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Assembly, Test and Launch Operations for a Nuclear-enabled NASA Mission: Considerations that are Specific to Use of a Nuclear Power System

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Abstract

For more than five decades, Radioisotope Power Systems (RPS) have played a critical role in the exploration of space, enabling missions of scientific discovery to destinations across the solar system by providing electrical power to explore remote, challenging and extreme environments. In particular, RPS enable deep space missions where increased heliocentric distances reduce the ability of solar power to adequately meet spacecraft and instrumentation power requirements. Some previous notable missions that were enabled by RPS include *Nimbus III*, the Apollo Surface Experiments, the *Pioneers 10 and 11*, the Viking Mars Landers, *Galileo, Ulysses, Cassini, New Horizons* and *Curiosity*. The current operating set of missions that are enabled by RPS are *Voyagers 1 and 2*, *Cassini, New Horizons*, and *Curiosity*. The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the current RPS used for *Curiosity* and upcoming Mars 2020 missions. An enhanced version of this generator outfitted with higher efficiency thermoelectrics is under development for potential use in the future. Other previously deployed power systems include the Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG) and the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG). The common thread for all of these power systems is that they are fueled with Pu-238 in the oxide form. To ensure mission success and meet safety and security challenges, the use of this unique isotope involves additional planning activities and requires specific actions when the devices are delivered to the National Aeronautical and Space Administration (NASA) John F. Kennedy Space Center (KSC), and incorporated into the assembly, test and launch operations (ATLO) process.. It has been forecasted that the use of a nuclear reactor-based power system is on the horizon. This nuclear reactor-based power system could be used for either specifically powering spacecraft's propulsion system or for surface power use once the mission arrived at its destination. Since a nuclear reactor-based system has never been handled or integrated into a spacecraft at KSC, an integration of this nuclear reactor-based power system would potentially introduce further challenges than those of RPS that must be accounted for in the ATLO process. This paper will explain ATLO considerations for recent MMRTG-enabled missions that have occurred and those planned for the near future (Mars 2020 NASA mission). In addition, this paper will discuss challenges for integrating a nuclear reactor-based power system onto a space mission. Specifically, the following topics will be addressed:

- **Approach for nuclear safety planning for nuclear material use and its transportation to space mission launch site**
- **Plan for security posture for nuclear materials at launch site**
- **Preparation for transportation of the nuclear power system from the fueling and testing location to the launch site**
- **Preparation of documentation and procedures for nuclear material use at launch site**
- **Plan for coordination between nuclear power system and space mission teams**
- **Plan for appropriate staffing and scheduling of testing and operations**

- **Plan and considerations for the integration operations of the nuclear powered spacecraft into the launch vehicle systems**
- **Future Considerations for a Nuclear Reactor-Enabled Space Mission**

I. Introduction

The use of Radioisotope Power Systems (RPS) enabling a NASA mission has occurred several times since the late 1960's when the first one was used on a lunar mission. Earlier use of RPS in a satellite had occurred by the Navy. The handling of these special power systems has evolved and has been focused on ensuring the safety of all those involved as well as delivering a reliable RPS for the mission. The use of RPS does enable missions that might otherwise not be possible or provide for a richer portfolio of science to be performed. However, the use of RPS does come with some additional burden in the planning and operational aspects of a mission. It is the intention of this paper to illustrate these aspects to provide discussion as to the "what?", "why?" and "how?".

