonium through semiconductors, with no moving parts. For DRPS, a convertor transfers heat from decaying plutonium to drive a mechanical device, such as a Stirling piston, to produce electricity using an alternator. Initial efforts to develop an efficient DRPS convertor began with a DOE contract with Lockheed Martin Space Systems Company (LMSSC) who subcontracted the Stirling Technology Company (later renamed Infinia) in 2001 to produce and test a preliminary Stirling cycle-based DRPS generator, called the SRG-110 that incorporated an early Technology Development Converter (TDC) prototype. After the Fall of 2006, NASA had changed its requirements provided to DOE which the DOE changed their requirements and awarded a new convertor contract to Sunpower Inc. to demonstrate a second Stirling convertor that had projected higher performance, the Advanced Stirling Convertor (ASC) [47–53]. Ultimately, the output of this converter did not achieve this benchmark [51].

However, following intial successful of testing on the ASC, all TDC-based SRG-110 efforts were redirected to focus on developing an SRG-110 using ASCs (Figure 2) and Infina was dismissed [49]. By 2008, initial development and testing of the now ASC-based generator design was complete and power output was encouraging. With additional funding, the SRG-110 generator and project was renamed the Advanced Stirling Radioisotope Generator (ASRG) project [54] and ASRG development was directed to become a flight-ready technology.

In the Fall of 2008, NASA announced the Discovery and Scout Mission Capabilities Expansion Program (DSMCE) to solicit mission studies that included one or two ASRGs for a hypothetical launch in 2013 [51]. However, despite this continued effort and enthusiasm, the ASRG's readiness for flight use remained a distant target as technical questions and challenges remained. Technical issues that had been under investigation and/or closed for the Infinia TDC design had to be revisited for the ASC [47–48]. For instance, the ASC used different insulation and structural bonding materials from the TDC that were not yet tested to perform at operating temperatures nor in the presence of space based radiation or radiation from the generator's plutonium [47–48].

Despite these technical challenges, in 2010, NASA decided to include the ASRG as government furnished equipment to incentivize the ASRG's use in the 2010 Discovery-12 AO. Meanwhile, the ASRG design failed a final design review and subsequent delta design review held in 2012 due to technical questions about the ASRG's ability to meet mass and system power requirements [45], [47]. Despite these issues, including being more than a year and a half behind schedule, reports from the ASRG development team stated the ASRG would be flight-ready for the 2016 Discovery-12 deadline [55-56].

While ASRG supporters remained hopeful that a near-term mission was still viable, those hopes began to fade in August 2012 when NASA passed over both ASRG proposals for Discovery-12 and instead selected a solar powered Mars lander, InSight, proposed by NASA JPL and Lockheed Martin [57]. In 2013, the DOE and GRC's contract with LMSSC and Sunpower for development of the ASRG was terminated. In spite of the non-selection of an ASRG-enabled mission for Discover 12, ASRG developers began looking to the next Discovery-class planetary mission as an opportunity to demonstrate the DRPS ASRG in a space application [55]. By this time in 2013, the DOE and NASA's standing review board failed the ASRG Project three times. In October 2013, NASA terminated the project [58].

After the ASRG's flight project's termination, the Stirling development activities at GRC were reformulated as the Stirling Cycle Technology Development Project (SCTDP) with the goal of continuing work on systems, converters, controllers, testing, and research. In 2016, the SCTDP released an industry Request for Information (RFI) seeking new approaches for dynamic convertor technology. With the submitted convertor designs (including both Infinia's TDC and Sunpower's ASC), the SCTDP is evaluating which convertors NASA could pursue in the future as a possible DRPS successor to the failed ASRG [59]. Also under the purview of the RPS Program Office is the Surrogate Mission Team (SMT), a cross-sectional team from NASA and DOE seeking to provide the flight mission perspective, identify potential mission risks and apply lessons learned from the ASRG project [59].

4. DRPS TECHNICAL AND ORGANIZATIONAL CHALLENGES

To better elucidate why DRPS has struggled to be deployed as a power system technology in space flight and anticipate possible challenges to future development, the technical and organizational issues are discussed in more detail in the following sections. The technical issues involve increased design complexity which leads to increased risk, as well as problems with the performance and incorrect technology readiness labeling. The organizational challenges can be broadly defined as an inability to set realistic expectations for the technology, but more specifically they can be distilled into four primary areas, which are the lack of organizational coherence, the need for an independent TRL assessment process, issues with the proposal firewall process and information dissemination, and the notion of heritage.

Technical Challenges

A technical challenge for an early DRPS was the 2005 NASA decision to switch the converter from the Infinia TDC to Sunpower's ASC because the power-output of a TDC, maxed at 55W, might not support NASA missions needing higher performing and efficient power sources [60]. Because of this switch, the new contractor, Sunpower, NASA/GRC, Lockheed, and DOE had to align their technology development approaches, which caused delays in development and testing of the technology.

Another challenge inherent to the ASRG is the complexity of the ASRG design, especially when compared to the solid-state RTG design, and the associated increase in risk. The ASRG includes a moving piston, displacer, magnet can, and bounce spring, which increase the likelihood of a failure when compared to the passive and highly-redundant RTG design, especially when considering the physics of spaceflight. The long history of solid-state RTG space flight success, another example of heritage, is effectively a confidence barrier for engineers considering the risks of including a new DRPS. Moreover for those missions requiring hard-surface landings, the risk of a non-flight-tested, mission-critical power supply with this potential limitation could be seen as too high [1–2].

Another significant technical challenge was the actual performance of the ASRG engineering unit, which ultimately led to its failing of both the final design review in 2011 and the delta design review in 2012 due to significant power fluctuations in the ASC as well as failures of the ASC control unit to limit piston overstroke in the generator [61]. While there were some ASRG successes post the 2012 timeframe, these were not enough to continue the program [59].

