Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-4321

JPL

May 18,2001

Dr. Earle K. Huckins III, Deputy Associate Administrator
Office of Space Science
NASA Headquarters – Code S
M/S Bldg.: HQ, Rm: 5A30
Washington DC 20546-0001

Dear Dr. Huckins:

A pre-decisional document entitled "Report of the RPS Provisioning Strategy Team" is enclosed. This report is in response to your request for a recommended strategy for the provisioning of safe, reliable and affordable radioisotope power systems (RPS) that enable the NASA 2004-2011 space robotic missions.

A summary of this report was presented to senior NASA and DOE management on May 8, 2001. As acknowledged at the meeting, agency action on several issues raised in the report (particularly considering the likelihood of a much smaller mission set than specified in the Terms Of Reference) is needed, including plutonium-238 isotope acquisition, and the recommended management and funding arrangements.

The RPS Strategy Team is appreciative of having had the opportunity to address this important question, and hopes that its findings and recommendations will be useful.

Sincerely,

John R. Casani
Jet Propulsion Laboratory

cc: Dr. E. Wahlquist – DOE
Enclosure

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, California 91109-8099

(818) 354-4321

JPL

May 18, 2001

Dr. Earl Wahlquist
Associate Director for Space and Defense Power Systems
Office of Nuclear Energy, Science and Technology
Department of Energy
Germantown, MD 20874-1290

Dear Dr. Wahlquist:

A pre-decisional document entitled "Report of the RPS Provisioning Strategy Team" is enclosed. This report is in response to your request for a recommended strategy for the provisioning of safe, reliable and affordable radioisotope power systems (RPS) that enable the NASA 2004-2011 space robotic missions.

A summary of this report was presented to senior NASA and DOE management on May 8, 2001. As acknowledged at the meeting, agency action on several issues raised in the report (particularly considering the likelihood of a much smaller mission set than specified in the Terms Of Reference) is needed, including plutonium-238 isotope acquisition, and the recommended management and funding arrangements.

The RPS Strategy Team is appreciative of having had the opportunity to address this important question, and hopes that its findings and recommendations will be useful.

Sincerely,

John Casani

John R. Casani
Jet Propulsion Laboratory

cc: Dr. E. Huckins – NASA
Enclosure

DOES NOT CONTAIN
OFFICIAL USE ONLY INFORMATION

Name/Org.: A. Caponiti, NE-75 Date: 8/7/2014

Report of the RPS Provisioning Strategy Team

May 8, 2001

Pre-Decisional Working Papers, For Internal Review Only

Report of the RPS Provisioning Strategy Team

—— Signature Page ——

Garry Burdick, JPL

Art Mehner, DOE

Bob Carpenter, OSC

Joe Parrish, NASA HQ

John Casani, JPL, Chair

Lyle Rutger, DOE

Tim Frazier, DOE

Reed Wilcox, JPL

Duncan MacPherson, JPL

Contents

Contents (Continued)

Illustrations

Tables

Executive Summary

Last year, it became apparent to NASA's Office of Space Science (OSS) and DOE's Office of Space and Defense Power Systems (NE-50) that a critical look at Radioisotope Power Systems (RPSs) for the next decade was needed. In December 2000, OSS and NE-50 jointly established this RPS Provisioning Strategy Team and charged them with the task of recommending a strategy for the provisioning of safe, reliable, and affordable RPSs to enable potential NASA 2004 – 2011 space robotic missions. Specifically, the Team was to consider a potential mission set consisting of the 2007 Mars Smart Lander (MSL), Europa Orbiter (EO), Pluto Kuiper-Belt (PKB), Solar Probe (SP), and 2011 Mars Sample Return (MSR) missions. The Team was also charged to discuss certain management issues related to the provisioning of these systems.

A number of factors bear critically on the question of providing RPSs for the potential missions in the near term. These factors, which the Team regarded as the driving considerations in developing a recommended strategy, encompassed mission scenarios, mission requirements, existing assets, fuel availability, process and process limitations, safety and launch approval, redundancy, and converter technologies.

Provisioning Strategy

Relevant to the first charge, the Team recommends undertaking a dual development activity that would provide both a Stirling RPS and a new RTG, each of which would be able to operate in deep space and on the surface of Mars. The Stirling offers substantial improvement in conversion efficiency, but the relative immaturity of the system design could lead to development delays and result in unwarranted programmatic risk to the early using missions. The new RTG, designed to serve as a backup to the Stirling RPS, would eliminate the programmatic risks. In addition it would allow scaling back of the Stirling RPS requirements, if required, to mitigate Stirling RPS development risks.

Alternate Strategies

In addition to the recommended Dual Strategy, an All-Stirling Strategy and an All-RTG Strategy were also considered. The All-Stirling Strategy was ruled out primarily because of the technology development uncertainty and the consequential risk of delivering a mission-qualified Stirling RPS for the highly schedule critical 2007 Mars Smart Lander mission.

The All-RTG Strategy was ruled out primarily because it would not offer the potential for significant reduction in plutonium use that the Dual Strategy would, even though the costs would be somewhat less. During the Cassini launch timeframe, both agencies were quoted in the open literature as having the intent to develop higher efficiency systems for future missions. The Dual Strategy follows through on that intent, while effectively addressing the Stirling RPS development concerns by incorporating the new RTG design in the program as a backup to the Stirling RPS.

Cost Considerations

The total run-out cost through 2011 for any strategy would be highly dependent not only on the number of missions that would require RPSs in this period, but also on the distribution in time of these missions and other ongoing activities. Several hypothetical mission scenarios were

constructed to test the strategy sensitivity. The upper bound scenario for the recommended strategy would result in a total run-out cost of about $460 million, while the lower bound run-out cost would be about $315 million.

The All-RTG Strategy run-out costs for the two bounding scenarios would be about $435 million and $300 million respectively. Most of the difference between the All-RTG Strategy and the recommended Dual Strategy is due to the Stirling RPS development cost of about $40 million in the early years. However, it is important to note that this difference is small compared to differences resulting from scenario to scenario variations. The difference is also on the order of that which could result from small changes in the costing assumptions used in the development of these estimates.

Use of Existing Assets

The Team considered the use of existing RTG assets, one fueled spare RTG and one partially assembled unit residual to previous programs, and has come to the conclusion that the value of these assets would be limited to a potential mission that would be launched prior to 2007. Once the new systems become available, use of the existing assets would not be cost effective and would not permit the incorporation of a planned enhancement to the current GPHS module.

Implementation

The Team made several specific recommendations related to the implementation of the recommended strategy.

Development Concept

The Team recommends that the development of the new RTG and the Stirling RPS proceed on the basis that these developments would result in generic off-the-shelf designs that could operate both in space and in an atmosphere. These designs would be available to future user missions, rather than designs specifically tailored to or driven by the needs of each mission. Inherent to this notion is the concept that the design requirements would be amenable to the spectrum of missions likely to be flown with minimal adaptation to the standard design. Such adaptation, if required, would be funded by the using mission.

