INL/CON-17-42559-Revision-2

Radioisotope Power Systems: Considerations for use of Dynamic versus Static Conversion Technologies for NASA Missions

Stephen G. Johnson, Kelly L. Lively, Young H. Lee

June 2018

INL/CON-17-42559-Revision-2

Radioisotope Power Systems: Considerations for use of Dynamic versus Static Conversion Technologies for NASA Missions

Stephen G. Johnson, Kelly L. Lively, Young H. Lee

June 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract Unknown

Radioisotope Power Systems: Mission Considerations for Use of Dynamic versus Static Conversion Technologies for NASA Missions

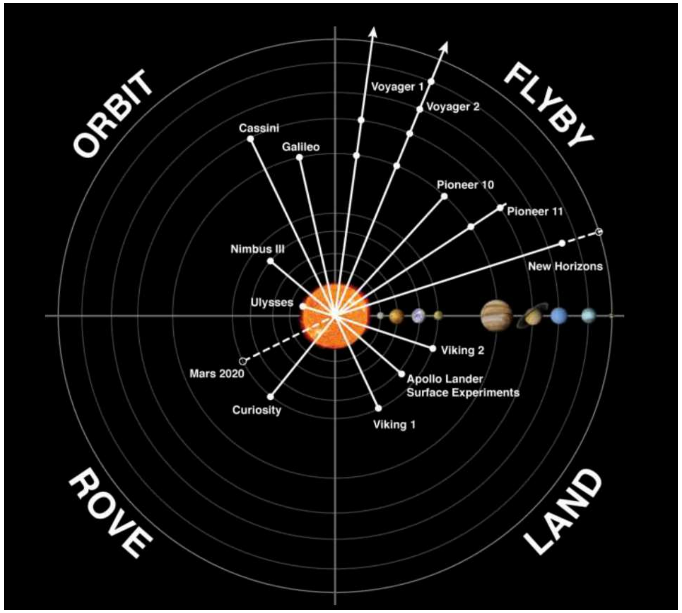
Stephen G. Johnson[1] **and Kelly L. Lively**[2]
DOE Idaho National Laboratory, Idaho Falls, ID 834, USA
208-533-7496 stephen.johnson@inl.gov
208-533-7388 kelly.lively@inl.gov

And

Young H Lee[3]
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
818-354-1326 young.h.lee@jpl.nasa.gov

[1] Director, Space Nuclear Power and Isotope Technologies Division and Technical Integration Office for Department of Energy Space and Defense Power Systems, 2525 Fremont Drive, Mail Stop 6122
[2] Department Manager, Radioisotope Power Systems, 2525 Fremont Drive, Mail Stop 6122
[3] Mission Analysis Lead, Radioisotope Power Systems Program's Mission Analysis Team and Technical Group Supervisor, Advanced Design Engineering Group, Systems Engineering and Project Formulations Section, 4800 Oak Grove Drive, Mail Stop 301-165.

Introduction



RPS could enable many deep space missions where increased heliocentric distances reduce the ability of solar power to adequately meet spacecraft and instruments requirements. In particular, RPS could meet the demand of many long-duration mission concepts for continuous power to conduct science investigations independent of change in sunlight or variations in surface conditions like shadows, thick clouds, or dust. Some previous notable National Aeronautics Space Administration (NASA) missions that were enabled by RPS include *Nimbus III*, the Apollo Lunar Surface Experiments Package, the *Pioneers 10 and 11*, the Viking Mars Landers, *Galileo, Ulysses* and *Cassini*. The current operating set of missions that are enabled by RPS are *Voyagers 1 and 2*, *New Horizons*, and *Curiosity.*

Mars 2020 is designed to utilize the RPS and making a steady progress towards the scheduled launch at Kennedy Space Center (KSC) in 2020. (See Figure 1).

Static vs. Dynamic RPS

- Earlier use of RPS in a satellite had occurred by the Navy. Then, the use of RPS enabling a NASA mission has occurred several times since the late 1960's when the first one was used on a lunar mission. Static RPS have been utilized by all the past and current missions since 1960's; whereas, dynamic RPS have been under technology development since 1970's.