Related to the performance assessment of the ASRG is the difficulty of testing long-lifetime spaceflight systems, especially to the degree of confidence engineers prefer. Because of the longevity of nuclear systems like the ASRG (e.g., 17 years desired), lifetime testing would require extending system testing well into two decades, likely creating missed opportuntiites. Another option is the use of abbreviated lifetime modeling analysis, like the Risk-informed Lifetime Testing (RILT) [59] that is based on similar accelerated testing and probabilistic risk assessments used by NASA [62].

In order to address potential concerns with the risk and reliability of ASRG systems, a secondary/redundant generator that runs in parallel is sometimes considered necessary for mission concept by different mission proposers. This difference of opinion has considerable ramifications as the addition of a second generator would negate the positive attributes of the ASRG's reduced need for Pu-238, as well as reductions in cost, size, and mass [1], [4]. Unfortunately, without spaceflight testing, which has never occurred for a Dynamic RPS, it will be difficult to gain confidence in these systems, which represents a critical Catch-22 for NASA that often relies on heritage for risk mitigation.

Lastly, another major technical challenge specific to the Discovery AO was forecasting what the ASRG's TRL would be at the end of Phase B. Proposers were incentivized to include the ASRG in the Discovery AO at a savings of up to ~$50 million dollars, with the AO stating that the government furnished ASRG would be at TRL 6 by the end of Phase B. This means that the Engineering Unit of the ASRG would have completed its development by 2013, with successful demonstrations in relevant, simulated mission environments [63]. This presumes that at the time of the AO release in 2010, the TRL was 5, meaning that the ASRG had at least demonstrated successful operation in a simulated and ideal environment. However up until the ASRG's ultimate closeout in 2015, the system-level technology never surpassed TRL 3/4, that is moving beyond successful demonstration of the technology outside of a laboratory setting [63]. After ASRG closout, GRC integrated the ASC and ACU together, designated as the ASRG EU2. During testing power flucuations and anomalous behaviors were observed [64] further demonstrating that the ASRG design lacked the appropriate robustness and reliability to suitably classify it as at TRL 5, let alone the required TRL 6.

So, while the initial ASRG expectation for the AO RFP release in 2010 was that it would be at TRL 6 by 2013, there were significant technical issues with the converter design that were obvious by 2012. For the Discovery AO Phase A teams, these ASRG problems were unknown to the two of three mission teams relying on the GFE-incentivized ASRG as their primary power system. This is discussed in more detail in the next section.

Organizational Challenges

As is often the case with complex multiagency projects like the development of the ASRG, a major organizational challenge was promoting effective and timely collaborations between the myriad of agencies and contractors involved. DOE, GRC, GSFC, JPL, and JHU-APL all have their own perspectives on technology development, and while similar in many ways, they each have their own culture in how they approach spaceflight projects, which will be further investigated in forthcoming work.

In addition to differring spaceflight technology developers, the ASRG program was dependent on the DOE since the generator would be fueled with PU-238, ,and the lack of well-defined roles and responsibilities between NASA (the customer for the ASRG flight units) and DOE (ASRG provider) led to strained and conflicted interactions between the two government agencies.

A 2017 report from the Government Accountability Office describes how the DOE could improve communication of its efforts and impediments to reestablishing its PU-238 production to sustain NASA's space RPS-based missions [65]. The report also describes how NASA's request to the DOE now likely underestimates NASA's need for PU-238 as its request presumed the success of the more efficient ASRG. NASA subsequently stated it believes there will be enough fuel for RPS missions planned in the last Decadal study [65-66]. In response, when NASA and the DOE renewed their MOU in October 2016, agency responsibilities were updated to better reflect each agency's funding authority. The DOE has since consolidtated communications with the DOE to Deputy Assistant Secretary for Nuclear Infrastructure Programs [12–13].

The second major organizational challenge identified was how TRLs are assigned to existing or future technologies. As the DOE did not fully implement a DOE-wide TRL model and process at the agency until 2011, the agency had no consistent means of ensuring that a technology would actually work as intended (since the agency self-reported its assessment of technologies) [65],[67]. Furthermore, even NASA's own research centers' TRL assessment methods have been found to vary [68]. Other significant limitations to an accurate and consistent TRL process at NASA have included a lack of external validation for the centers' TRL assessments, which are typically self-administered and result in reports that do not adequately represent uncertainties both in the assessment and technology [68].

This unreliable forecasting of the ASRG's TRL in the Discovery AO, perpetuated by the assumed readiness of the ASRG in the DSMCE and Decadal studies, had a direct impact on the proposal process. Because of NASA's incentivization, several teams assumed the ASRG was more capable than it really was, leading to six ASRG-based mission proposals out of the total 28 considered for the Discovery AO [69-70]. Even though two of the three Phase A awards had an ASRG, the final award was made to a solar powered platform. Such outcomes, despite the NASA endorsement of ASRGs, causes frustration in mission proposal teams and distrust of future promises of government-furnished equipment.

The third major challenge that exacerbated problems with the ASRG was the firewall that is required by NASA for communications between mission proposers and technology developers for competed missions like Discovery-12 [43], [71]. While this is required so as not to give any proposer an unfair advantage, because the proposers were not aware of the delays in the ASRG's converter development as well as the failures in testing, they were not aware of the risks of including an ASRG in a proposal though they were under the impression from the AO that the technology would be ready. In the case of Discovery-12, a status report and Q&A of the ASRG's development was presented to the two ASRG-enabled candidates, TiME and Chopper. However complications facing the technology were obscured as the generator had yet to face a critical design review at the time of the status report and later updates were not made available to the mission proposers [72].