Implementation Concept

The Team strongly recommends that an implementation office for development and project coordination be established by NASA with sole responsibility for providing technical requirements and coordinating with DOE in the development and deployment of these generators.

Industrial Contracting

A competitive procurement is already underway by the DOE for a Stirling RPS with selection and award due this summer. The Team recommends that the appropriate findings and information developed over the course of this study be incorporated in the planned contract prior to its execution.

Activities are also underway leading to the release of the RFP for the new RTG. The Team also recommends that NASA and DOE move with all deliberate haste to establish the necessary funding arrangement so that selection of a system contractor can proceed in a timely fashion.

Plutonium Procurement

Domestically produced ^{238}Pu is scheduled to be available starting in late 2008 to early 2009. Although some domestic fuel could conceivably be available in time for the 2011 Mars Sample Return mission, this would be too late for the earlier missions. To guarantee availability for all the potential missions in the 2007-2011 timeframe, it would be necessary to procure Russian fuel.

The Team recommends that an initial procurement of Russian ^{238}Pu be completed in FY01. This initial procurement would allow for early verification of Russian fuel properties and processing losses and confirm the time required to place an order and receive the material in the United States. In addition, this initial procurement would alert the Russians of the United States intention to procure material and set the stage for a new contract in December 2002 when the current contract expires.

Production Capability

Pursuant to its authority and responsibility for developing space nuclear power systems for NASA, DOE maintains the infrastructure required to develop, produce, assemble, and test these systems. Currently the infrastructure is sized to support only a minimal production throughput capability. This capability falls short of that which would be required to support any of the hypothetical mission scenarios, and the lead-time required to hire, train and certify the additional staff that would be required is on the order of two years. To date NASA has not projected its potential requirements for the 2004–2011 timeframe sufficiently in advance for DOE to plan for the production throughput that would be required. The Team recommends that NASA and DOE agree on and commit to a production rate that would support the potential future mission requirements.

Safety and Launch Approval

Because NASA requirements for RPS/RHU missions could double to triple over the next decade relative to the last ten years, the Team recommends that NASA and DOE ensure that planning, schedule considerations and selection processes provide sufficient lead times to ensure cost-effective and timely satisfaction of the environmental and nuclear launch safety approval process requirements.

Redundancy

Single string non-redundant RTGs have consistently been flown in the past owing to the inherent redundancy provided by the series-parallel configuration of RTG thermocouples. Stirling systems intrinsically lack this feature, being more akin to momentum wheels or gyroscopes in this regard. Consequently, the Team recommends that spacecraft systems using Stirling RPSs carry at least one redundant RPS.

Sparing

Flight spares are normally provided for all replaceable spacecraft assemblies as a protection against equipment loss due to failures, mishaps or planning contingencies. The recommended development concept would permit the use of a single common spare across programs. The Team recommends a revolving spare be provided for both the Stirling RPS and the new RTG. The next mission would then inherit the spare. The Team further recommends that the cost of the revolving spare be subsumed in the non-recurring development costs.

Technology Development Funding

Finally, the Team recommends a technology investment strategy that would aggressively fund advanced segmented thermoelectric converter technology in preference to AMTEC or thermoacoustic Stirling converter technology.

Discussion of Interagency Relationship

Relevant to the second charge, the Team explored a number of management and interface issues relevant to the effective provisioning of these systems. One, concerning funding arrangements, was set forth in a 1995 exchange of letters between the agencies. Under previous arrangements, DOE was responsible for funding the non-recurring development costs of these systems, while NASA was responsible for funding the recurring costs. The recurring costs were pre-negotiated, after which NASA transferred funding to DOE on an agreed-to schedule. DOE as the managing agent assumed responsibility of any and all cost and development risk, both for the non-recurring activities and the recurring ones.

In the 1995 exchange of letters it was posited that NASA should fund both the non-recurring as well as the recurring costs. Further, NASA would be responsible for all costs and cost growth, even though DOE would retain management responsibility for the work. DOE is accountable for successfully executing an RPS development, yet its discretion to act accordingly is limited by NASA funding authority. The Team concludes that this is an intractable situation, which effectively provides minimal capability for NASA to manage its cost and cost risk exposure.

The Team also observes the absence of a Supplemental Agreement as contemplated in the existing MOU, and the absence of a Management Interface Agreement document that would establish the respective management responsibilities and interface protocols.

1. Introduction

1.1 Background

Last year, it became apparent to NASA's Office of Space Science (OSS) and DOE's Office of Space and Defense Power Systems (NE-50) that a critical look at Radioisotope Power Systems (RPSs) for the next decade was needed. In December 2000, OSS and NE-50 jointly established this RPS Provisioning Strategy Team (hereinafter referred to as the Team) with the task of recommending a strategy for the provisioning of safe, reliable, and affordable RPSs to enable potential NASA 2004 – 2011 space robotic missions (see Appendix A). Specifically, the Team was to consider a potential mission set consisting of the 2007 Mars Smart Lander (MSL), Europa Orbiter (EO), Pluto Kuiper-Belt (PKB), Solar Probe (SP), and 2011 Mars Sample Return (MSR) missions.

The Terms of Reference identify a number of issues that the Team was asked to include in their deliberations. Typically the issues are those that the decision makers may want to consider in reviewing the Team recommendation, including use of existing RPS assets, ^{238}Pu (plutonium-238 isotope) acquisition, transition to an advanced converter technology, safety, cost, and schedule.

The RPS technology options to be considered include the existing GPHS-RTG and MHW-RTG, and new Stirling RPS and new RTG designs. In addition to a RPS provisioning strategy, the Team was to discuss inter-agency funding responsibilities, risk management scenarios, and organizational structure options for interfacing among NASA HQ and DOE and JPL.

1.2 Terms of Reference

The Terms of Reference were submitted to the Team by the Deputy Associate Administrator for Space Science, NASA and the Associate Director, Office of Space and Defense Power Systems, DOE, and appear in Appendix B. The activities of the Team were based on these Terms of Reference.

The Terms of Reference for the Team did not include investigation of non-nuclear options. Consequently, any conclusions or findings reached should not be construed as reflecting on the desirability, technical feasibility, or economic viability of non-nuclear technologies.

