DISCOVERY 2010

ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG)

INFORMATION SUMMARY

Preface

The Advanced Stirling Radioisotope Generator (ASRG) unit used in missions proposed for this AO, including the services associated with their provisioning on space missions (e.g., National Environmental Policy Act (NEPA) Compliance, Nuclear Safety Launch Approval, Emergency Preparedness and Planning), will be provided by NASA and the Department of Energy (DOE) as Government Furnished Equipment (GFE) and Services (GFS). Funding for these units and services will be provided directly by the Discovery Program and hence not included in the cost cap. Up to two units will be provided if mission power exceeds that of one unit.

This document provides a background of radioisotope power systems and the ASRG system currently in development. A companion ASRG document in the AO Library is the *ASRG User Interface Control Document (ICD)*. Please refer to this document for detailed information and the most recent ASRG parameter updates.

Missions selected for Phase A study selecting the ASRG as a NASA technology option for their mission, will be provided a NASA Point of Contact (POC) from the Radioisotope Power System Program Office (RPSPO) at Glenn Research Center that will support them in detailed technical information, analyses, etc., for incorporating the ASRG power system.

1.0 Introduction

Radioisotope power systems produce electrical power by converting heat released from the nuclear decay of a radioisotope into electricity. First used in space by the United States in 1961, these devices have consistently demonstrated unique capabilities over other types of space power. A key advantage is their ability to operate continuously, independent of orientation, obscuration of, or distance from the Sun. These systems are also long-lived, rugged, compact, highly reliable, and relatively insensitive to radiation and other environmental effects. As such, they are ideally suited for missions involving long-lived, autonomous operations in the extreme environments of space and planetary surfaces.

Most radioisotope power system concepts consist of two principal elements: a heat source and a power conversion system. The heat source includes the radioisotope fuel encapsulated within a series of barriers and protective shells that prevents its release into the environment. The heat produced from this thermal source flows to a power conversion system, which transforms a portion of the heat into electricity. The remaining unconverted heat is removed, and rejected to space via radiators.

Previous units employed by NASA have used plutonium-238 (Pu-238) fuel and thermoelectric devices to convert decay heat into electricity. Forty-four Radioisotope Thermoelectric Generators (RTG's) have been launched on 25 U.S. missions over the last four decades. The Apollo missions to the Moon, the Viking missions to Mars, and the Pioneer, Voyager, Ulysses, Galileo, and Cassini missions to the outer Solar System have all used RTG's. In each instance, the units met or exceeded their operational requirements. As a testament to their reliability and longevity, the RTG's on the Pioneer 10 spacecraft, which was launched in 1972, have operated reliably now for over three decades and continue to generate power well beyond the orbit of Pluto.

The Galileo, Ulysses, Cassini, and New Horizons Pluto missions were each powered by one or more General Purpose Heat Source RTG's (GPHS-RTG's) shown in Fig. 1-1. Each unit was designed to deliver a nominal power level of 285 We (watts electric) upon final assembly from a stack of 18 General Purpose Heat Source (GPHS) modules.