The last organizational challenge for ASRG deployment relates to a concept known internally to NASA personnel as "heritage". The concept of heritage refers to "the original manufacturer's level of quality and reliability that is built into parts and which has been proven by time in service, number of units in service, mean time between failure performance, and number of use cycles" [62]. While this designation of heritage is not theoretically applied for or against a technology until after a mission's first key decision gate, heritage helps mission planners and assessors determine mission's anticipated risks, costs, and schedule [26], [62]. However, heritage is not consistently interpreted across NASA and the concept has been a cause of confusion when determining the risk and readiness of a new technology [72].

For instance, the original designs of the new MMRTG claimed heritage, decreasing the perceived risk of the new technology, based on the generator's use of similar thermocouple designs as the SNAP 19 RPS models used on the Viking lander mission and it was manufactured by the same company today who built the SNAP 19 and sells similar RTGs to other government agencies. Given the benefit of hindsight and nearly six years of the MMRTG's successful operation on the MSL, the claim of heritage may be warranted. However, NASA's policies on the appropriate application of heritage can become subjective as any modification of a heritage system or use in a new environment, as was the case with the MSL's MMRTG, could be considered "a wholly new technological development" [72]. Thus, claiming heritage could mask actual risk for derivative systems that incorporate new technologies.

As stated by the NASA System's Engineering Handbook, without a more unified and transparent means of evaluating the appropriateness of a technology's claim of heritage, mission planners can lose their objectivity when determining the technology's maturity [62]. If mission proposals containing ASRGs or other unproven systems continue to be rejected because they do not have heritage, they will never have an opportunity to be flown in space and scientific discoveries will not be made for subjective, and not scientific, reasons.

5. MITIGATION STRATEGIES

As with any complicated technology development and integration program, many technical challenges can be alleviated with the addition of more time and money (although, as Perrow notes, unanticipated failures in complex systems can never be wholly avoided [74-75]). However, understanding the mission need, and the technology readiness required to meet that need are the fundamental building blocks that actually determine the actual resoures needed to mitigate challenges whereever possible. There are many other sociotechnical issues that need to be addressed alongside the technical ones, which include inter-agency difficulties between the DOE and NASA, unreliable or ambigeous TRL assessments, communication firewalls, and an unclear application of heritage.

With respect to mitigating DRPS challenges stemming from a lack of organizational coherence among NASA, DOE, and their contractors, our recommendation echoes the National Research Council's 2011 "Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions". Specifically, that NRC assessment asserts that NASA can mitigate impediments to effective collaboration among partners through good systems engineering and collaborative oversight that allows NASA to be a more involved and selective of the DOE's involvement in DRPS development [76].

Key recommendations included making sure the following are incorporated into all collaborations in the design process: a small and achievable list of priorities; clear processes to make decisions and settle disputes; clear lines of authority and responsibility for projects; a shared commitment to success and collaboration; and a single entity to manage technical and management reviews as well as project spending [76]. We interpret the phrase, "a shared commitment to success and collaboration," to include the notion of transparency needed to truly assess risk. At the beginning of 2018, NASA GRC and the DOE formulated integrated flight project teams for RPS missions to better streamline their interactions [77]. Specifically, NASA will lead development of RPS projects as the Project Manager while the DOE assists with implementation [12], [66]. However, moving forward, streamlining coordination between these two agencies will be even more critical as plutonium production increases and the need for nuclear-based space power grows.

Improving the TRL assessment process is another critical step in mitigating barriers to the successful development and adoption of innovative space technologies. NASA does not have a codified and consolidated TRL assessment process and there is no requirement for the independent review of TRL assessments. To help mitigate these challenges, we reiterate the recommendation of a NASA TRL Assessment Team's 2016 report calling for the creation of a consolidated TRL Handbook including standardized assessment criteria and best practices that would be used across all NASA agencies. Currently, the RPS program is in the process of establishing its own independent review process and gate decision criteria for future technology development efforts [59]. Specifically, a new technology maturation process called for by the RPS program calls for technology gates to be established that ensure developing technologies are "objectively evaluated by external specialists in missions, systems, technology and project management before proceeding to [flight system development]" [78] . The TRL Assessment Team also recommended NASA follow the Department of Defense's requirement of independent TRL assessments for unbiased feedback [67], [79]. Further, we also recommend that unqualified technologies not be offered for missions, as was the case with the ASRG for Discovery-12. This recoomendation has already been supported as the RPS program has refrained from offering the eMMRTG for New Frontiers-4 missions.

Such improvements to the NASA TRL process could also address potential bias associated with the concept of heritage as independent assessments of a technology could limit inappropriate confidence in a derivative technology. However, it should be noted that while a technology with heritage implies an increased TRL with reduced risk, an overreliance on heritage for technology development ultimately results in incremental, evolutionary technologies instead of revolutionary ones, in effect stifling innovation. Moreover, reliance upon TRL and heritage do not ensure success, as they can be misunderstood or become outdated over time.

Another recommendation to help mitigate the challenges of successful technology adoption is for NASA to increase and facilitate mission proposers' and evaluators' interactions with experts involved in the development of new technologies under consideration for space flight, while still ensuring the Agency's competitive processes are still fair. With increased access to subject matter experts, mission proposers and evaluators to more easily learn of and/or challenge the technology's alleged readiness for space flight and adjust their plans accordingly. The development of competed mission proposals is an intense and challenging endeavor, which often promotes future collaborations for team members even if a proposal is not awarded. However, losing a Phase A competition because an officially sanctioned technology is not actually available as promised can be very demotivating and sow the seeds of frustration and distrust. This recommendation has been introduced in the New Frontiers 4 proposal opportunity (similar in process to Discovery Missions) with the MMRTG Users Guide provided to mission proposers [80].