1.3 Participants

Team Members

Garry Burdick, JPL
Bob Carpenter, OSC
John Casani, JPL, Chair
Tim Frazier, DOE
Duncan MacPherson, JPL
Art Mehner, DOE
Joe Parrish, NASA HQ
Lyle Rutger, DOE
Reed Wilcox, JPL

Technical Consultants

Howard Eisen, JPL - Mars Program

John Klein, JPL - Europa Orbiter Project and Sun-Earth Connection Program

Support Staff

John Elliott, JPL - System Engineering Support

Paul VanDamme, JPL - Executive Secretary

Ed Sewall, JPL - Technical Writer

1.4 General Approach

The Team used the following process to develop the recommended strategy:

- Consulting with the projects potentially needing RPSs in the 2004 – 2011 timeframe
- Consulting with organizations involved with acquiring and processing ^{238}Pu, assembling General Purpose Heat Sources (GPHSs), assembling thermoelectric converters, final RPS assembly, acceptance testing and transportation, and safety testing and analyses
- Consulting with NASA HQ to determine potential mission launch date scenarios
- Formulating a reasonable set of RPS candidate strategies for Team consideration
- Determining a set of criteria that would be used to evaluate strategies
- Evaluating the strategies
- Down selecting to a recommended strategy.

1.5 Committee Meetings and Activities

9 - 11 January 2001	Kickoff Meeting at JPL, Pasadena CA
22 - 25 January 2001	Technology Proposal Orals at DOE, Germantown MD
25 January 2001	Stirling Briefing by Glenn Research Center and DOE at DOE, Germantown MD
25 - 27 January 2001	Planning Meetings at DOE, Germantown MD
5 February 2001	Planning Meeting at JPL, Pasadena CA
13 February 2001	Visit to DOE Mound Facility, Dayton OH
15 February 2001	Visit to Los Alamos National Laboratory NM
27 February 2001	Visit to Lockheed Martin, King of Prussia PA
28 February 2001	Visit to Teledyne, Hunt Valley MD
1 March 2001	Review/Planning Meeting at DOE, Germantown MD

15 - 16 March 2001	Review/Planning Meetings at DOE, Germantown MD
26 - 28 March 2001	Review/Planning Meetings at DOE, Germantown MD
29 March - 4 April 2001	Report Construction at JPL, Pasadena CA
6 April 2001	Presentation to NASA and DOE, Kennedy Space Center FL
9 - 11 April 2001	Report Revision at JPL, Pasadena CA and Delivery to NASA and DOE
1 - 3 May 2001	Report Revision at JPL, Pasadena CA
8 May 2001	Presentation to NASA and DOE, NASA HQ, Washington, D.C.

Note: Many terms are used throughout the report which are collected for the convenience of the reader in the Glossary and Acronyms list found at the back of this report

2. Driving Considerations

A number of factors bear critically on the question of providing RPSs for the potential missions in the near term. These factors, which the Team regards as the driving considerations in developing a recommended strategy, are briefly summarized in the following paragraphs of this section. A more complete treatment of each is contained in the Appendices.

2.1 Mission Scenarios

The Terms of Reference for this RPS study specifically identify five potential missions to be considered in the 2004-2011 timeframe. These are referred to in this study as the "baseline" missions and consist of the 2007 Mars Smart Lander (MSL), Europa Orbiter (EO), Pluto-Kuiper Express (since renamed Pluto Kuiper-Belt (PKB)), Solar Probe (SP), and the 2011 Mars Sample Return (MSR) missions.

The specific dates and sequences of these launches influence the RPS Provisioning Strategy in terms of the timing of development and delivery of RPS units and their fuel. These in turn shape both the cost profile and the cost risk posture of the RPS provisioning strategy.

There are many hypothetical variations on launch dates for these missions, but funding and other programmatic constraints limit the possibilities to a smaller number. A suite of potential mission scenarios was constructed by the Team based on various NASA funding profiles and is presented in detail in Appendix C.

Two scenarios, one for an early PKB (Scenario A) and one for a delayed PKB mission (Scenario B), provide a baseline for the evaluation of competing strategies. These scenarios were chosen as reasonable mission profiles (assuming all five missions covered in the Terms of Reference). In addition, two other mission profiles were developed for comparison purposes that consider reduced mission sets involving no SP mission (Scenario C), and no PKB or SP mission (Scenario D).

The potential mission launch date scenarios used by the Team are shown in Table 2.1-1.

Table 2.1-1. Potential Mission Launch Date Scenarios

	2004	2005	2006	2007	2008	2009	2010	2011
Scenario A (Early PKB)	∇ PKB 12/04			∇ MSL 09/07	∇ EO 03/08	∇ SP 04/09		∇ MSR 11/11
Scenario B (Delayed PKB)				∇ MSL 09/07	∇ ∇ EO PKB 03/08 12/08	∇ SP 04/09		∇ MSR 11/11
Scenario C (Early PKB, No SP)	∇ PKB 12/04			∇ MSL 09/07	∇ EO 03/08			∇ MSR 11/11
Scenario D (No PKB, No SP)				∇ MSL 09/07	∇ EO 03/08			∇ MSR 11/11

Scenarios A and B would require the delivery of RPSs for five missions in the 2004-2011 timeframe. Scenario A would necessitate an early start on processing of fuel and construction of E-8 (see Section 2.4), should that asset be chosen for the PKB mission. Scenario B would yield more time for first system delivery, but would require systems to be delivered at a higher rate from 2007 through 2011, thus increasing fuel processing and RPS assembly and acceptance testing efforts during this time. In the context of this study, Scenarios C and D allow the effects of a reduced mission set to be evaluated.

These scenarios were used for evaluating the relative schedule and costs involved with different candidate strategies.

2.2 Mission Requirements

The baseline missions would levy several significant requirements on a radioisotope power system. All of the baseline missions would require power levels in the 150-350 W_e range, and there are several additional mission attributes that would drive the design of the power system. These attributes are summarized in Table 2.2-1 and discussed in more detail in Appendix D.

Table 2.2-1. Key Drivers Summary Table

Baseline Missions	*Mission Duration*	*EOM Power Requirement*	*Key RPS Design Drivers*
Mars Exploration Program			
Smart Lander; Sample Return	3+ years	200 W_e	Atmospheric operation Dust accommodation Waste heat rejection while encapsulated Launch vehicle integration (sterilization)
Deep Space			
Europa Orbiter	5 years	340 W_e	Long cruise duration High radiation environment Thermal control of propulsion module
Pluto Kuiper-Belt	10+ years	TBD (200-300 W_e)	Long cruise duration Microphonics Thermal control of propulsion module
Solar Probe	3-5 years (per pass)	156 W_e	Long cruise duration Waste heat rejection during high insolation Instrument sensitivities to radiation, EMI

The outer planet and Sun-Earth Connection (SEC) missions would be conducted in vacuum conditions. This is both an asset and a liability—temperature fluctuations can be extreme depending on the level of insolation, but heat can be easily rejected by radiators if adequate clear views to space can be provided. Some missions would depend on waste heat from the RPS for thermal control. Missions to the outer solar system typically would have a long cruise phase, which demands long life from the power system. Some of the selected instruments could be sensitive to vibrations and/or EMI. Some missions, such as the Europa Orbiter mission, would operate in high radiation environments, and therefore the RPS control electronics (if any) must be hardened.