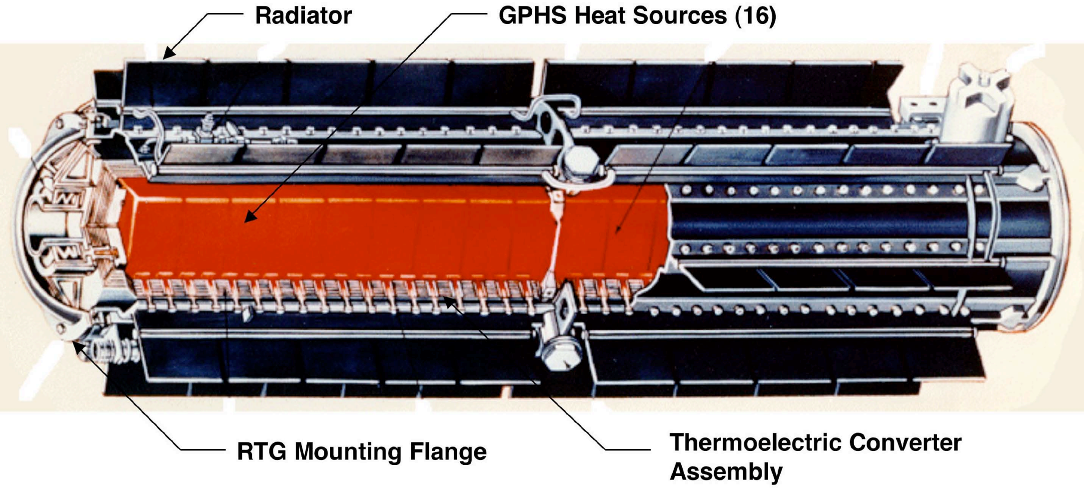

Figure 1-1 GPHS RTG

The GPHS-RTG was designed to operate solely in space, but NASA's requirements for radioisotope power systems (RPS) on future missions have been expanded to include operation on planetary bodies, such as Mars. To accommodate this broadened range of capabilities, DOE and NASA has initiated the development of a new RPS option: the Advanced Stirling Radioisotope Generator (ASRG). This unit uses the GPHS modules and operates at a power level greater than 140 watts electric (We) at beginning of mission (BOM). As with previous RTG's, the output power decreases over time due to the decay of the Pu-238 fuel, and the gradual degradation of power system components.

Sections 2.0 and 3.0 describe the ASRG, including requirements, design and capabilities.

Section 4.0 provides an overview of the GPHS, the basic building block for RPS and also the ASRG thermal source. Finally, Section 4.0 summarizes the activities and processes that AO respondents should assume in proposing an ASRG powered mission.

2.0 Advanced Stirling Radioisotope Generator (ASRG)

The ASRG employs an advanced, high efficiency, dynamic Stirling Cycle for heat-to-electric power conversion. This process is roughly four times more efficient than thermoelectric conversion. As a result, the ASRG produces comparable power to an RTG with only a quarter of the Pu-238, extending radioisotope power available for future space missions with the current proposed US production of Pu-238.

The ASRG utilizes an advanced Stirling free-piston design consisting of two major assemblies that reciprocate to convert heat to electrical power. Heat from the GPHS module is conductively coupled to the heater head. Helium is used as the working fluid and is hermetically contained within the converter enclosure. The displacer shuttles helium between the expansion space where heat is received and compression space, where waste heat is removed.

The changes in pressures and volumes of the converter working spaces drives a power piston that reciprocates to produce electrical power via an attached permanent magnet linear alternator.