Static Radioisotope Power Systems

- Static power systems conventionally have utilized a thermoelectric material such silicon-germanium or lead-bismuth to harness the heat from a thermopile consisting of a radioisotope that produces heat when it undergoes radioactive decay. Several radioisotopes have been used and/or proposed over the last fifty years. The most common have been strontium-90 and plutonium-238, although others such as polonium-210 have also undergone experimentation. The use of americium-241 is also being pursued by the European Space Agency with a predicted use date in the 2020's.
- The characteristics of the typical static system are: (1) ease of use once fueled, (2) lack of moving parts, (3) low conversion efficiency (<10%), (4) large fraction of heat produced being either "waste heat" or used to keep instrumentation warm, (5) modest electrical power to weight ratio of 2-5 W_e/kg, (6) several well-documented long-duration missions to demonstrate durability of power systems (*Voyager* for 40+ years, *Cassini* for 20 years, and *New Horizons-Pluto* for 12+ years) and (7) long proven track record of enabling mission success from early 1960's to present.
- The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the current RPS used for *Curiosity* and upcoming Mars 2020 missions (See Figure 2). An enhanced version of this generator (eMMRTG) outfitted with higher efficiency thermoelectrics is under development for potential use in the near future. Other previously deployed power systems include the Multi-Hundred-Watt Radioisotope Thermoelectric Generator (MHW-RTG) that was used for two *Voyager* missions and the General-Purpose-Heat-Source Radioisotope Thermoelectric Generator (GPHS-RTG) that was used for *Cassini*, *Ulysses*, *Galileo* and *New Horizons-Pluto* missions.

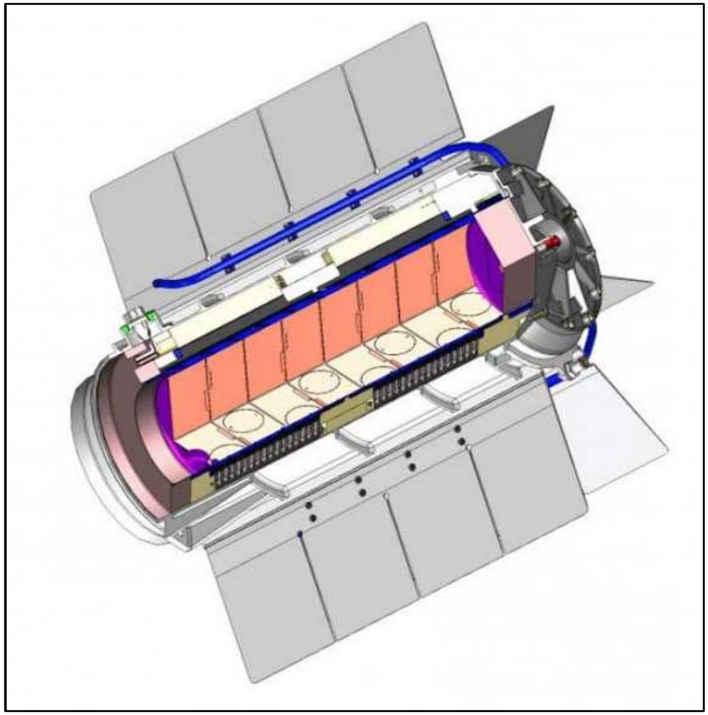


Figure 2: MMRTG

Dynamic Radioisotope Power Systems

- Dynamic power systems have been proposed and some built and tested. They promise conversion efficiencies of upwards to 30% which is a vast improvement over static systems. Two types have been examined in the US, linear alternators and turbine-alternators over the last several decades. In a turbine-alternator, a working fluid is heated and used to work a turbine which then drives a generator to produce electrical power. If gas is the working fluid in the system, then it is a Brayton system. If the fluid is vaporized and then condensed in the system, then that is considered a Rankine system. If a piston is part of the system, the device is considered a Stirling system (See Figure 3 below). Among them, the Stirling system seems to be drawing the most interest in the US at present.

- The characteristics of the typical dynamic system are: (1) more efficient use of radioisotope heat sources, (2) higher electrical power-to-weight ratio, >5 W_e/kg, (3) larger power output due to mechanical design in general, and (4) less "waste heat" with which to contend. As of this date, no dynamic power systems have been flown using radioisotope heat sources on any space missions although the use of this technology has been successful on the International Space Station in the form of cryocoolers.