The Mars missions involve cruise in vacuum. The operational phase would be performed in Martian atmospheric and surface conditions, including potentially significant dust accumulation on external surfaces, including any radiators. During cruise, the encapsulation of the landed element behind an entry aeroshell could complicate waste heat rejection—in this case, waste heat is a liability, not an asset.

2.3 Existing Assets

The existing assets in the DOE inventory have potential applicability for use on future deep space missions. The most promising are the F-5 Radioisotope Thermoelectric Generator (RTG) (a fueled and flight qualified spare from the Galileo, Ulysses, and Cassini missions), and E-8 (a partially assembled generator, residual to the Cassini mission) that could be made ready for flight. In fact, NASA has stated in the PKB Announcement of Opportunity (AO) that either or both of these assets could be made available for that mission should it be authorized.

These generators, based on SiGe unicouple technology, are designed for high power (150-300 W_e/RTG) and use in deep space missions. These assets cannot be operated on the surface of Mars. Lower-powered (40 W_e) PbTe/TAGS RTGs have been successfully used in space and on the surface of Mars; however, no residual hardware exists.

In addition to F-5 and E-8 there are a number of other assets that conceivably could be used. These include unfueled Multi-Hundred Watt (MHW) converters residual to the Voyager and LES 8/9 missions, a number of Radioisotope Heater Units (RHUs), and a collection of various components as described in Appendix E.

2.4 Fuel Availability

In addition to the ^{238}Pu in F-5, there is about 9.2 kg of ^{238}Pu available in the DOE inventory from the first and second Russian purchases in 1993 and 1995. This material is currently in storage at the Los Alamos National Laboratory (LANL), and is sufficient to produce 18 General Purpose Heat Source (GPHS) modules for use in NASA missions.

F-5 will contain about 6.7 kg of ^{238}Pu in December 2004 (reference mission launch date for PKB) due to the decay of ^{238}Pu. If F-5 is not used for PKB it would be defueled and the fuel returned to the DOE inventory. Even if programmatic priorities made this fuel available for space missions, the total quantity available would be insufficient to meet the potential needs through 2011, thus more would need to be procured or produced in the near term.

Domestically produced ^{238}Pu is scheduled to be available starting in late 2008 to early 2009. Although some domestic fuel could conceivably be available in time for the 2011 Mars Sample Return mission, this would be too late for the earlier missions. To guarantee availability for all the potential missions in the 2007-2011 timeframe, it would be necessary to procure Russian fuel.

In the development of the cost estimates for the various strategies, the Team assumed that procurements would be phased to support fueled clad production as necessary. It would be possible to procure all of the fuel in the FY02-FY06 timeframe with a concomitant increase in the early year funding requirements. However, procuring fuel early would have several advantages:

1. The early purchase of fuel would reduce or mitigate the schedule risk resulting from an interruption in the Russian supply.
2. There would be a minor advantage in the cost of the fuel, which is expected to escalate in price from $2M/kg in FY01 to $2.5M/kg in FY08.
3. It would permit early verification of Russian fuel properties and processing losses and revalidation of the lead-time and throughput requirements.

See Appendix F for a more complete discussion of the Russian fuel procurement.

Notes: Should domestic fuel ultimately become available in time to support the 2011 Mars Sample Return mission, NASA and DOE would have the option of using it in lieu of fuel that may already have been procured from Russia. In this eventuality, NASA would expect to receive credit for the purchased Russian fuel to be applied against domestic fuel on a mass basis.

2.5 Process and Process Limitations

DOE has the statutory authority to develop space nuclear power systems and the obligation under existing U.S. National Space Policy (Reference 1) to maintain the programmatic infrastructure to support the design, assembly, acceptance testing and delivery of RPSs. This infrastructure includes the facilities and the skilled, trained, and qualified personnel at each of the relevant DOE laboratories (see Appendix G).

The infrastructure can produce about four fueled clads per month, but production can be increased as described in Appendix G, and rates as high as 12 per month can be achieved.

Appendix H describes the fueled clad production and other key processes and throughput limitations based on the current DOE infrastructure capability.

2.6 Safety and Launch Approval

The safety performance of power systems that use GPHS modules would not be expected to be a discriminator in terms of selection of power system alternatives. More efficient conversion systems such as the Stirling converter would use less fuel and thus could present lower risks. However, when the reasons discussed in Appendix I are accounted for, most accident scenarios would involve no or limited releases, and would be expected to involve only one or two modules, irrespective of the total number of modules in a system.

RTGs have been approved for launch on previous missions and the new designs under consideration should present no new issues. Stirling RPSs would use less fuel than RTGs with similar power levels; however, they may have potential safety issues. Included is the potential hard points presented to the GPHS modules by the Stirling converter, and the safety consequences attendant to a potential converter failure while on pad. Presumably, these potential safety issues would be satisfactorily addressed during the development phase.

2.7 Redundancy

Some form of redundancy is required in almost all the hardware that support mission critical spacecraft functions. Spacecraft power systems are certainly no exception. RTGs provide adequate fault tolerance by the use of series-parallel string thermocouples. No other specific redundant elements are required (nor have any been incorporated in past missions). However, in the Stirling RPS designs, the possible failure of a converter and/or controller intrinsically introduces the requirement for redundancy (i.e., the incorporation of an additional Stirling RPS) for each mission. The addition of the redundant unit in the Stirling RPS would add system mass leading to a lower effective specific power and added cost. Redundancy also requires the assembly and acceptance testing of one additional Stirling RPS per mission, thus reducing the schedule margin at DOE Mound Facility (hereafter referred to as Mound). Appendix J contains a more detailed discussion of important redundancy issues.

2.8 Converter Technologies

The Team interpreted the Terms of Reference to limit the near term technology options to the use of existing assets (F-5, E-8, and MHWs), a new RTG (either SiGe or PbTe/TAGS), and the Stirling RPS. In addition, the Terms of Reference state that Advanced Stirling (i.e., thermoacoustic Stirling), AMTEC (Alkali Metal Thermal-to-Electric Conversion), and Segmented Thermoelectric converter technologies may be options for the post-2011 timeframe. The Team endorses this and has made technology development funding priority recommendations in Section 4.4.

The attributes of SiGe, PbTe/TAGS, and Stirling converter technologies are described briefly below, and more fully in Appendix K.

The driving advantage of SiGe and PbTe/TAGS thermoelectric converters is their inherent simplicity, demonstrated long life and reliability, and low potential for cost and mass growth. The system conversion efficiency of both is about 6.5% and this is the value that has been used throughout the report. Conversion efficiency improvement through segmented thermoelectric technology has been successfully employed with PbTe/TAGS converters, but this has not been demonstrated yet for flight applications. Depending on the specifics of the new RTG, system efficiencies on the order of about 8% or 9% could be realized.