2.1 ASRG Design

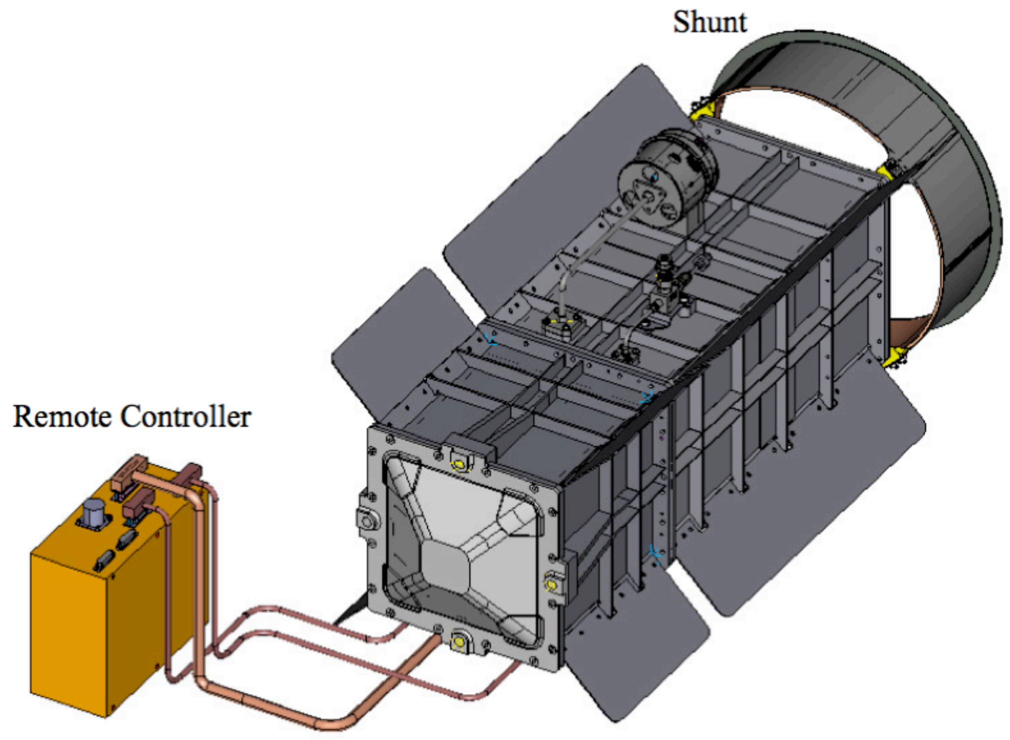

Figure 2-1 ASRG Flight Unit

The ASRG design, shown in Fig. 2-1, consists of a beryllium housing, two advanced Stirling convertors (ASC), an electronic controller externally located, two GPHS modules located at either end surrounded by bulk thermal insulation, and auxiliary components mounted on the housing exterior. Thermal-to-electric power conversion is performed by the free-piston Stirling engines, which are integrated with a linear alternator in a common pressure vessel. Each closed-cycle Stirling engine converts the heat from one GPHS module into reciprocating motion with a linear alternator.

The controller also synchronizes each ASC by matching their operating frequencies and phasing of piston motion. This minimizes the dynamic vibration imposed on the spacecraft. The controller operates autonomously and independently from the spacecraft electrical system, but does provide health monitoring and status telemetry data to the spacecraft and or Earth. The controller can receive commands to alter the ASRG operating conditions to optimize power output during the mission.

Two ASRGs can operate on the same bus, which can either be a battery or capacitive energy storage bus.

The controller provides steady state electrical power between the nominal 22-34 VDC range. The spacecraft electrical bus controls the voltage. Power is shunted by ASRG via the internal shunt to protect the ASRG in the event of a spacecraft bus failure. The controller assembly is mounted outside the housing assembly, which allows some limited flexibility in location to meet specific spacecraft needs.

The ASRG design can incorporate an optional user supplied active cooling system (ACS) that could be required for certain planetary mission phases.

The ASRG is equipped with a gas management system that maintains a cover gas within the housing for thermal management during storage, transportation and pre-launch operation. A barometrically operated relief valve vents the housing during launch ascent and remains open to the environment allowing full power vacuum operation.

Table 2-1 is the current best estimate (CBE) for the flight ASRG characteristics. A more comprehensive set of ASRG characteristics is provided in the *ASRG User Interface Control Document (ICD)* in the AO library, updated as required.

Parameter	**ASRG**
Power per Unit (BOM), (4 K, space eff. sink in vacuum)	~128 We (includes 5% program reserve on 135 We)
Power per Unit (BOM+ 1yr.), (Mars avg. temp, in CO_2)	~106.4 We (includes 5% program reserve on 112 We)
Voltage	22-34 VDC
Power Degradation Rate, [We/yr]	~ 1.4 (see Fig. 4.2-1 ASRG User ICD)
Mass per Unit, [kg]	~ 32 (includes 5% program reserve on 30.6 kg) (1)
Dimensions [mm]	Length: 76.2 cm Width: 39.4 cm Height: 45.7 cm
Radiation Tolerance	126 krad (2)
Additional Shielding, [kg]	Mission Specific, required only for controller in a high-radiation environment (3)
Number of GPHS Modules per Unit	2
Thermal Power (BOM), [Wt]	488-512 (min/max fuel load)
Mechanical Disturbance (axial)	22 N peak-peak, measured (35 spec)
Frequency (Hz)	102
Controller	Single-fault tolerant, with N+1 redundant controller cards and the capability for the engines to operate independently of one another in the event of single engine failure.
External Radiator Temperature (4)	~ 45º C (space vacuum, no Sun)
Operating Environment	Vacuum and Atmosphere
Lifetime requirement, [years]	14 + 3 (storage)

Table 2-1 Current Best Estimate (CBE) of the ASRG Flight Unit Characteristics

(1) Mass does not include optional spacecraft adapter ring for missions using launch vehicles (> ~ 0.1 g^2/Hz): adds 1.23 kg. ASRG housing to controller cable mass: adds 1.8 kg/m.
(2) Radiation Tolerance: from 50 kRad space and 13 kRad GPHS source requirement, with RDF 2 applied
(3) For ASRG additional shielding is required to protect the controller electronics. (As an example, controller shielding mass for a Europa type mission was previously estimated at ~ 11kg (TBR)).
(4) Case temperature for other environmental sink temperatures will vary