II. ATLO for a Nuclear-enabled Launch from a Department of Energy Perspective

Typically, ATLO begins about the 6 to 9 months prior to the launch of a NASA mission and encompasses several organizations. KSC staff, NASA mission staff [typically from Jet Propulsion Laboratory (JPL), Applied Physics Laboratory (APL) or Goddard Space Flight Center (GSFC) for robotic missions], United Launch Alliance (ULA), Cape Canaveral Air Force Station (CCAFS) and various support contractors. When the mission is a nuclear-enabled mission, the ATLO team also includes the Department of Energy (DOE) and its prime contractors from the National Laboratories. The DOE team is there to handle the various aspects and special issues that are involved with the handling of special nuclear materials (SNM) in the form of an RPS or perhaps in the future a reactor system. When dealing with SNM, there are certain considerations to be met: a certain structure of documentation, rigor and experience that DOE provides in fitting with its role as defined by the Atomic Energy Act of 1954[1]. This paper will examine those various aspects, seek to explain them and give them context. It is important to know that the tasks associated with providing an RPS for a NASA mission is typically a 5 to 6 year evolution if the RPS is an existing design (this timeline can be longer if a new design of RPS is to be used). This timeline includes manufacturing the power system, producing the heat sources, fueling and performing the acceptance tests, transportation from the fueling site to KSC, and providing ground support for 4 to 6 months prior to launch. Several of the tasks (although performed sequentially) have overlapping timelines when the preparation durations are included. Although we will not discuss all aspects of the process, Fig. 1 shows a notional timeline for the various steps that take place involving the DOE and their team (National Laboratories and sub-contractors).

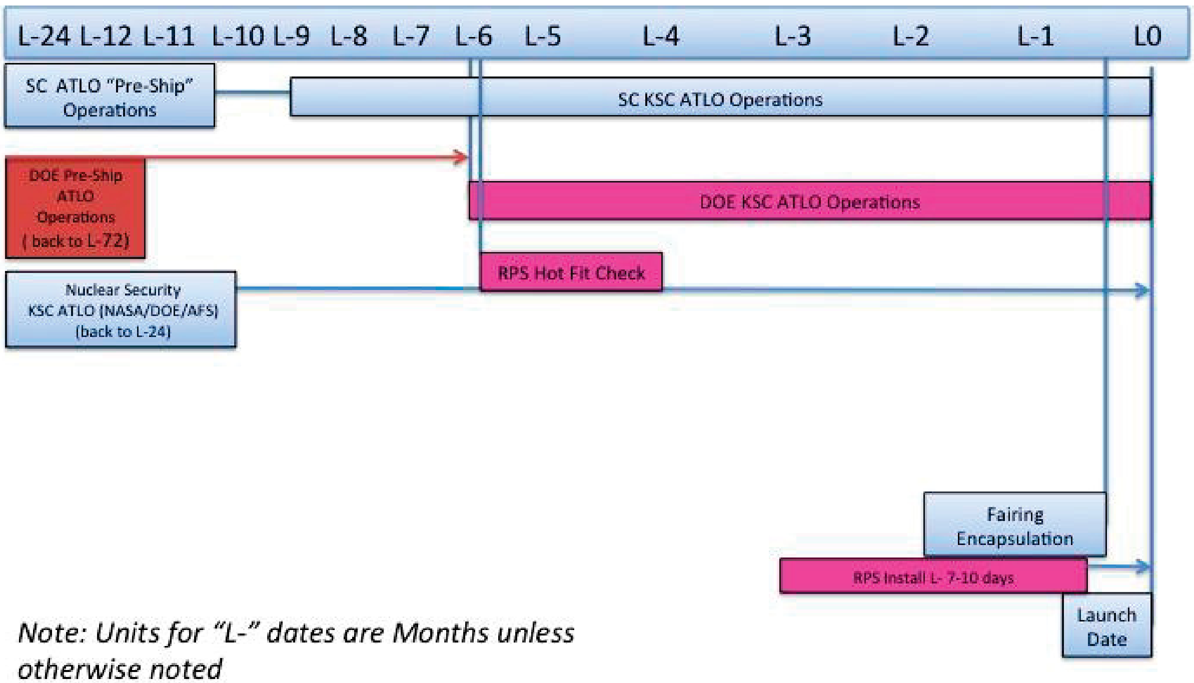

Fig. 1 A notional timeline for the DOE team to support an RPS-enabled launch.

A) Approach for Nuclear Safety Planning for Nuclear Material Use and its Transportation to Space Mission Launch Site

The transportation of the RPS used by NASA over the past 20 years (*Cassini, New Horizons*, and *Curiosity*) has been accomplished by using a Type B shipping container that was specially designed to be compliant with the United States Department of Transportation regulations for movement of SNM over public highways[2]. The container, the RTG 9904 Type B shipping container, is equipped with active cooling and is part of a complete transportation package that includes special vibration damping and monitoring, power monitoring, redundant cooling loops, redundant diesel power supplies and a specialized trailer to contain everything (see Fig. 2). The 9904 shipping container has the ability to contain different power systems so that the current package can contain either a General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) or a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). When new power systems are developed, they can be added to the list of approved items for this package once safety/accident analyses have been performed.