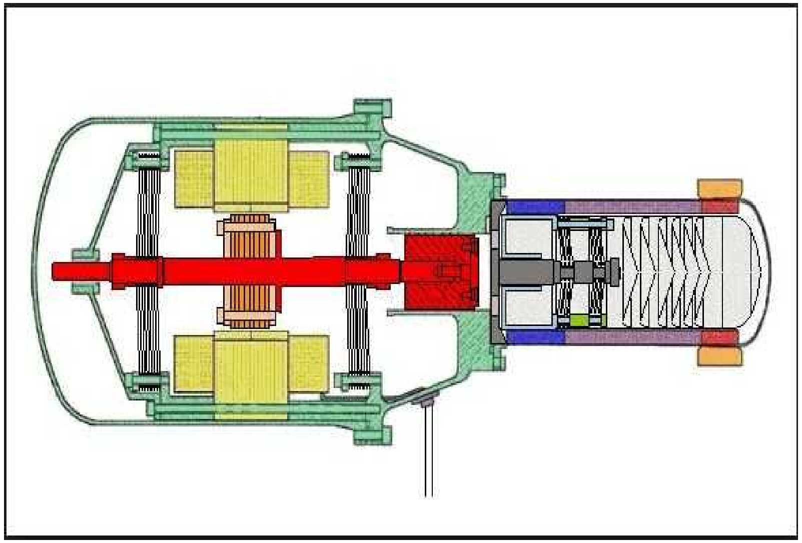


Figure 3: a Stirling dynamic system

Commonality between Static and Dynamic Radioisotope Power Systems

- The common thread for all of these radioisotope-based 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 NASA KSC, and incorporated into the assembly, test and launch operations (ATLO) process.
- Typically, ATLO begin about six to nine months prior to the launch of a NASA mission and encompass several organizations, such as KSC staff, NASA mission staff [typically from Jet Propulsion Laboratory, Applied Physics Laboratory or Goddard Space Flight Center for robotic missions], United Launch Alliance, Cape Canaveral Air Force Station 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 DOE's 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. When dealing with SNM, there are certain considerations to be met: a certain structure of documentation and rigor and experience that DOE provides in fitting with its role as defined by the Atomic Energy Act of 1954. It is important to know that the tasks associated with providing an RPS for a NASA mission is typically a five- to six-year evolution if the RPS is an existing design (this timeline can be longer if a new design of RPS is to be used).

Objectives of Static versus Dynamic Power System Evaluation

- The intent here is to rationally analyze the pros and cons of static and dynamic power systems so that all the pertinent factors are placed under the same examination light with equal brightness. As with any purchase made the "newness" of certain items, sometimes overrides a needed desire to fully vet all characteristics of the merchandise so that the best choice is made. To state this more plainly, the newness of a dynamic system should not override the more established static power systems without a clear comparison for the given application so that the best choice is arrived at. It may also be likely that the "best" choice for power systems could be different based on specifics of the mission considered.

Considered Evaluation Criteria-I

Mission Affordability

- Mission affordability attribute becomes more critical as resources are getting limited as space exploration gets expensive, in particular, to the outer space explorations where RPS are crucial to enable those missions. Considering NASA's increasingly constrained budgets, scientists and mission designers are exploring ways to develop effective, affordable planetary missions that could be implemented at a fixed cost that includes spacecraft and science payload development, launch, operations, science data analysis and all relevant mission-specific technology development. To assess mission affordability of RPS-enabled missions, the following two elements are essential to consider:

1) Projected power output to weight ratio (W_e/kg)
   - Power-to-weight ratio (or specific power or power-to-mass ratio) is the amount of power (time rate of energy transfer) per unit volume and this is an important consideration where less mass of power systems is highly desirable for spacecraft to save mission launch cost.

2) Amount of Pu-238 required per a fixed power output
   - The projected cost of producing more material is thought to be several millions of dollars per kg of isotope. Thus, less amount of Pu-238 for power systems' consumption is highly desirable.

Considered Evaluation Criteria-II

Mission Operability

Mission operability is linked to safety, reliability, robustness and performance. For a given mission, the mission time span that is considered for addressing mission operability assessment can be divided into three distinct phases: pre-ALTO, ATLO and Mission Operations. RPS have typically been used on robotic missions and are launched from KSC at Florida; that convention will be used here. Prior to arrival at the launch site, where ATLO takes place, the power system is fueled, tested and transported to KSC. This phase is termed simply “Pre-ATLO” since these activities get handled at DOE’s Idaho National Laboratory (INL). After arrival at KSC (approximately four to six months prior to launch) and until launch, the spacecraft is assembled and the various scientific instruments readied, called payloads, for their mission get integrated. This phase is termed “ATLO”. Once the mission is launched into space and the mission is either traveling to its destination or executing its mission, this phase is termed “Mission Operations”. Various elements per Pre-ATLO, ATLO and Mission Operations phases that are considered will be discussed using positive and negative aspects of RPS:

1) During Pre-ATLO Mission Phase

- Planetary protection protocol during fueling and testing of RPS
- Fueling operations during assembly by the DOE
- Transportation operations from DOE assembly site to KSC – logistics and operations

2) During ATLO Mission Phase

- Timing of the placement of the RPS onto spacecraft/rover
- Remote operations at KSC prior to launch during ATLO phase including off-nominal operations at KSC

3) During Mission Operations Phase

- Excess heat available to be rejected or used

Comparison-I

This paper will describe the comparison effort that was performed based around the evaluation criteria mentioned above of Mission Affordability and Mission Operability. The tables below captures the various elements mentioned above and describes the positive and negative aspects of each element considered. The below Table 1 describes elements that are considered for Mission Affordability evaluation criteria.