GPHS = General Purpose Heat Source
BOM = Beginning of Mission

2.2 Program Risk Posture

The ASRG flight unit development project has a preliminary design review planned for August 2010 (see ASRG Development schedule in the AO library), and therefore the RPSPO is holding a 5% reserve on both power output and mass from current best estimates for the final ASRG flight unit at this time. Proposers should use 128 We (includes 5% program reserve) BOM (4/2015) as adjusted from the 135 We specification (minimum predicted fuel loading) and a system mass of 32 kg (includes 5 % program reserve, which is in addition to any mission reserves) for planning purposes until the RPSPO updates the reserve values as the development matures. This mass includes the connectors located on the ASRG housing, controller and cable ends. Users should plan on a maximum separation distance of the ASRG housing to controller spacecraft mounting locations of ~ 2m.
The power levels cited here are based on an estimated GPHS thermal loading of 244 Wth, the minimum estimated value. An additional ~ 8.0 We could be achieved if the fuel loading ultimately is the maximum 256 Wth predicted value. Plutonium processing for the ASRG flight GPHS is planned to occur in 2011. The thermal power level of the GPHS would be established at that time.

The ASRG characteristics shown in Table 2-1 are primarily for space vacuum application with a 4 K sink temperature, however the ASRG maybe considered for planetary missions such as Mars or Titan. The power output is dependant on the effective sink temperature "seen" by the ASRG radiators, where higher sink temperatures decrease power output. The NASA RPSPO will assist proposers in determining ASRG performance for specific sites on Mars and other destinations. Also certain lunar applications are possible and the RPSPO will provide guidance/assessments on what is required for adaptation/de-rating for a successful ASRG lunar mission proposal.

2.2.1 Planetary Protection

The requirement for COSPAR Category IVc planetary protection has been added to the ASRG requirement in February 2010. The RPSPO has engaged the NASA Planetary Protection Officer, Dr. Cassie Conley, for guidance concerning processes of dry heat microbial reduction (DHMR) and vapor hydrogen peroxide (VHP) sterilization methods.

The current ASRG planetary protection plan calls for clean room assembly, DHMR sterilization of all internal components prior to fueling, VHP environment during fueling to avoid recontamination of previous sterilized components and final exterior surface sterilization with VHP.

VHP has yet to be adopted by COSPAR or NASA as a replacement to DHMR sterilization but is being investigated by the planetary protection community. It is anticipated that VHP will be an approved alternative to DHMR sterilization since many current spacecraft materials have difficulty with the DHMR process. VHP chemical compatibility has been demonstrated with the ASRG's external thermal paint coating.

The RPSPO is developing a plan for Category IVc sterilization compliance for the ASRG should a mission require it.

2.2.2 Electro-magnetic Interference (EMI)

Discovery 12 Mars surface missions are encouraged to make use of the Electra UHF data and relay infrastructure as defined by the Mars Exploration Office. Initial EMI testing on the ASRG engineering unit revealed the EMI signature to be greater than that required for the Electra radio specification. Note that the ASRG engineering unit, at that time, did not have an EMI requirement for Electra.

The RPSPO has added a requirement that the flight ASRG also meet the Electra radio's UHF interference specification to meet a potential ASRG Mars surface mission. An EMI working group has been formed to guide the ASRG design to be fully compliant with Electra interference required interference levels.

2.3 ASRG Development Plan

The Department of Energy (DOE) has initiated development of the ASRG under a contract with Lockheed Martin (Valley Forge, PA) and advanced Stirling convertor subcontractor, Sunpower (Athens, OH). NASA Glenn Research Center (Cleveland, OH) is also providing technical support. The ASRG project currently plans to build one qualification unit followed by two flight units available to this Discovery AO with an anticipated delivery date to KSC no earlier than October 2014.

The most current schedule is available in the Discovery AO library and will updated as required.

3.0 General Purpose Heat Source (GPHS)

The GPHS is the basic building block for the heat sources within the ASRG. It includes the Pu-238 radioisotope fuel encapsulated within a protective clad that prevents its release into the environment, and a series of protective shells that prevent damage to the clad during inadvertent atmospheric re-entry and impact. The GPHS is designed as a module to allow development of ASRG units with different thermal outputs and power levels, and to enhance safety during launch.