The use of Pu-238 SNM heat sources in DOE facilities is governed by 10CFR830, Nuclear Safety Management, and several DOE orders[3-5]. When the RPS is transported to KSC, DOE puts in place the documentation framework to make several KSC facilities and activities under a similar regulatory stance. This is done using a documented safety analysis (DSA). The document will describe all activities and facilities that will be involved with the RPS during its 4 to 6 month-stay at KSC prior to launch. For example, activities would be such as the receipt of the RPS and its use for an initial integration with the spacecraft, "hot fit check" (see Figs. 2-4). It also describes any possible events that could lead to the release of SNM, the means of mitigating those events and how to ensure the mitigation is effective (engineered controls, administrative means, etc.). All activities by all parties involved become procedures and any changes to those procedures are reviewed against the defined safety envelope described in the DSA in order to ensure that the consequences/frequency of the analyzed accident scenarios are not changed and also that no new accidents not previously analyzed are added[3]. The execution of DSA activities requires a physical presence of staffing that are familiar with the operation of a DOE nuclear facility continuously when the RPS is at KSC for the 4 to 6 months prior to launch. This is typically done by a team of 2 or more senior individuals to monitor the RPS and any nearby activities for compliance with the DSA. The DSA is reviewed and approved by all concerned parties [KSC, NASA mission, USAF, DOE and the Idaho National Laboratory (INL)].

The writing of the DSA is typically performed about 2 to 3 years prior to launch. It is checked carefully during the full-scale walk-through (Trailblazer) that takes place 12- to 18 months prior to launch, which involves all parties that will interface with the RPS during its 4 to 6 months at KSC. The emphasis is to ensure that all activities are captured completely and any hazards are analyzed fully.

B) Plan for Security Posture for Nuclear Materials at Launch Site

A security plan is written by the KSC NASA security and is reviewed and approved by DOE. This plan must be consistent with how DOE secures and monitors SNM at its sites[4,5]. When the RPS is stored at KSC, continuous physical security measures are in effect with controlled access. Whichever buildings the RPS is in for whatever length of time must be secured in an equivalent fashion. The security plan is usually written 1 to 2 years prior to launch and approved for use prior to the RPS arriving at KSC.

C) Preparation for Transportation of the Nuclear Power System from the Fueling and Testing Location to the Launch Site

The Office of Secure Transportation, which is a federal agency must perform the movement of SNM, of the type used in the RPS. Typical transportation scheduling requires a 12-month look ahead with the schedule being firmed up at the 60 day out point. A support team from the DOE is part of the transportation group for the ride from INL to KSC. This support team consists of individuals with the appropriate skill mix to address any possible issues that arise with the shipping container, the trailer it rides within and any associated systems. Typical make up would be: an electrician or instrumentation technician, a mechanic, an engineer, a health physics technician, a quality assurance representative and a management representative.

A separate team is required to receive and un-package the RPS at KSC when it is delivered. All necessary equipment to un-package the RPS would already have been staged at KSC. Procedures are all in final form having been revised after the Trailblazer activity. All procedures used at KSC must be reviewed and approved by KSC 50 days prior to their first-use. The typical make up for a receipt and un-packaging crew at KSC is as follows: heavy equipment operators, 2 health physics technicians, 5 technicians for Type B shipping container operations and other associated activities, 2 quality assurance staff, 1 engineer for shipping container operations, 1 engineer for power monitoring operations, 1 engineer for RPS movement operations, 2 nuclear safety analysts, 1 KSC safety engineer, and 2 management representatives. This team should be considered a minimum and more may need to be added to allow for additional shift work or contingency.

Fig. 2 The RTG 9904 Type B shipping container being delivered into the storage facility at KSC. The lines for active cooling system are shown, as is the impact limiter base.

Fig. 3 The building at KSC used to house and store the RPS during the majority of its time at KSC with the specialized trailer system used to transport the RTG 9904 Type B shipping container in the foreground.