6. CONCLUSION

In this paper, we have examined the influences of many technical and organizational factors affecting NASA's attempt to develop, adopt, and fly dynamic radioisotope power systems and presented initial mitigation strategies to help overcome the underlying challenges to success. As NASA and mission proposers set their sights toward more ambitious objectives into deeper reaches of the solar system, these ambitions are limited, in part by, by the lack of progress in DRPS development, including the fact that it has not yet flown in space, with no discernible plan to do so on the horizon.

To close this gap, not only is more work and funding needed to develop the technology itself, but also more effort is needed to better understand risk assessment techniques and processes, particularly for nuclear-based space power technologies. In particular, we are interested in the extent to which these techniques and processes may vary for different stakeholders and how, if at all, these differences may correlate with how far askew the perception of risk may be from actualized risk. To this end, our future work will be examining how risk assessments are made for DRPS systems, with a focus on the emerging Risk-informed Lifetime Testing methodology mentioned earlier, and how different stakeholders, including engineers, managers, and scientists, perceive such risks.

ACKNOWLEDGEMENTS

This research was sponsored by NASA through contract NNN06AA01C, subcontract 143008.

REFERENCES

[1] Office of the Under Secretary of Defense for Aquisition Technology Logistics, "The Role of Autonomy in DoD Systems," Dept. of Defense, Washington DC, USA, Final Rep., 2012. [Online] Available: https://fas.org/irp/agency/dod/dsb/autonomy.pdf. [Accessed: Jun. 22, 2018]

[2] R. Mittu., D. Sofge, A. Wagner, and W. Lawless, Eds., *Robust Intelligence and Trust in Autonomous Systems*. Boston, MA, USA: Springer US, 2016.

[3] J. Paur, "Can Killer Drones Land on Carriers Like Human Top Guns?," *WIRED*. [Online]. Available: https://www.wired.com/2009/11/can-killer-drones-land-on-carriers-like-human-top-guns/. [Accessed: 22-Jun-2018].

[4] M. Cummings, M. Buchin, G. Carrigan, and B. Donmez, "Supporting intelligent and trustworthy maritime path planning decisions," *Int. J. of Human-Comput. Stud.*, vol. 68, no. 10, pp. 616–626, Oct. 2010.

[5] C. Heitmeyer and E. I. Leonard, "Obtaining Trust in Autonomous Systems: Tools for Formal Model Synthesis and Validation," *Formal Methods in Software Eng. (FormaliSE), 2015 IEEE/ACM 3rd FME Workshop*, pp. 54–60, 2015.

[6] A. Hutchins, M. Cummings, M. Draper, and T. Hughes, "Representing Autonomous Systems' Self-Confidence through Competency Boundaries,"in *Proc. Human Factors Ergon. Soc. Annu. Meet.*, vol. 59, no. 1, pp. 279–283, Sep. 2015.

[7] E. Johnson, "Agencies and Science-Experiment Risk," *University Of Illinois Law Review*, vol. 2016, no. 2, p. 61, 2016.

[8] J. D. Lee and K. A. See, "Trust in Computer Technology and the Implications for Design and Evaluation," *Etiquette for Human-Computer Work: Tech. Rep. FS-02-02*, pp.20-25, 2012.

[9] A. Stimpson, M. Tucker, M. Ono, A. Steffy, and M. Cummings, "Modeling risk perception for mars rover supervisory control: Before and after wheel damage," in *2017 IEEE Aerosp. Conf.*, 2017, pp. 1–8,

[10] National Research Council, *Priorities in Space Science Enabled by Nuclear Power and Propulsion*. Washington, D.C., USA: Nat. The National Academies Press, 2006. [Online]. Available: https://www.nap.edu/catalog/11432/priorities-in-space-science-enabled-by-nuclear-power-and-propulsion. Accessed May 23, 2018.

[11] National Research Council, *Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration*. Washington, DC: The National Academies Press, 2009. [Online] Available: https://www.nap.edu/catalog/12653/radioisotope-power-systems-an-imperative-for-maintaining-us-leadership-in [Accessed: 23-May-2018].

[12] T. Bishop, "Statement of Tracey L. Bishop before House Committee on science, space and technology," Washington DC, USA, Oct. 4, 2017. [Online]. Available: https://docs.house.gov/meetings/SY/SY16/20171004/

106469/HHRG-115-SY16-Wstate-BishopT-20171004.PDF. Accessed: May 23, 2018.

[13] D. Woerner, V. Moreno, L. Jones, R. Zimmerman, and E. Wood, "The Mars Science Laboratory (MSL) MMRTG In-Flight: A Power Update," in Proc. of Nucl. and Emerging Technologies for Space, pp. 8, 2013.

[14] G. Landis, Kinnison, J., Fraeman, M., Roufberg, L., Vernon, S., Wirzburger, M., and Schmitz, P., "Solar Power System Design for the Solar Probe+ Mission," in 6th Int. Energy Convers. Eng. Conf. (IECEC),. 2008. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090004577.pdf

[15] National Aeronautics and Space Agency, "Solar Probe: Report of the Science and Technology Definition Team," Greenblet, MD, USA, Rep. NASA/TM—2005–212786, Sep. 2005. [Online] Available https://solarprobe.gsfc.nasa.gov/SolarProbe_STDT2005.pdf

[16] A. J. Colozza and R. L. Cataldo, "Applicability of STEM-RTG and High-Power SRG Power Systems to the Discovery and Scout Mission Capabilities Expansion (DSMCE) Study of ASRG-Based Missions," Greenbelt, MD, USA, Rep. NASA/TM—2015-218885, Oct. 2015. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150023042.pdf

[17] National Aeronautics and Space Agency, "Europa Clipper 2012 Report" Europa Study Team Jet Propulsion Laboratory, California Institute of Technology, May, 2012. [Online] Available: https://europa.nasa.gov/resources/63/europa-study-2012-report/ [Accessed: 23-May-2018].