The driving advantage of the Stirling technology is its higher system conversion efficiency (~25%) compared to SiGe and PbTe/TAGS converters. Concerns are the immaturity of the Stirling RPS at the system level and the attendant absence of advantages listed in the previous paragraph. In addition to complexity and the potential for cost and mass growth, there is uncertainty in the system-level effects on other spacecraft functions after a Stirling RPS is integrated with the spacecraft.

3. Candidate Strategies

For the purpose of this study two new RPS concepts were considered each of which would be able to operate in deep space and on the surface of Mars. One would be a new RTG powered by eight GPHS modules. The other would be a Stirling RPS design using two GPHS modules and controller electronics. The converters (Stirling engine and linear alternator) would be aligned to almost totally eliminate the dynamic effects induced by the vibrating converters.

Consistent with the direction given to the Team as described in Section 1.2, three candidate strategies were developed for RPS implementation in the next decade. Two of these strategies represent the limiting cases of using Stirling RPSs for all baseline missions and of using RTGs for all baseline missions. The third is an intermediate case of using Stirling RPSs for baseline Mars missions and new RTGs for baseline outer planet missions. These strategies are illustrated in Figure 3-1 below.

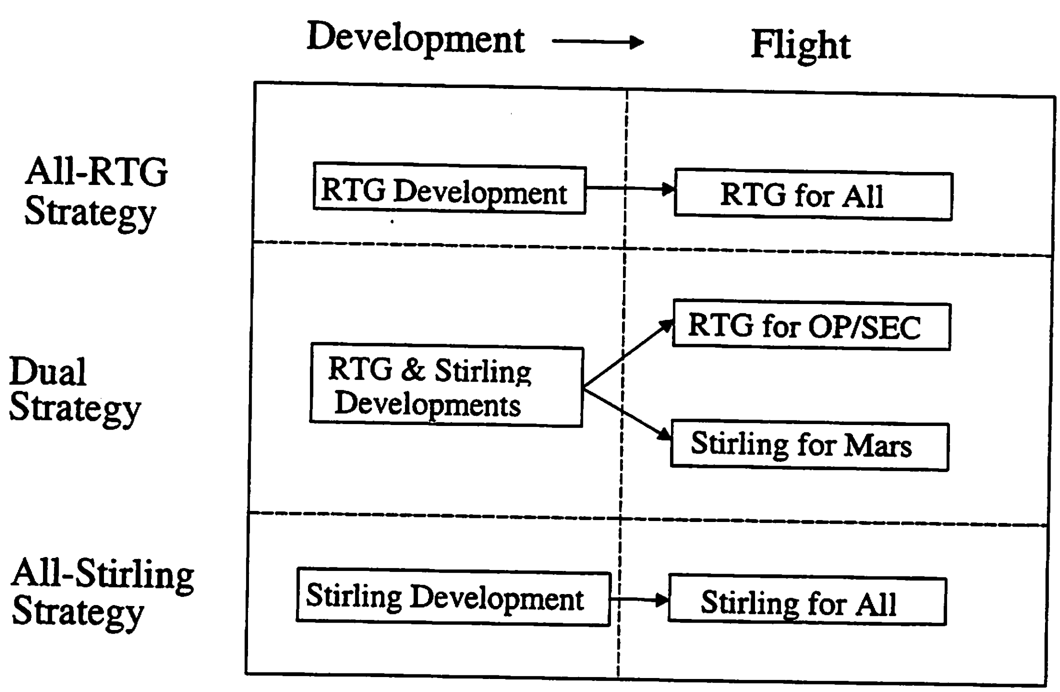


Figure 3-1. Candidate Strategies

The costs, schedules, and other factors associated with these strategies are included in this section and in Appendix L.

Note that all of the strategies assume that existing assets (F-5 and E-8) would be used for an early PKB (discussed in detail in Section 4.2), and that all other missions (including a late PKB) would use either the Stirling RPS or the new RTG designs.

3.1 All-Stirling Strategy

This strategy would provide for the development of the Stirling RPS only, meaning that all missions (except early PKB) in the foreseeable future requiring RPSs would use the Stirling RPS. This strategy would minimize the need for ^{238}Pu and GPHS modules, but would require acceptance of a greater development risk for the new Stirling RPS.

Cost Profile

Cost estimates for this strategy have been developed for the four mission scenarios shown in Section 2.1 and presented in detail in Appendix L. Table 3.1-1 shows the estimated annual costs associated with each scenario.

Table 3.1-1. Estimated Costs for All-Stirling Strategy ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	31	42	43	76	44	45	25	17	14	6	2	345
B (Delayed PKB)	17	25	27	43	66	58	36	21	15	7	2	317
C (Early PKB, No SP)	30	42	41	60	39	35	14	14	13	6	2	295
D (No PKB, No SP)	14	25	26	34	33	37	21	13	12	6	2	223

3.2 All-RTG Strategy

This strategy would only provide for the development of the new RTG, meaning that all missions through 2011 (except early PKB) requiring RPSs would use the new RTG. This strategy has the advantage that there is considerable design heritage from the existing and previous RTGs, much of which would be applicable to a new design, resulting in a low development risk.

This strategy would carry a penalty in terms of the amount of ^{238}Pu and the number of GPHS modules needed to meet any of the proposed scenarios. The fuel requirements of 6.5% conversion efficiency RTGs would make it imprudent to plan solely on their use for missions beyond 2011, depending on the mission model.

Cost Profile

Cost estimates for this strategy have been developed for the four mission scenarios shown in Section 2.1 and presented in detail in Appendix L. Table 3.2-1 shows the estimated annual costs associated with each scenario.

Table 3.2-1. Estimated Costs for All-RTG Strategy ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	31	56	60	92	65	58	32	17	14	6	2	433
B (Delayed PKB)	23	46	48	61	82	71	47	19	13	6	2	418
C (Early PKB, No SP)	31	55	61	86	43	37	22	15	11	6	2	369
D (No PKB, No SP)	22	39	41	56	41	38	31	14	11	6	2	301

3.3 Dual Strategy

This strategy would provide for the development of both the Stirling RPS and a new RTG for use on all missions except for early PKB. The new RTG development would inherently serve to back up the Stirling RPS and would be available for use by EO, thus eliminating the requirement for radiation-hardened control electronics. All missions could choose the generator that was the better match for their mission characteristics and requirements. For the purposes of costing this strategy, it was assumed that Stirling RPSs would be used for Mars missions and that new RTGs would be used for all other missions (except early PKB), although other assumptions are possible.

Cost Profile

Cost estimates for this strategy have been developed for the four scenarios shown in Section 2.1 and presented in detail in Appendix L. Table 3.3-1 shows the estimated annual costs associated with each scenario.