D) Preparation of Documentation and Procedures for Nuclear Material Use at Launch Site

All operations involving the RPS are performed using Type I procedures that provide precise instructions in a step-wise fashion. Execution of these procedures is done via three-way communication among an engineer-reader and trained technicians. All operations are followed by quality assurance staff, who are trained in a similar fashion as the technicians performing the steps.

The procedures are typically written about 2 years prior to launch and then they are exercised in training several times prior to performing a high fidelity training exercise at KSC (Trailblazer) with all the various entities that will be involved in the actual operation. This will typically utilize a training model or engineering unit of the RPS, the Type B shipping container, forklift, and all facilities that are involved. No SNM is involved in the Trailblazer. The exercise typically consumes 2 weeks at KSC and is used as a final "tune-up" on the procedures and personnel training prior to shipping the RPS to KSC 4 to 6 months prior to launch. The Spacecraft contractor typically provides the RPS mechanical handling integration hardware and Spacecraft integration staff and procedures to support the Trailblazer activities. DOE and the Launch Vehicle provider also provide their handling hardware, staff and procedures for the Trailblazer. An independent group critiques the activity during the 2-week performance.

There are several associated documents that must be prepared for KSC operations in addition to the specific procedures and safety analyses that were previously described. If any presence of the RPS falls between May and November, then a Hurricane Plan is required that details what operations would be undertaken if a hurricane is thought to be heading towards the vicinity of KSC. For example, the trailer system, which was used to transport the RPS down to KSC and around KSC once it is there, may require cable tie-downs to secure it. The possibility of a launch accident must be considered and a plan would be written on how the RPS is to be retrieved and removed from KSC. This plan will likely go through several scenarios involving different Type B shipping containers depending on the physical condition of the RPS and its SNM. Activities involving the RPS must also be included in the Missile System Pre-launch Safety Package, which captures all safety related items for the entire mission. There is also the Launch Site Support Plan, which details the various support items that KSC will provide for the mission.

E) Plan for Coordination Between Nuclear Power System and Space Mission Teams

It is especially important that the coordination among the DOE team, the NASA Spacecraft and KSC mission teams, the ULA team, CCAFS personnel and the various KSC support team members is as concise as possible. The approximate number of people involved in various aspects of the movement, storage and integration of the RPS onto the spacecraft can at times be several hundred. An important means of organizing the essential communications and identifying and agreeing to organizational roles and responsibilities is the formation of the Ground Operation Working Group (GOWG) and execution of GOWG meetings. These are typically started 3 to 4 years prior to launch and nominally take place quarterly. These are held at KSC and provide a forum to discuss the various issues from planetary protection, positioning of equipment on various levels of the ULA Atlas Vertical Integration Facility (VIF) (where the Atlas rocket is assembled for launch), physical protection specifics, dates for the Trailblazer, dates for delivery of the RPS to KSC, dates for the "hot fit check", etc. A second set of meetings is performed at a higher level and is termed as the Mission Integration Working Group (MIWG) and they are held in a similar fashion to the GOWG. The "hot fit check" is one of critical "Test Like You Fly" activities for the Spacecraft where for the first time the Spacecraft is integrated with the RPS and powered up by the actual RPS it will fly with.

Fig. 4 The team of RPS handlers inside the clean room used to house the spacecraft for New Horizons. The RPS has been mounted to the spacecraft to perform the "hot fit check" for a functional check on the systems.

F) Plan for Appropriate Staffing and Scheduling of testing and Operations

Section C above described some of the staffing requirements for shipping package receipt and initial operations. It has also been mentioned that a continuous physical presence once the RPS has been delivered to KSC to maintain the posture of a DOE nuclear facility. Another key timeline item that must be considered is the delivery of the RPS

7 to 10 days prior to launch for integration onto the spacecraft. To ensure traffic flow is only minimally effected, delivery typically takes place before morning rush hour at KSC. The length of the integration activities is variable depending on the mission. For example, the *New Horizons* integration was completed by noon of the first day. The integration activities for the *Curiosity* took roughly 36 hours. The latter example required manning two shifts with quality assurance, technicians, nuclear safety analysts and management representatives to support the JPL staff involved with the operations.