[18] J. Crowder and S.A. Friess, *Systems Engineering Agile Methodologies*. New York, NY, USA: Springer-Verlag New York, 2013.

[19] S. G. Vick, *Degrees of Disbelief: Subjective Probability and Engineering Judgment*. Reston, VA, USA: ASCE Press, 2002.

[20] National Aeronautics and Space Administration, *MSL Science Corner: Science Goals*. [Online]. Available: https://msl-scicorner.jpl.nasa.gov/ScienceGoals/. Accessed Sept. 17, 2018.

[21] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*. Washington, D.C.: National Academies Press, 2003. [Online] Available: https://www.nap.edu/catalog/10432/new-frontiers-in-the-solar-system-an-integrated-exploration-strategy. [Accessed: 17-Apr-2018].

[22] F. Ritz and C. E. Peterson, "Multi-mission radioisotope thermoelectric generator (MMRTG) program overview," in *2004 IEEE Aerospace Conference Proceedings*, 2004, vol. 5, pp. 2950-2957. - [Online] 10.1109/AERO.2004.1368101

[23] S. Patel, "Powering Curiosity on Mars—And Beyond," *POWER Magazine*, Oct. 2012. [Online]. Available: http://www.powermag.com/powering-curiosity-on-marsand-beyond/. [Accessed: 17-Apr-2018].

[24] Department of Energy, *Mars Science Laboratory - Idaho National Laboratory Research Fact Sheet*. Idaho National Laboratory [Online]. Available: http://www4vip.inl.gov/research/mars-science-laboratory/. [Accessed: 17-Apr-2018].

[25] T.S. Balint and J.F. Jordan, "RPS strategies to enable NASA's next decade robotic Mars missions," *Acta Astronautica*, vol. 60, no. 12, pp. 992–1001, Jun. 2007.

[26] National Aeronautics and Space Administration, *NASA space flight program and project management handbook.* Office of the Chief Engineer, Sept., 2015. [Online] Available: https://ntrs.nasa.gov/search.jsp?R=20150000400. [Accessed: 17-Apr-2018].

[27] T.S. Balint, "Comparison of Power System Options Between Future Lunar and Mars Missions," In *International Lunar Conference 2005 Proceedings*, 2005. [Online]. Available: https://www.researchgate.net/publication/228982729_Comparison_of_Power_System_Options_Between_Future_Lunar_and_Mars_Missions. [Accessed: 22-Apr-2018].

[28] J. Naugle, *First Among Equals: The Selection of Space Science Experiments.* Washington, DC: Government Printing Office, 1991.

[29] J. Randolph, "NASA Solar Probe Mission And System Concepts," *Advances in Space Research*, 17(3), pp.3-12, 2016. [Online] Available: https://www.sciencedirect.com/science/article/pii/027311779500491V?_rdoc=1&_fmt=high&_origin=gateway&_docanchor=&md5=b8429449ccfc9c30159a5f9aeaa92ffb [Accessed: 22-Jun-2018].

[30] National Aeronautics and Space Administration, *Solar Probe Plus Fact Sheet*. Johns Hopkins Applied Physics Lab, Oct. 2014. [Online]. Available: https://web.archive.org/web/20160418160052/http://solarprobe.jhuapl.edu/common/content/SolarProbePlusFactSheet.pdf. [Accessed: 22-Jun-2018].

[31] H. Zell, “Missions Supporting the Study of the Sun-Earth Connection: Heliophysics,” *NASA.gov*, Mar., 2015. [Online]. Available: http://www.nasa.gov/mission_pages/sunearth/missions/index.html. [Accessed: 22-Jun-2018].

[32] National Aeronautics and Space Administration, *Solar Probe: Report of the Science and Technology Definition Team*, Goddard Space Flight Center, Sept., 2005. [Online]. Available: https://solarprobe.gsfc.nasa.gov/SolarProbe_STDT2005.pdf. [Accessed: 22-Jun-2018].

[33] National Research Council, *The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics*. Washington, D.C.: National Academies Press, 2003. [Online] Available: https://www.nap.edu/catalog/10477/the-sun-to-the-earth-and-beyond-a-decadal-research. [Accessed: 22-Jun-2018].

[34] R. Abelson, T.S. Balint, K. Coste, J.O. Elliott, J.E. Randolph, G.R. Schmidt, T. Schriener, J.H. Shirley, and T.R. Spilker, “Expanding frontiers with standard radioisotope power systems.,” *Jet Propulsion Laboratory*, 2015. [Online] Available: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.694.694 [Accessed: 22-Jun-2018].

[35] C.B. Vining and G.L. Bennett, “Power for Science and Exploration: Upgrading the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG),” In *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2010, pp. 6598.

[36] T.C. Holgate, R. Bennett, T. Hammel, T. Caillat, S. Keyser, and B. Sievers, “Increasing the Efficiency of the Multi-mission Radioisotope Thermoelectric Generator,” *Journal of Electronic Materials*, vol. 44, no. 6, pp. 1814–1821, Jun. 2015.

[37] L.G. Thieme and J.G. Schreiber, “Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn,” in *AIP Conference Proceedings*, vol. 746, no. 1, pp. 674-681. AIP, 2005.

[38] National Aeronautics and Space Agency, *SolarProbe+ Mission Engineering Study Report* Johns Hopkins Applied Physics Lab, Mar. 2008. [Online]. Available: https://solarprobe.gsfc.nasa.gov/SolarProbe+ME.pdf. [Accessed: 22-Jun-2018].

[39] G. Brown, “Solar Probe Mission Renamed to Honor Pioneering Physicist,” *NASA.gov*, May 2017. [Online]. Available: http://www.nasa.gov/feature/goddard/2017/nasa-renames-solar-probe-mission-to-honor-pioneering-physicist-eugene-parker. [Accessed: 22-Jun-2018].