A cut-away view of a single GPHS module is shown in Fig. 3-1. Each module contains four plutonium dioxide (PuO_2) fuel pellets, with a thermal output of approximately 62.5 watts per pellet. Each pellet is encapsulated within a vented iridium capsule, which functions as the primary fuel containment. The encapsulated pellet is called a Fueled Clad (FC). Each GPHS module contains four FC's encapsulated within two cylindrical Fine Weave Pierced Fabric (FWPF) containers, known as Graphite Impact Shells (GIS's). Thermal insulators made from Carbon Bonded Carbon Fiber (CBCF) surround each GIS. These insulators are designed to provide acceptable iridium temperatures during possible reentry, descent and impact. Two GIS's with thermal insulator disks and sleeves are placed in a rectangular aeroshell to form a GPHS module. The aeroshell is the primary heat source structure that provides reentry thermal protection for the FC's.

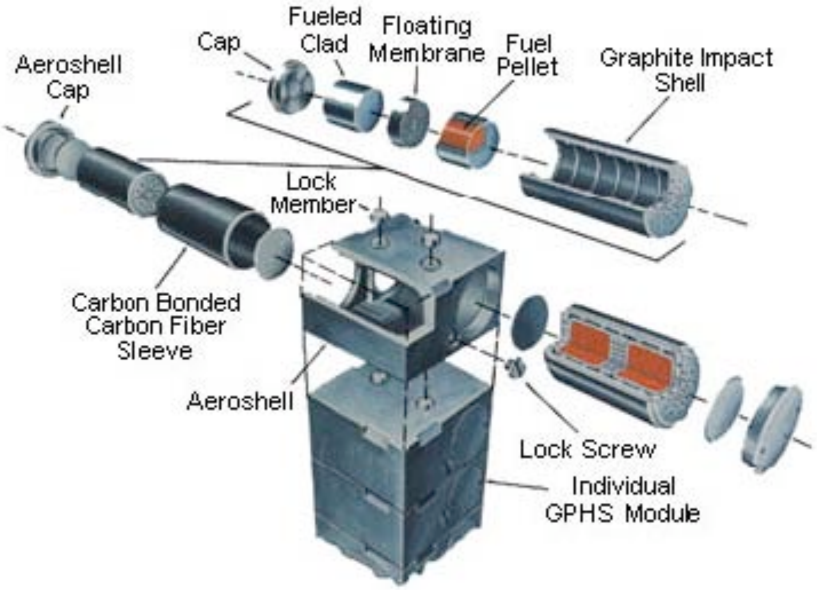

Figure 3-1: General Purpose Heat Source (GPHS)

The GPHS is designed to assure, to the maximum extent possible, containment and immobilization of the PuO_2 fuel. This applies to all mission phases, including ground handling, transportation, launch, ascent, temporary orbit, and during unplanned events such as reentry, impact and post-impact situations. The GPHS design requirements pertaining to fuel loading, mass, and dimensional envelope are summarized in Table 3-1.

Table 3-1: GPHS Module Design Characteristics

Fuel	Plutonium Dioxide (PuO_2)	
Fuel Loading	PuO_2 (grams)	Thermal Power (W)
GPHS Module	604	250 (BOM nominal)
Fueled Clad	151	62.5 (Nominal)
Max Mass (kg)	1.6 kg	
Envelope (single GPHS)	5.82 cm (height) x 9.32 cm x 9.96 cm	

The cylindrical, solid ceramic fuel pellet contains approximately 151 grams of PuO_2 fuel and provides a thermal inventory of approximately 62.5 watts at BOL. Each fuel pellet is individually encapsulated in a welded iridium alloy (DOP-26) clad. The DOP-26 alloy is capable of resisting oxidation in a post-impact environment while also being chemically compatible with the fuel and graphitic components during high temperature operation and postulated accident environments. The fueled clad also has an iridium frit vent that permits release of helium gas while blocking fuel particulates. The average activity is about 7400 curies per module (12.3 curies/gram PuO_2).

4.0 Provisioning of ASRG for Nuclear-powered Missions

Potential use of ASRG and radioisotopes in space requires many special considerations that must be accounted for in the budgeting and scheduling of a space mission. Most of these elements, such as National Environmental Policy Act (NEPA) Compliance and Nuclear Safety Launch Approval (NSLA), are well-defined, multi-year processes involving development of specific documentation and coordination among several government agencies.

Many of these elements are delineated in NASA guidelines available through links in the Discovery Program Library, while some have evolved as accepted practices over the years. For the Discovery AO, the special considerations for use of ASRG have been divided into the six elements described below.