In general, RPS operations at KSC are covered with the following skill mix and the numbers include contingency: hands on technicians (8), quality assurance (4), nuclear safety analysts (3), engineers (4), safety engineers (3), and management representatives (3). All would have the appropriate training for their respective duties in addition to specific KSC training. For example, the hands on technicians would have radiation safety training and crane training.

G) Plan and Considerations for the Integration Operations of the Nuclear Powered Spacecraft into the Launch Vehicle Systems

The use of specialized equipment and the general close quarters to support the final integration of the RPS into the rocket fairing at the VIF requires careful planning. The specialized cart is used to handle the RPS so that it can be physically attached (*New Horizons* spacecraft or *Curiosity* rover). The cart was designed to enable a thermally hot RPS, additional a radiation source, to be attached to the spacecraft (or rover) in a reliable and safe fashion (see Figs. 5 and 7). The deck that was used to stage the RPS and the specialized RPS integration cart was considered as a radiation control area and the number of persons that could be co-located was physically limited to about 20. The RPS was hoisted to that deck in a specialized cage in an about 150-foot lift (see Fig. 6). These operations were fully vetted in the Trailblazer activity mentioned elsewhere but were further practiced about 1 week prior to their execution to ensure correct performance. Precise coordination among facility staff, DOE team members and mission staff is essential for these operations.

Fig. 5 The RPS integration cart used to attach the MMRTG to Curiosity when it was inside the fairing on top of the Atlas 541 rocket.

Fig. 6 The area immediately adjacent to the VIF showing the cage assembly used to house the RPS during movement at KSC and CCAFS. This is immediately prior to an about 150-foot elevation lift to a high level in the facility to prepare for insertion of the RPS through the fairing door atop the rocket and attachment to Curiosity. The solid rocket boosters can be seen on the upper-right corner of the photo.

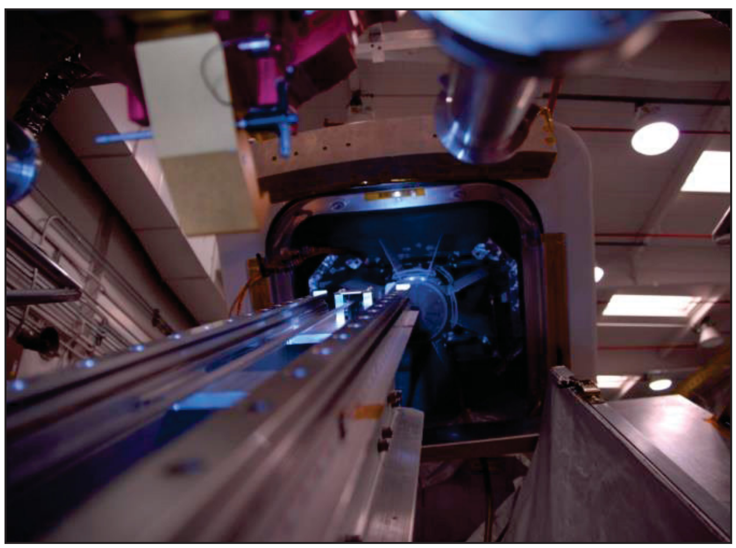

Fig. 7 This shows the insertion of the RPS using the integration cart through the removable hatch in the fairing of the rocket for Curiosity.

H) Future Considerations for a Nuclear Reactor-Enabled Space Mission

A short primer on space reactors here may be of some applicability. A space reactor, similar to a regular terrestrial reactor, will consist of several components: (1) a fuel core that contains the material and is capable of sustaining critical behavior and providing heat to be used either as heat or converted into electrical power, (2) the structure of the reactor which will house the core, reflectors, control technology, containment and a mechanism or medium for conveying the heat out of the reactor to where it is needed, and (3) a conversion system for converting the heat to electrical power. Weight is always one of the key factors for space applications and much effort goes into making every component as light as possible. The current thinking on how a reactor would be transported to a staging area at KSC prior to a reactor-enabled NASA mission is of two main streams: (1) fuel a reactor before it is shipped to KSC and (2) ship the reactor and the core separately to KSC and integrate them there. Quick look analysis has shown that the second option provides an additional flexibility in shipping methods as the core could be shipped using any one of several existing shipping containers whereas shipping a reactor with the core in place is likely to require a new shipping methodology entirely. In either case, testing the reactor with the core in place at KSC is consistent with a “test as you fly” philosophy.