[40] E.R. Stofan , C. Elachi, J. Lunine, R.D. Lorenz, B. Stiles, K.L. Mitchell, S. Ostro, L. Soderblom, C. Wood, H. Zebker, S. Wall, M. Janssen, R. Kirk, R. Lopes, F. Paganelli, J. Radebaugh, L. Wye, Y. Anderson, M. Allison, R. Boehmer, P. Callahan, P. Encrenaz, E. Flamini, G. Francescetti, Y. Gim, G. Hamilton, S. Hensley, W.T. Johnson, K. Kelleher, D. Muhleman, P. Paillou, G. Picardi, F. Posa, L. Roth, R. Seu, S. Shaffer, S. Vetrella, and R. West, "The Lakes of Titan." *Nature*, vol. 445, no. 7123, pp.61., Jan. 2007.

[41] National Aeronautics and Space Agency, *Discover 2010 Announcement of Opportunity*. Lunar and Planetary Institute, June. 2010. [Online] Available: https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=234098/solicitationId=%7B70D505D2-9B11-5907-029A-89AD44684EBD%7D/viewSolicitationDocument=1/DSC10%20Amendment%203.pdf. [Accessed: 22-Jun-2018].

[42] National Aeronautics and Space Agency, *Discovery and Scout Mission Capabilities Expansion Abstracts of selected proposals*, Planetary Science Division Science Mission Directorate, Feb. 2008. [Online]. Available: https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=135950/solicitationId=%7B01B70287-331E-25C2-B95F-6C80E03A1AF3%7D/viewSolicitationDocument=1/DSCME07%20Selections.pdf. [Accessed: 22-Jun-2018].

[43] National Aeronautics and Space Agency, *Guidebook For Proposers Responding To A Nasa Research Announcement (NRA) Or Cooperative Agreement Notice (CAN)*. Jan. 2010. [Online] Available: https://www.hq.nasa.gov/office/procurement/nraguidebook/proposer2018.pdf. [Accessed: 22-Jun-2018].

[44] J. Hsu, “Nuclear-Powered Robot Ship Could Sail Seas of Titan,” *Astrobiology Magazine*, 2009. [Online] Available: https://www.space.com/7372-nuclear-powered-robot-ship-sail-seas-titan.html. [Accessed: 23-May-2018].

[45] L.A. Dudzinski, J.A. Hamley, P.W. McCallum, T.J. Sutliff, and J.F. Zakrajsek, “NASA’s Radioisotope Power Systems Program Status,” *In 12th International Energy Conversion Engineering Conference*, pp. 3462. 2014.

[46] R.D. Lorenz and J.L. Mann, “Seakeeping on Ligeia Mare: Dynamic Response of a Floating Capsule to Waves on the Hydrocarbon Seas of Saturn’s Moon Titan,” *Johns Hopkins APL Technical Digest*, vol. 33, no. 2, p. 13, 2015.

[47] Department of Energy, *Atomic Power In Space I - A History*. Idaho National Library. [Online]. Available: https://www.inl.gov/wp-content/uploads/2014/10/AtomicPowerInSpaceII-AHistory_2015_chapters3-5.pdf. [Accessed: 23-May-2018].

[48] J.G. Wood, "Development of the Sunpower 35 We Free-Piston Stirling Convertor," *In AIP Conference Proceedings*, vol. 746, no. 1, pp. 682-687. AIP, 2005.

[49] J.G. Schreiber, "Status of the NASA Stirling Radioisotope Project," *NASA Glenn Research Center*, pp. 25, 2007.

[50] R.K. Shaltens, "Future Opportunities for Dynamic Power Systems for NASA Missions," *NASA Glenn Research Center*, pp. 20, 2007.

[51] W.A. Wong, J.G. Wood, and K. Wilson, "Advanced Stirling Convertor (ASC)—From Technology Development to Future Flight Product," *NASA Glenn Research Center*, pp. 20, 2008.

[52] J.G. Schreiber, L.G. Thieme, and M. El-Genk, "GRC Supporting Technology for NASA's Advanced Stirling Radioisotope Generator (ASRG)," *In AIP Conference Proceedings*, vol. 969, no. 1, pp. 582-592. AIP, 2008.

[53] B. Berger, "Discovery Mission Finalists Could Be Given Second Shot," *SpaceNews.com*. [Online]. Available: http://spacenews.com/36485discovery-mission-finalists-could-be-given-second-shot/. [Accessed: 22-Apr-2018].

[54] W.A. Wong, K. Wilson, E. Smith, and J. Collins, "Pathfinding the Flight Advanced Stirling Convertor Design with the ASC-E3," *In 10th International Energy Conversion Engineering Conference*, p. 4251. 2012.

[55] D. Leone, "NASA Planning Mock Mission for Next-gen Nuclear Battery", *SpaceNews.com*, 2013. [Online]. Available: http://spacenews.com/nasa-planning-mock-mission-for-next-gen-nuclear-battery/. [Accessed: 22-Apr-2018].

[56] D. Leone, "Start of Next Discovery, New Frontiers Competitions Uncertain," *SpaceNews.com*, 2013. [Online]. Available: http://spacenews.com/36271start-of-next-discovery-new-frontiers-competitions-uncertain-nasa-official/. [Accessed: 27-May-2018].

[57] D. Agle, G. Webster, and D. Brown, "New NASA Mission to Take First Look Deep Inside Mars," *NASA and Jet Propulsion Laboratory at California Institute of Technology*, 2012. [Online]. Available: http://www.jpl.nasa.gov/news/news.php?feature=3480. [Accessed: 23-May-2018].