Table 3.3-1. Estimated Costs for Dual Strategy ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	44	71	75	87	70	47	23	19	14	6	2	458
B (Delayed PKB)	36	65	65	64	76	63	33	20	14	6	2	444
C (Early PKB, No SP)	44	70	74	85	42	31	14	14	12	6	2	394
D (No PKB, No SP)	34	54	58	51	39	32	16	12	10	6	2	314

3.4 Strategy Evaluation

In order to arrive at a recommended provisioning strategy the Team considered the three candidate strategies discussed above.

3.4.1 Development Risk Assessment

All new developments have uncertainties and associated risks in cost and schedule, but the magnitude of these risks would not be the same for all developments. The Stirling RPS design is relatively immature at the system level. This immaturity would introduce risks that unforeseen technical issues might preclude the timely development of the Stirling RPS or its integration on the spacecraft. This risk might be tolerable for a single project with fallback launch opportunities, but would be intolerable if it placed a high-profile mission such as the proposed 2007 Mars Smart Lander mission at risk. This risk could be mitigated by backing up the Stirling RPS development with the development of a new RTG until the Stirling RPS maturity has advanced to the point that programmatic risk is acceptably low. As a result, although a Stirling RPS development without backup would be the lowest cost and would use the least fuel, it was ruled out based on technical development risk considerations.

The All-RTG Strategy would have the advantage of considerable design heritage from the existing and previous RTGs, much of which would be applicable to a new design, resulting in a low development risk. Therefore, a new RTG development would not require a backup development to achieve an acceptable total development risk level.

Consequently, only the All-RTG Strategy and the Dual Strategy were considered to be candidates for recommendation. These two strategies have outcomes as shown in Figure 3.4-1.

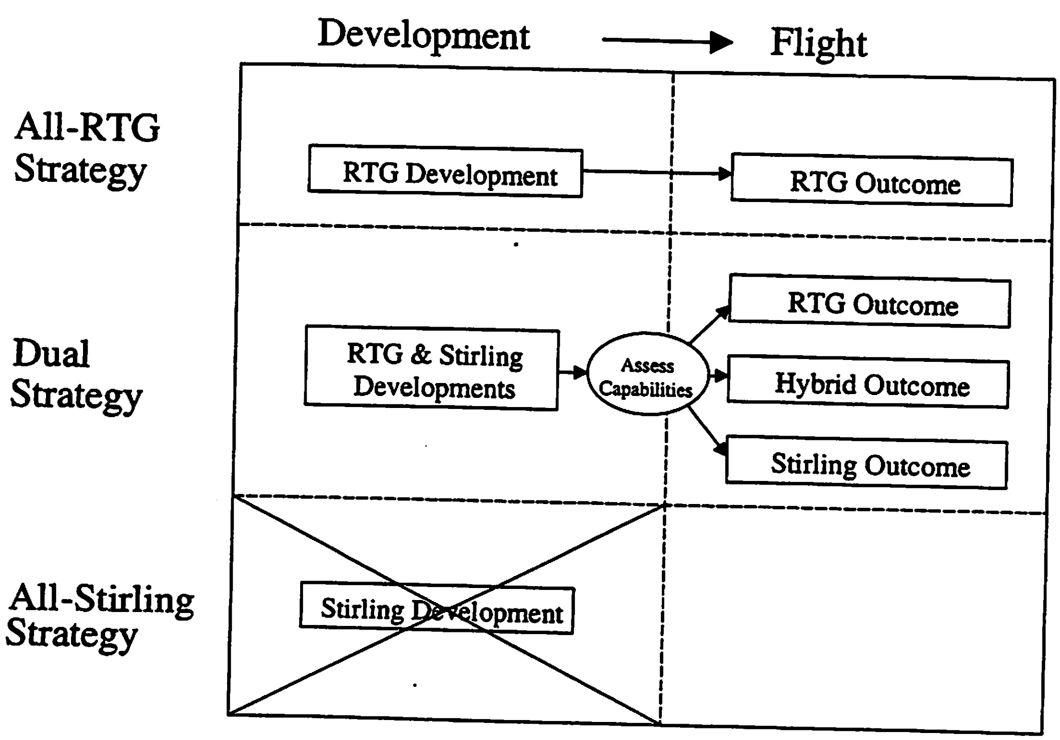


Figure 3.4-1. Outcomes

3.4.2 Integrated Schedule Assessment

The projected schedule for an All-RTG Strategy is shown in Figure 3.4-2 and is in general similar for all strategies. The schedule (calendar year) is for Scenario A, which includes all the potential missions and is the most stressing case.