4.1 NEPA Compliance/Environmental Impact Statement (EIS)

NEPA requires federal agencies to consider, before an action is taken, environmental values in the planning of activities that may have a significant impact on the quality of the human environment. NEPA accomplishes this by directing agencies to evaluate alternative courses of action that may mitigate the potential environmental impact of a planned activity, such as use of radioactive material on a space mission. NASA's implementing regulations for NEPA can be found at 14 CFR 1216.1 and 1216.3. These regulations specify actions that can be expected to have a significant effect on the quality of the human environment. Such actions, which include the development and operation of nuclear systems, require preparation of an EIS.

Development of the EIS commences as early as possible in the development program (at least 5 years before launch), with a target for completion by Critical Design Review (CDR) or earlier (at least 3 years before launch). NASA Headquarters is responsible for preparation of the EIS and has enlisted subcontractors to assist in its development. Development of the EIS also requires development of a nuclear risk assessment by the Department of Energy (DOE), and participation by NASA Kennedy Space Center (KSC) and the Jet Propulsion Laboratory (JPL), NASA's launch nuclear approval engineering technical representative.

4.2 Nuclear Safety Launch Approval (NSLA)

For any U.S. space mission involving use of nuclear energy for heating or electrical power, launch approval must be obtained from the Office of the President per Presidential Directive/National Security Council Memorandum #25 (PD/NSC-25) paragraph 9. The approval decision is based on an established and proven review process that includes an independent evaluation by an ad hoc Interagency Nuclear Safety Review Panel (INSRP). The NSLA begins with development of a launch vehicle data book (i.e., a compendium of information describing the mission, launch system, and potential accident scenarios). DOE uses the data book to prepare a preliminary safety analysis report (PSAR) for the space mission. In all, three safety analysis reports (SAR's) are typically produced and submitted to the INSRP – the PSAR, an updated SAR (USAR) and a final SAR (FSAR). The DOE project office responsible for providing the nuclear power system develops these documents.

The ad hoc INSRP conducts its nuclear safety/risk evaluation in three sequential steps following the PSAR, USAR and FSAR. The results of the INSRP evaluation are documented in a nuclear Safety Evaluation Report (SER). The SER contains an independent evaluation of the mission radiological risk. The DOE uses the SER as its basis for accepting the SAR. If the DOE Secretary formally accepts the SAR-SER package, he/she forwards the package to the NASA Administrator for use in the launch approval process.

NASA distributes the SAR and SER to other cognizant government agencies, such as DOD and EPA, and solicits their assessment of the documents. After receiving responses from these agencies, NASA conducts internal management reviews to address the SAR and SER and any other nuclear safety information pertinent to the launch. If the NASA Administrator recommends proceeding with the launch, then a request for nuclear safety launch approval is sent to the Office of Science and Technology Policy (OSTP) within the Office of the President.

Although this schedule has emerged as a convention, it is not a requirement. In fact, there are incentives to begin the data book preparation process earlier and complete it sooner, if possible.

NASA Headquarters is responsible for implementing the NSLA process for NASA missions. It has traditionally enlisted JPL to assist in this activity. DOE supports the process by analyzing the response of ASRG hardware to the different accident scenarios identified in the data book, and prepares a probabilistic risk assessment of the potential radiological consequences and risks to the public and the environment for the mission. NASA KSC is responsible for overseeing development of data books, and traditionally uses JPL to characterize accident environments. KSC subcontractors are also under contract to provide information relevant to launch vehicle accident probability analysis, and other contractors assist in performing impact assessments and analyses. The development team ultimately selected for this Discovery mission would be responsible for providing payload descriptions, describing how the nuclear hardware integrates into the spacecraft, describing the mission, and supporting NASA KSC and JPL in their development of the data books for the EIS and NSLA processes.

4.3 Emergency Preparedness and Planning

Any launch involving significant amounts of radioisotope materials requires special accommodations at the launch site to ensure mitigation of associated hazards arising from an unlikely launch anomaly. This activity involves deployment of emergency response team assets at the launch site and preparations to respond to any launch anomaly with radioisotope materials onboard. It also includes the detailed planning that must be conducted prior to deployment of these assets, including formulation of procedures for handling different accident scenarios. The deployed assets range in capability and size from a small contingent (from one of DOE's Radiological Assistance Program (RAP) Regions) to larger resources (which could form the basis of a Federal Radiological Monitoring and Assessment Center (FRMAC)). The radiological emergency preparedness and planning requirements are tailored for each launch based on the understood risk (documented in the FSAR) and experience/lessons learned from previous missions using radioisotope materials.