Element Considered	Positive	Negative
Projected power to weight ratio (W_e/kg)	Static: Values have been historically in the 2-5 W_e/Kg range although systems currently under development (eMMRTG) have predicted values that could increase this to 7-10 We/kg. Dynamic: Predicted values have been around 7 W_e/kg for Stirling systems.	Static: Through the last 50 years of the use of these systems, the highest value obtained has been around 5 W_e/kg with the current system (MMRTG) only achieving half of this value for a system capable of being used on Mars. Dynamic: No systems have been demonstrated in actual space use, yet, so actual power to weight ratio remains unconfirmed at present.
Amount of Pu-238 required	Static: The amount of heat source material Pu-238 oxide remains well known and current supplies are thought to be enough for several more missions and domestic production has been reestablished in the US. Dynamic: The predicted higher conversion efficiency, as much as 4-6 times that of static systems, make these systems worth further development.	Static: The projected cost of producing more material is thought to be several millions of dollars per kg of isotope; thus, making missions requiring larger generators >100 W_e very pricey. Dynamic: NA

Table 1: Evaluation Criteria for Mission Affordability

Comparison-II

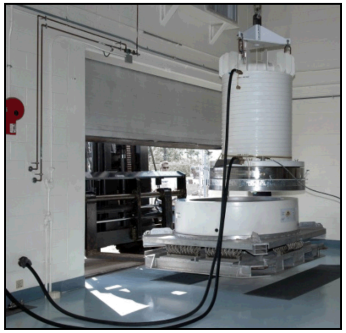
Table 2 describes elements that are considered for mission operability evaluation criteria during Pre-ATLO mission phase.

Element Considered	Positive	Negative
Planetary protection protocol during fueling and testing	Static: The typical static system, MMRTG or GPHS-RTG, exhibits a skin temperature of 150-200 C, which is sufficient to sterilize microbes. This heat condition enables NASA planetary protection protocols to be met. Dynamic: Dynamic systems do not exhibit a high enough skin temperature. Thus, an additional piece of environmental control system could be used in the fueling process to ensure the internals of the power system do not carry microbes to another planet or moon.	Static: NA Dynamic: The selection of a device to sterilize the environment where the power system is fueled is based on the use of vaporized hydrogen peroxide or ethylene oxide. Neither of these agents are yet fully approved by NASA although they may be in the near future. The addition of this type of equipment does add complexity and the issue of the external surfaces of the power systems remain to be sterilized at KSC prior to emplacement of the system onto the vehicle.
Ease of fueling operations by DOE	Static: This fueling operation has remained virtually unchanged for the last 30 years since the adoption of the GPHS in the early 1980's. It is a known and routine operation. The only variable is the type of insulation used after the heat sources are placed into the central cavity and the amount and manner in which the pre-load is applied. Dynamic: The only variable here is the fact that the dynamic system will start once the heat source begins to warm the device so this must be planned for especially if more than one placement of heat sources is required.	Static: If many heat sources are to be stacked up, such as the GPHS-RTG which contained 18 GPHS, a mechanical strength member is considered necessary every 8-9 modules. This adds some complexity to the fueling operation. Dynamic: The degree to which the initiation of motion within the power system will increase the difficulty of placing additional heat sources into the power system is unknown.

Table 2: Evaluation Criteria for Mission Operability During Pre-ATLO Mission Phase

Comparison-II-cont.

Table 2 describes elements that are considered for mission operability evaluation criteria during Pre-ATLO mission phase.