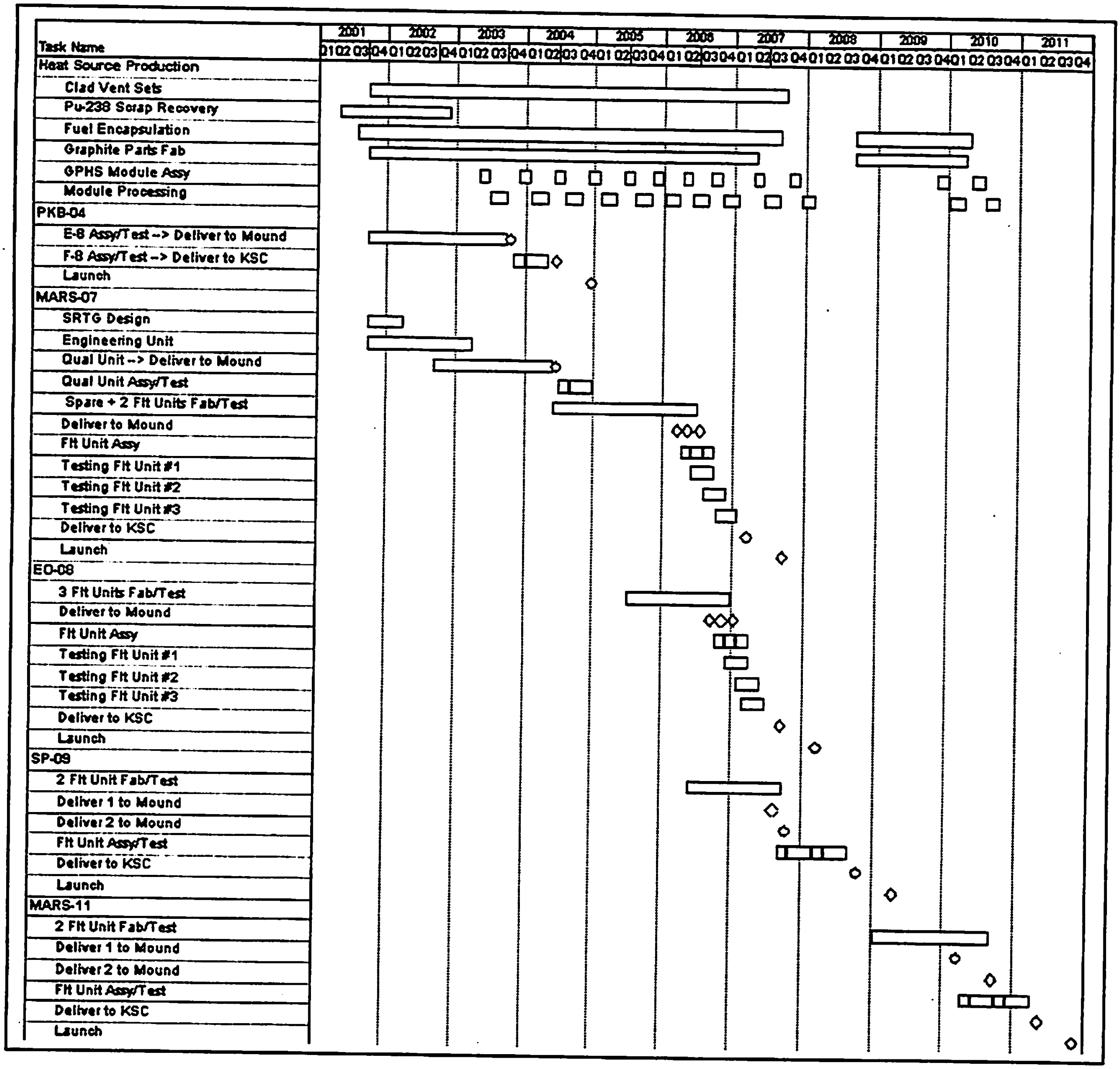


Figure 3.4-2. Projected All-RTG Strategy Integrated Schedule

Heat source component fabrication would need to begin in 2001. The projected schedule assumes that the production rate of these components would be leveled to maximize the component fabrication capabilities of the DOE infrastructure. The ^{238}Pu processing and encapsulation at LANL are the pacing activities for this schedule.

During the 2006-2007 timeframe, the Mound activities would become the pacing items for this schedule with the assembly, acceptance testing, and delivery of six new RTGs (see Appendix C). The projected schedule assumes the RTGs would need to be ready for shipment to KSC six months prior to launch. Mound personnel would be involved both in monitoring the RTGs while at KSC and in returning the spare to Mound for storage.

The projected schedule for the Hybrid Outcome of the Dual Strategy is shown in Figure 3.4-3 for Scenario A. This schedule is similar to the one for the All-RTG Strategy (shown above in Figure 3.4-2) with the addition of the Stirling RPS development and use of Stirling RPS flight units for some missions. The schedule assumes RTGs for use on outer planet missions, Stirling RPSs for Mars missions, and a spare for each. This schedule also reflects a redundant Stirling RPS for each mission. This strategy would require additional effort at Mound to assemble, acceptance test, and deliver the additional two RPS units in the 2006–2007 timeframe.

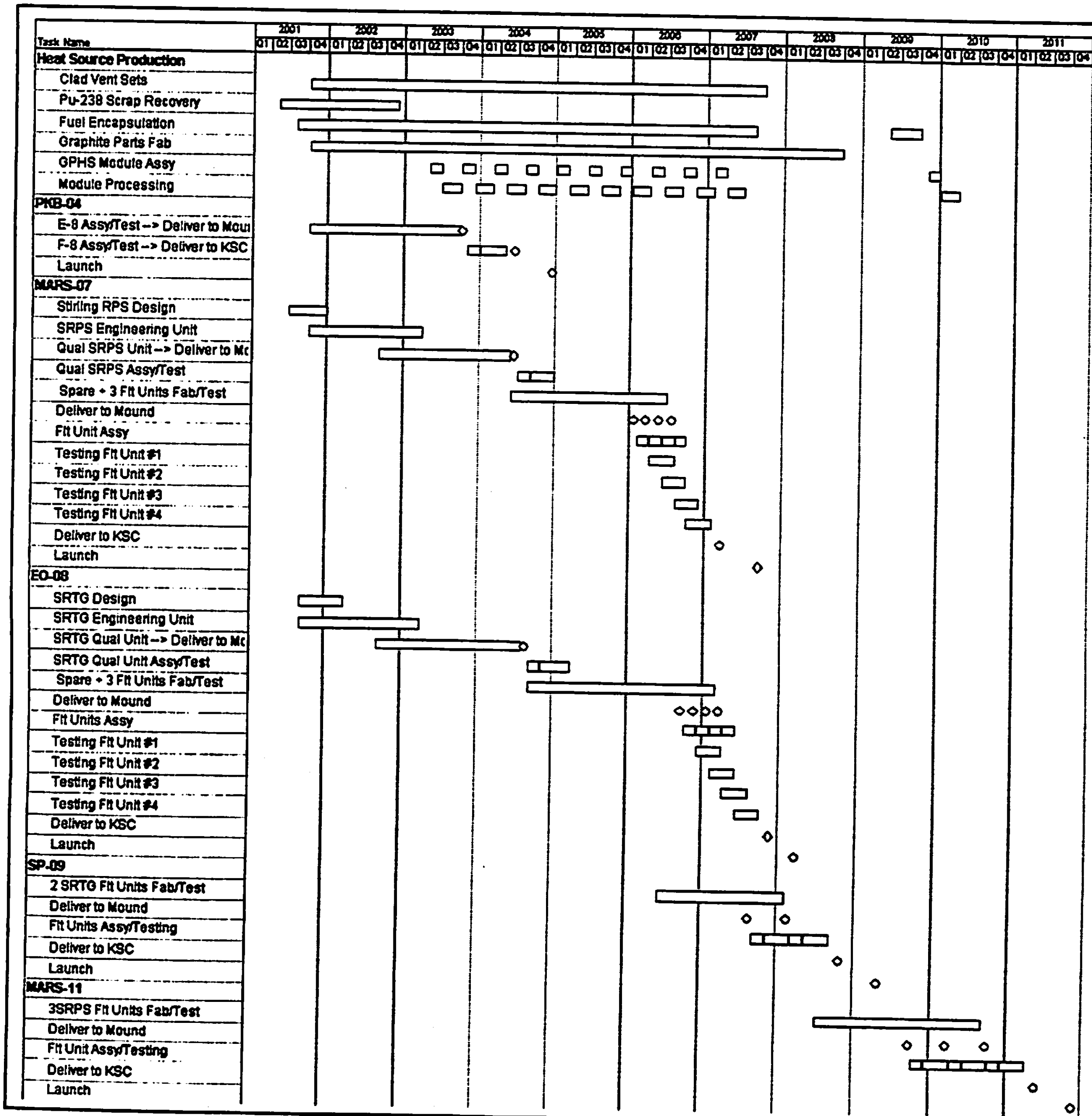


Figure 3.4-3. Projected Dual Strategy/Hybrid Outcome Integrated Schedule

3.4.3 Expected Value Approach

The three potential outcomes of the Dual Strategy are mutually exclusive, requiring each of the three outcomes to be independently evaluated against the outcome of the All-RTG Strategy. To come to a reasoned conclusion, each evaluation should be weighted by the probability of occurrence of each respective outcome.