The use of a fission power system (nuclear reactor) on a spacecraft to be launched from CCAFS introduces several additional specific considerations beyond those encountered for use of an RPS on a spacecraft. These considerations would be similar whether the reactor was used for propulsion or was carried to provide surface power at a destination (Moon, Mars, etc.). These additional considerations are driven by two primary factors: (1) security of the fissile material (uranium) and (2) safety of operating a reactor in a facility at KSC.

Uranium-235 is the only fuel type that is accepted for use in space [6]. Most current concepts as well as all historical tests for use in space-based reactor systems used highly enriched uranium (HEU) which is ≥20% Uranium-235 enrichment [7-11]. The facilities to be used to house the reactor prior to integration into the spacecraft would be controlled in a similar fashion to an RPS (i.e., as DOE nuclear facilities). The security requirements for DOE nuclear facilities are described in DOE order 474.2, “Nuclear Material Control and Accountability”[4], and DOE manual 470, “Physical Protection”[5]. The use of HEU in the quantities mentioned in current scenarios would potentially drive a significant increase in both capital and staffing costs on the order of tens of millions of dollars per use[6].

The primary driver for enhanced security considerations fall into 3 distinct areas: (1) enrichment of the uranium used, (2) quantity of uranium used, and (3) chemical form of uranium used. As noted above, most historical and recently proposed reactor designs are based on using HEU. To provide further clarification, HEU is strictly defined as ≥20 wt% U-235, however, historically space reactor fuel has been >90 wt% U-235. Material of this type of enrichment is similar to that used for nuclear weapons which is the reason for enhanced security measures. The amount of uranium involved also further specifies the type of security posture. The amount of uranium in historical and recently proposed reactor designs has been >>10 kg. The chemical form is also very important for determining the security posture. For example, the used of uranium oxide (similar to that used for conventional light water reactors that provide power for civilian needs although of much higher enrichment of U-235) is considered less attractive than uranium metal alloy fuel where the alloying agent is present in very small quantities. The uranium metallic alloy is considered readily recastable.

The expense of an enhanced security posture is focused in two primary areas of emphasis. The first of these is one-time cost of engineered barriers or systems. The various detection systems required to secure nuclear material can be fairly expensive. The enhancements to the physical structure or a new structure to house the system are also expensive [6]. The periodicity of nuclear-enabled launches also adds some complexity to the equation in that the security posture is likely to be utilized in a campaign manner and thus “stood up” and “stood down” every few years. The lack of a continuously maintained security posture will add additional expense for readiness activities and drive upgrades that might not be required had the security infrastructure been in a continuously operating mode. The second area of emphasis will be the human resources required to man the security organization. With the projected number of resources required, it will be very unlikely that they can be “borrowed” from an standing organization, i.e., a national laboratory or the military[6]. The length of the campaign would likely be very similar to that for an RPS-enabled launch, i.e., about 6 months.

The safety considerations inherent in staging, testing and integrating a reactor at KSC would likewise lead to additional costs and complexities. This statement is based on the philosophy mentioned above that you would “test like you fly”. This would drive towards integration of the core and the reactor housing in a facility at KSC and some sort of test that the reactor or core had not been damaged during shipment. The initiation of reactor operations in a facility at KSC, even if it were just an “approach to criticality” test, would drive towards establishing a facility, at a minimum, as a Type B reactor hazard category II facility. The requirements for the various types of DOE hazard category facilities can be found in DOE standard 1027, “Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480,23, Nuclear Safety Analysis Reports” [12]. The level of infrastructure, support personal, safety basis and training requirements for personnel would increase substantially. The creation of fission products with an associated radiation field will complicate handling for integration into the spacecraft.

Another important consideration is the types of radiation associated with testing a reactor at KSC prior to launch would drive an enhanced health physics presence versus the relatively simple system of an RPS. The nuclear material in an RPS is well contained and a driven by a single isotope, Pu-238, which has a well-defined radiation signature (neutron and gamma). The operation of a reactor, even if for a short time, will generate fission products (Sr-90, Cs-137, etc.) and activation products (Co-60, etc.) which will have a much more varied signature of radiation. Different types of radiation will require more and different types of equipment to provide for personnel safety.