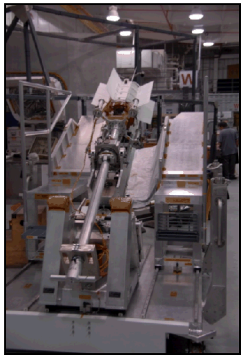
9904 shipping container for RPS

Transportation from DOE site to KSC, logistics and operations	Static: The placement of the current MMRTG into a Type B shipping container, which is cooled via external liquid lines encircling the container, is a well-known operation and has been used for the last 20 years. The equipment exists and the ground support at KSC is established. Dynamic: The same shipping container would be used with the controller for the dynamic system which would be likely placed inside the container with the power system rather than outside therby not using the limited electrical feed-thrus available. This type of arrangement was the plan for the Advanced Stirling Radioisotope Generator.	Static: The existing shipping container limits the geometry of the power system to something roughly 2 feet in diameter by 4 feet in length. Dynamic- The suggested configuration of the controller system being placed inside the shipping container may place an undue burden on the durability of the controller to a heated environment.

Table 2: Evaluation Criteria for Mission Operability During Pre-ATLO Mission Phase

Comparison-III

Table 3 describes elements that are considered mission operability evaluation criteria during ATLO mission phase.



Specialized RPS handling device

Preparing to lift and place into Fairing of Atlas 5

Element Considered	Positive	Negative
Timing and placement of RPS onto spacecraft/rover	Static: The MMRTG and GPHS-RTG have traditionally been placed on the spacecraft/rover after the fairing has been seated onto the rocket. This has been accomplished through a removable hatch. This is a labor-intensive operation but is well known and can be accomplished in 0.5-2 days approximately a week before launch. Dynamic: The lower amount of radioactive material being used may make this operation less stressful as the workers are typically very close to the source term during this phase of operations.	Static: The close working environment when mating the RPS to the spacecraft or rover can lead to larger radiation exposure for some workers. The presence of the removable hatch is not guaranteed for all future rocket designs so alternative mounting schemes are likely to be necessary in the future. Dynamic: The placement of the controller in addition to the power system could lead to even higher radiation exposure to workers due to the additional time involved to perform this. It is unclear whether this would be a significant addition or not. This would have to be measured against the lower amount of heat source material being used.

Table 3: Evaluation Criteria for Mission Operability During ATLO Mission Phase

Atlas 5

Comparison-III-cont.

Table 3 describes elements that are considered mission operability evaluation criteria during ATLO mission phase.

Remote operations at KSC prior to launch during ATLO phase, including off-nominal operations at KSC	Static: The storage of a static system is relatively straightforward and typically requires a single building with some safety and security protocols established. Staffing to support this during non-active periods is usually 2 individuals. Active times when flight hardware is to be added or a hot fit check performed might require additional staffing. Dynamic: This system should be similar to the static system providing operations are regular with no off-normal behavior.	Static: The typical protocol calls for arrival of the RPS 4-6 months prior to launch to perform hot fit check to retire this risk. This confirms the basic tenants of "test like you fly". This is a long duration to sustain remote operations and can cause a strain on personnel. Dynamic: The timing of arrival would be the same as for the static system. It is unclear if staffing would have to be enhanced to ensure that the right qualified manpower is present to deal with any controller issues that might arise. This could place additional restrictions on qualifications of personnel stationed at KSC during this time frame.

Table 3: Evaluation Criteria for Mission Operability During ATLO Mission Phase

Comparison-IV

Table 4 describes elements that are considered for mission operability evaluation criteria during mission operations.

Element Considered	Positive	Negative
Excess heat to be rejected or used	Static: The excess heat generated has been useful for some missions such as New Horizons-Pluto where it was passively coupled into the spacecraft and used to heat instruments. On curiosity, an active heat rejection system was used to circulate this heat throughput the rover to keep the instruments warm. Dynamic: On missions where heat rejection is problematic and/or the presence of excess heat is deleterious to the mission the lower excess heat of a dynamic system could be a large positive.	Static: If excess heat is not desired or where there is more than what is desired, a heat rejection system would add mass to the spacecraft which is not providing value to the mission but adding mass and complexity. Dynamic: If there is a need for excess heat to keep instruments warm that surpassed the ability of the dynamic system to supply, then this could cause the inclusion of additional radioisotope heater units which add some complexity and mass to the mission.

Table 4: Evaluation Criteria for Mission Operability During Mission Operations

Conclusion

Preliminary analysis results show that there are many factors involved in comparing and contrasting the use of static and dynamic power systems from operations and affordability viewpoints. There is no clear deciding factor when performing this analysis. It seems inevitable that a dynamic power system will be developed and put to use for robotic missions by NASA. There are current efforts to vet and prepare one or more systems for that goal currently. Similar to the static systems that posed several challenges for their applications in the 1960-70's, those challenges that are specific to the dynamic system will be met and overcome.