[58] J. Green, "Important Changes in the NASA Planetary Science Division's (PSD) Radioisotope Program.", *NASA*, Nov. 2013. [Online] Available: https://www.lpi.usra.edu/planetary_news/2013/11/15/important-changes-in-the-nasa-planetary-science-divisions-psd-radioisotope-program/ [Accessed: 14-Jun-2018].

[59] K.E. Hibbard, L.S. Mason, O. Ndu, C. Smith, and J.P. Withrow, "Stirling to Flight Initiative," *In Aerospace Conference, 2016 IEEE*, pp. 1-11. IEEE, 2016.

[60] W.A. Wong, "Status of NASA's Advanced Radioisotope Power Conversion Technology Research and Development," *In AIP Conference Proceedings*, vol. 813, no. 1, pp. 340-347. AIP, 2006.

[61] National Aeronautics and Space Agency, *Fiscal Year 2012 Final Report*. NASA Glenn Research Lab, Radioisotope Power Systems Program Office, 2012.

[62] National Aeronautics and Space Agency, *NASA Systems Engineering Handbook*, NASA Scientific and Technical Information Program Office, pp. 62, 2007. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook.pdf. [Accessed: 14-Jun-2018].

[63] J. Green, "Tech Development for PSM Decadal Study Follow Up", *NASA and National Academies of Science*, Jul. 2017. [Online] Available: http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_183732.pdf. [Accessed: 15-May-2018]

[64] E. Lewandowski, M. Dobbs, and S. Oriti, "Advanced Stirling Radioisotope Generator Engineering Unit 2 Anomaly Investigation," In International Energy Conversion Engineering Conference, American Institute of Aeronautics and Astronautics, p. 26, AIAA, 2018.

[65] United States Government Accountability Office, *DOE Could Improve Planning and Communication Related to Plutonium238 and Radioisotope Power Systems Production Challenges.* GAO, 2017. [Online]. Available: https://www.gao.gov/assets/690/687031.pdf. [Accessed: 01-Jun-2018].

[66] National Research Council, *Visions into Voyages for Planetary Sciences in the Decade 2013-2022: A Midterm Review*. Washington D.C.: National Academies Press, 2018. [Online] Available: https://www.nap.edu/catalog/25186/visions-into-

voyages-for-planetary-sciences-in-the-decade-2013-2022 [Accessed: 4-Oct-2018].

[67] Department of Energy, *US DOE Technology Readiness Assessment Guide*, DOE Office of Management, Oct. 2009. [Online]. Available: https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04/@@images/file. [Accessed: 15-May-2018].

[68] S. Hirshorn and S. Jefferies, "Final Report of the NASA Technology Readiness Assessment (TRA) Study Team," *NASA Office of the Chief Engineer and NASA Office of the Chief Scientist*, Mar. 2016.

[69] T.J. Sutliff and L.A. Dudzinski, "NASA Radioisotope Power System Program - Technology and Flight Systems," *In 7th International Energy Conversion Engineering Conference*, pp. 4575, 2009.

[70] D.C. Brown and L. Cantillo, "NASA Selects Investigations For Future Key Planetary Mission." *NASA.gov*, 2015. [Online]. Available: https://www.nasa.gov/home/hqnews/2011/may/HQ_11-132_Future_Plantary.html. [Accessed: 14-Jun-2018].

[71] D.J. Anderson, C.E. Sandifer, T.R. Sarver-Verhey, D.M. Vento, and J.F. Zakrajsek, "Planetary Science Technology Infusion Study," *NASA Glenn Research Center*, pp. 60, 2014.

[72] National Aeronautics and Space Agency, *Discovery 2010 AO QA*, NASA Lunar and Planetary Institute, 2010. [Online]. Available: https://discovery.larc.nasa.gov/PDF_FILES/Discovery2010AOQA.pdf. [Accessed: 14-Jun-2018].

[73] W. Peters, S. Doskey, and J. Moreland, "Technology Maturity Assessments and Confidence Intervals," *Systems Engineering*, vol. 20, no. 2, pp. 188–204, Mar. 2017.

[74] Charles Perrow, Normal Accidents: Living with High Risk Technologies-Updated Edition. Princeton University Press, 2011.

[75] Charles Perrow, "The Limits of Safety: The Enhancements of a Theory of Accidents," Journal of Contingencies and Crisis Management, vol. 2, no. 4, Dec. 1994.

[76] National Research Council, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*. Washington, D.C.: National Academies Press, 2011. [Online] Available: https://www.nap.edu/catalog/13042/assessment-of-impediments-to-interagency-collaboration-on-space-and-earth-science-missions. [Accessed: 14-Jun-2018].

[77] J.A. Hamley, "Radioisotope Powersystem Program Status and Expectations," 2017. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170008806.pdf/. [Accessed: 20-Jul-2018].

[78] J.F. Zakrajsek, D.F. Woerner, D. Cairns-Gallimore, S.G. Johnson, L.Qualls, "NASA's Radioisotope Power Systems Planning and Potential Future Systems Overview," 2016. [Online]. Available: https://ieeexplore.ieee.org/document/7500646/ [Accessed: 4-Oct-2018].

[79] Department of Energy, *Technology Readiness Assessment Guidance*, Office of the Assistant Secretary of Defense for Research and Engineering, Apr. 2011. [Online]. Available: https://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf. [Accessed: 14-May-2018].

[80] National Aeronautics and Space Agency, *New Frontiers 4 Announcement of Opportunity*. Lunar and Planetary Institute. December, 2016. [Online] Available: https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=548004/solicitationId=%7BF65A5657-0E72-362E-2D4C-DE87A16A82B7%7D/viewSolicitationDocument=1/NF4%20AO.pdf. [Accessed: 22-Jun-2018].