As the Lead Federal Agency (LFA), per the Federal Radiological Emergency Response Plan (FRERP), NASA has responsibility for overall emergency preparedness and planning. As part of that effort, DOE performs the planning and preparedness functions, both on and off-site, associated with any response to launch anomalies possibly involving the release of radiological materials. DOE would provide the initial radiological response team, including command and control, for resources off-site under provisions of the FRERP. The funding for these activities would be provided to DOE directly by NASA as part of the overall project cost.

4.4 ASRG/Spacecraft Accommodations, Processing and Integration

Use of ASRG requires special provisions for accommodations and processing at the launch site. There are also unique aspects that have to be accounted for when integrating the unit(s) with the launch vehicle. ASRG also requires special security to protect the units and the radioisotope fuel. This element begins early in the design process and culminates in activities directly supporting processing and integration at the launch site.

4.5 Risk Communication

The unique issues associated with using nuclear materials on missions require extra measures to ensure communication of risk throughout all activities in the program. The design of nuclear powered spacecraft depends on how technical decisions impact safety and development risk of the entire system. Most importantly, these impacts dictate how risks to the populace and environment are communicated to the public and key stakeholders. This activity ultimately supports all other nuclear-unique activities, such as NEPA Compliance, NSLA, and Emergency Preparedness, in addition to the activities usually conducted for any space science mission, such as education and public outreach.

4.6 Delivered Hardware

DOE provides ASRG units for NASA missions per a 1991 interagency Memorandum of Understanding (MOU). Details relevant to specific flight missions and development programs are detailed in Supplements to the MOU. The provision and delivery of ASRG units for this Discovery mission will be covered in a new MOU Supplement that will reflect the budget allocation for ASRG units and mission safety analyses.

4.7 Summary

Should the Discovery 2010 selected mission utilize an ASRG power system, a point of contact will be assigned to provide technical assistance to the design team throughout all aspects of the mission design and development process as shown below.

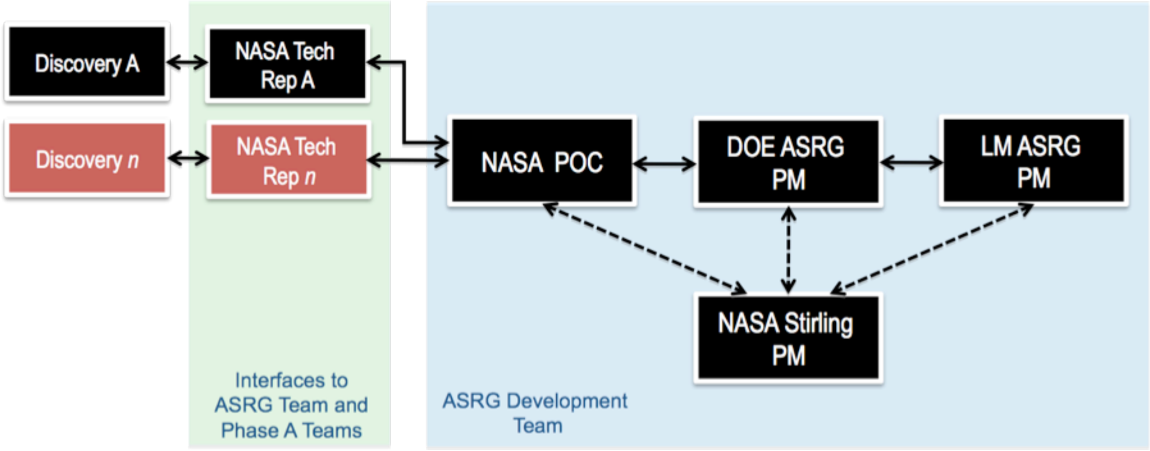

Figure 4-1 RPSPO/Discovery 2010 Organization.

4.8 References

A list of references are provided here as resources providing additional information and background.

Radioisotope Power Systems- An Imperative for Maintaining U.S. Leadership in Space Exploration, National Research Council, 2009, National Academies Press, www.nap.edu

Development of Advanced Stirling Radioisotope Generator For Planetary Surface and Deep Space Missions, Chan, J., 6 th International Energy Conversion and Engineering Conference, Cleveland, OH, July 2008

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