Closing Remarks

The use of radioisotope power systems has been an enabling technology for certain space missions. The use of RPS, which can provide power for years to decades to spacecraft and associated systems, does add complexities to ATLO phase of a space mission. Additional planning starting approximately 5 years before the launch date has been required for NASA missions that have used this technology. Detailed procedures, including security plans and safety analyses, are necessary for a smooth operations posture to be maintained. Rigorous training that fully integrates all associated team members from NASA-KSC, NASA mission, CCAFS, ULA and the DOE has proven to be very beneficial for ensuring safe, secure and efficient operations. The use of a dedicated crew for RPS handling that had been involved in the fueling and testing of the device at the fueling and testing site prior to it being transported to KSC contributed to a well disciplined approach to operations which led to predictable results and a well maintained schedule.

The potential use of nuclear reactor-based power systems in the future would add complexity to the ATLO operations beyond that encountered presently with RPS-enabled missions. The complexities would be primarily in the areas of enhanced physical security measures (both engineered barriers and manpower) and enhanced health physics presence (both physical means and manpower).

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Acronym List

Table of Acronyms	
APL	Applied Physics Lab (of the Johns Hopkins University)
ATLO	Assembly, Test and Launch Operations
CCAFS	Cape Canaveral Air Force Station
CFR	Code of Federal Regulations
DOE	Department of Energy
DSA	Documented Safety Analysis
GOWG	Ground Operations Working Group
GPHS-RTG	General Purpose Heat Source Radioisotope Thermoelectric Generator
GSFC	Goddard Space Flight Center (NASA)
HEU	Highly Enriched Uranium
JPL	Jet Propulsion Lab (of the California Institute of Technology)
KSC	John F. Kennedy Space Center (NASA)
INL	Idaho National Laboratory (DOE)
LANL	Los Alamos National Laboratory (DOE)
MHW-RTG	Multi-Hundred Watt Radioisotope Thermoelectric Generator
MIWG	Mission Integration Working Group
MMRTG	Multi-Mission Radioisotope Thermal Generator
NASA	National Aeronautical and Space Administration
ORNL	Oak Ridge National Laboratory (DOE)
Pu-238	Plutonium, 238
RPS	Radioisotope Power Systems
RTG	Radioisotope Thermal Generator
SMN	Special Nuclear Material
ULA	United Launch Alliance
USAF	United States Air Force
VIF	Vehicle Integration Facility
WBS	Work Breakdown Structure

References

[1] Atomic Energy Act of 1954.

[2] 49CFR 172 Transportation of Hazardous Materials.

[3] 10CFR830, Nuclear Safety Management.

[4] DOE Order, "Nuclear Material Control and Accountability", DOE O 474.2-1, August 2011.

[5] DOE Manual, "Physical Protection", DOE M 470.4-2, March 2006.

[6] R. McNutt and P. Ostdiek, "Nuclear Power Assessment Study", TSSD-23122, Applied Physics Laboratory, Johns Hopkins University, 2015.

[7] R. Wiley, Ch. 5 (Nuclear Systems), in Spacecraft Power Technologies, Imperial College Press, 2000.

[8] Clark, John S., et al., "Nuclear Thermal Propulsion Technology: Results of an Interagency Panel in FY1991", NASA Technical Memorandum 105711, April 1993.

[9] M.S. El-Genk, "Deployment history and design considerations for space reactor power systems," *Acta Astronautica*, **64**, pp. 833-849 (2009).

[10] National Aeronautics and Space Administration, Fission Surface Power Team, *Fission Surface Power System Initial Concept Definition*, NASA/TM-2010-216722 (2010).

[11] Space exploration initiative fuels, materials and related nuclear propulsion technologies panel. Final report , NASA TM-105706, Bhattacharyya, S.K. ; Olsen, C. ; Cooper, R. ; Matthews, R.B. ; Walter, C. ; Titran, R.J. , Sept 1993.

[12] DOE Standard 1027, "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480,23, Nuclear Safety Analysis Reports", DOE-STD-92-1, September 1997.