BIOGRAPHY

Scott "Esko" Brummel *is a graduate of Duke University's Master in Bioethics and Science policy. Through this degree, he has developed skills to best interpret the relevancy of emerging scientific research and development with progressive and discovery-focused policy. In Duke Robotics Humans and Autonomy Lab (HAL), Esko works with Dr. Missy Cummings to study strategies to appropriately assess risk for new technological devices for complex space flight. Beyond HAL, Esko also serves as the lead editor for all things robotics and artificial intelligence at Duke University's online science policy tracking website, SciPol, and a researcher within Duke's Science, Law, & Policy (SLAP) Lab.*

Kenneth Hibbard *received his B.S. in Aerospace Engineering from the Pennsylvania State University, and his M.S. in Systems Engineering from the Johns Hopkins University. He spent eight years as a spacecraft systems and operations engineer at NASA Goddard working on the ACE, SOHO, and Swift spacecraft. At APL, Mr. Hibbard previously worked as the MESSENGER Deputy Mission Operations Manager, Formulation Deputy Project Systems Engineer for the Europa flagship mission study, the MSE for Implementation of the Precision Tracking Space System (a demonstration flight of APL-designed spacecraft hosting a new space-based sensor in support of MDA's Ballistic Missile Defense System), and as the Mission Systems Engineer for the Titan Mare Explorer (TiME) and Io Volcano Observer (IVO) Discovery proposals. Mr. Hibbard is currently a principal systems engineer on multiple programs and proposals, including supporting the Stirling development efforts led by NASA GRC. He is also the Acting Deputy Program Development Manager at APL for Civil Space, and the Group Supervisor of APL's Space Systems Engineering Group.*

Paul H. Ostdiek *is a program manager in APL's Space Exploration Sector and the Sector's chief technologist. He holds a Ph.D. in electrical engineering from the University of Virginia (1991), an M.S. in engineering physics from the Air Force Institute of Technology (1985), and a B.S. in physics from the U.S. Air Force Academy (1979). Previously, he served as chief of staff for APL's Civil Space Mission Area. He was director of engineering at Advanced Vision Technologies, Inc., a start-up company pursuing field-emitter technologies. Lieutenant Colonel Ostdiek retired from U.S. Air Force active duty as acting chief scientist for the AFRL Sensors Directorate. He has led research in microelectronics and photonics, monitored nuclear treaties, taught at the U.S. Naval Academy and the Air Force Institute of Technology, and teaches today at the Johns Hopkins University. His gallium-arsenide planar Schottky mixer diodes have flown in 183-GHz water vapor sensors on Air Force and NOAA weather satellites. He taught NASA's Jet Propulsion Laboratory to make these diodes, which have been used in space-based sensors at frequencies up to 2.5 THz.*

Ellen Stofan *was NASA's Chief Scientist from 2013 to 2016, where, among many other innovative projects, she helped develop a long-range plan to get humans to Mars. She supported NASA's science programs in everything from astrophysics to Earth and planetary science and collaborated on science policy with the National Science and Technology Council and as President Barack Obama's science advisor. Before serving as Chief Scientist, Ellen was a post-doctoral fellow at NASA's Jet Propulsion Laboratory, where she was Chief Scientist for the New Millennium Program. Her research has also focused on the geology of Venus, Mars, Saturn's moon Titan, and Earth. Stofan is an associate member of the Cassini Mission to Saturn Radar Team and was a co-investigator on the Mars Express Mission's MARSIS sounder. She also was principal investigator on the Titan Mare Explorer In 2018, Dr. Stofan joined the National Air and Space Museum as its Director.*

Dave Woerner *has more than 30 years' experience as a systems engineer and manager at JPL including as the MMRTG Office Manager for the Mars Science Laboratory mission. He is presently leading the engineering of an enhanced MMRTG and is the RTG Integration Manager and Deputy Program and Planning Manager for NASA's Radioisotope Power System Program. Woerner has worked at JPL on such missions as Galileo, Cassini, Magellan, Mars Pathfinder, and MSL. He was the Chief Engineer of the avionics for the Mars Pathfinder mission that successfully landed on Mars on July 4, 1996. He is the Chair of the Board of Directors for the IEEE Aerospace Conferences. He has won numerous NASA awards including earning NASA's Exceptional Service and Exceptional Achievement Medals.*

June F. Zakrajsek *has over 20 years of aerospace systems development, research and project management experience. She has led internal discipline teams for space systems health management, ISS power systems analysis, and Biotechnology. She has worked as a project manager in the areas of health management, systems engineering and analysis, propulsion system development, Orion Crew Module and Test & Verification, and Radioisotope Power Systems. Currently June serves as the Program Planning and Assessment Manager for NASA's Radioisotope Power Systems Program. This area is responsible to develop and maintain the implementation strategy for the Program by managing mission and systems analysis functions,* *integration of new technology into generators, and interfaces with potential missions considering utilizing Radioisotope Power Systems. She holds a Masters in Biomedical Engineering from Case Western Reserve University and Masters and Bachelors in Mechanical Engineering.*

Mary (Missy) Cummings *received her B.S. in Mathematics from the US Naval Academy in 1988, her M.S. in Space Systems Engineering from the Naval Postgraduate School in 1994, and her Ph.D. in Systems Engineering from the University of Virginia in 2004. A naval officer and military pilot from 1988-1999, she was one of the U.S. Navy's first female fighter pilots. She is currently a Professor in the Duke University Mechanical Engineering and Electrical and Computer Engineering Departments, and the Director of the Humans and Autonomy Laboratory. She is an American Institute of Aeronautics and Astronautics (AIAA) Fellow, and a member of the AIAA Board of Trustees, the Defense Innovation Board, and the Veoneer, Inc. Board of Directors. Her research interests include human supervisory control, explainable artificial intelligence, human-autonomous system collaboration, human-robot interaction, human-systems engineering, and the ethical and social impact of technology.*