Because the three outcomes are mutually exclusive, each can be assigned probabilities summing to 100 percent. The Team's consensus assessment was that the probability of the Stirling Outcome is low (about 10%), the probability of the RTG Outcome is moderate (about 30%), and the probability of the Hybrid Outcome is the highest (about 60%).

An expected value can be computed using the probability to weight the different outcomes. This expected value gives a more valid comparison because the different probabilities of the outcome are appropriately incorporated. For this reason, expected values are given for the Dual Strategy in the following comparisons of cost and GPHS module production requirements.

3.4.4 Cost Assessment

Non-recurring Costs

The non-recurring costs estimated for the three potential RPS development strategies are shown in Table 3.4-1. These non-recurring costs include the systems contractor, material, and shipping. The existing DOE ^{238}Pu inventory would be used to support the development. Since NASA is not intending to launch the development units, the cost of the fuel would not be charged to NASA and is not included in the table. The existing DOE infrastructure is sufficient to support the development activities required by the Dual Strategy.

Table 3.4-1. Estimated Non-recurring Costs ($M)

Strategy	FY02	FY03	FY04	Total
All-Stirling	12	17	12	41
All-RTG	11	14	12	37
Dual	23	31	24	78

Relative Total Costs

The scenario costs are shown in Tables L-4 through L-8 and Figures L-1 through L-4 in Appendix L. Table 3.4-2 shows the cost differences between the various outcomes of the Dual Strategy relative to the All-RTG Strategy. The increase in the estimated cost of the RTG Outcome of the Dual Strategy simply reflects the Stirling RPS development costs. The differences between the different outcomes results from the non-linear production throughput costs. The difference between the expected Dual-Strategy outcome and the All-RTG outcome is about 5% of the total cost.

Table 3.4-2. Estimated Outcome Costs Relative to All-RTG Strategy ($M)

	Dual Strategy				All-RTG Strategy
Mission Scenario	RTG Outcome	Hybrid Outcome	Stirling Outcome	Expected Outcome	RTG Outcome
A (Early PKB)	+46	+25	-45	+24	0
B (Delayed PKB)	+43	+26	-55	+24	0
C (Early PKB, No SP)	+45	+25	-29	+26	0
D (No PKB, No SP)	+45	+13	-31	+18	0
Average	+45	+22	-40	+23	0

Expected Total Costs

Details of the total costs are shown in Tables L-5 through L-8 in Appendix L. These total costs have been weighted by the outcome probabilities to derive the expected outcome costs for the Dual Strategy. These expected Dual Strategy costs and the costs for the All-RTG Strategy are shown in Table 3.4-3.

Table 3.4-3. Expected Cost Summaries by Scenario ($M)

Scenario	All-RTG	Expected Dual
A (Early PKB)	433	457
B (Delayed PKB)	418	441
C (Early PKB, No SP)	369	395
D (No PKB, No SP)	301	319

In summary, the expected cost differences shown in Table 3.4-3 are insensitive to scenario and are about 5% of the total costs. While this slight cost advantage of the All-RTG Strategy would probably be maintained for reasonable variations in modeling assumptions, the relative magnitude of this advantage would also remain small. Since the difference is small relative to uncertainties in estimation, the Team believes that this difference should not be a significant factor in strategy selection.

3.4.5 *Evaluation of Outcomes*

A comparison of the various outcomes was made in order to assess all the issues related to strategy recommendation; this total process is described in Appendix M. The driving issues in strategy selection are related to the PuO_2 and DOE infrastructure-related issues as discussed below. Other issues including cost and management considerations as well as mission flexibility and technical constraints are discussed in Appendix M.

Production Throughput and RPS Assembly and Acceptance Testing Capability

Required fueled clad production throughput levels would vary widely among outcomes. The RTG Outcome of the Dual Strategy would require the highest and sustained fueled clad production levels. As shown in Table 3.4-4, the Stirling Outcome would require the lowest fueled clad production levels, and, as expected, the Hybrid Outcome would require an intermediate fueled clad production level. Outcomes that do not require the highest rate of fueled clad production would offer additional schedule margin and therefore would lessen schedule risk.

The fueled clad production throughput required at LANL depends on the scenario and the outcome as shown in Table 3.4-4.

Table 3.4-4. Fueled Clad Throughput Requirements at LANL

Scenario	Dual Strategy				All-RTG Strategy
	RTG Outcome	Hybrid Outcome	Stirling Outcome	Expected Outcome	RTG Outcome
A (Early PKB)	432	360	224	368	424
B (Delayed PKB)	424	352	176	356	416
C (Early PKB, No SP)	368	296	200	308	360
D (No PKB, No SP)	296	224	128	236	288

The All-RTG Strategy would have eight fewer fueled clads than the Dual Strategy during the development phase. These eight fueled clads are used in the Stirling RPS qualification unit. This is a minor factor since no additional resources at LANL would be required to produce eight additional fueled clads.

Mound assembly and acceptance testing activities would be influenced by the number of RPS units per mission. The number of RPS units that would be assembled and tested at Mound for each scenario is shown in Table 3.4-5. The Stirling and Hybrid Outcomes would require more RPS units than the RTG Outcome due to inclusion of a redundant system on each spacecraft utilizing a Stirling RPS (see Section 2.7).

Table 3.4-5. Number of RPS Units Assembled and Tested at Mound

Scenario	Dual Strategy				All-RTG Strategy
	RTG Outcome	Hybrid Outcome	Stirling Outcome	Expected Outcome	RTG Outcome
A (Early PKB)	14	17	18	16	13
B (Delayed PKB)	14	17	19	16	13
C (Early PKB, No SP)	12	15	15	14	11
D (No PKB, No SP)	10	13	13	12	9

Expected Number of Modules

Similarly, the expected number of GPHS modules that would be used for the Dual Strategy may be determined. Table 3.4-6 compares these results with the number of GPHS modules that would be used in the All-RTG Strategy.

Table 3.4-6. Estimated Number of GPHS Modules by Scenario

Scenario	All-RTG	Expected Dual
A (Early PKB)	106	91
B (Delayed PKB)	104	89
C (Early PKB, No SP)	90	77
D (No PKB, No SP)	72	59

Notes: The estimated number of required GPHS modules depends on a number of factors, including the assumed conversion efficiency of the Stirling RPS and the new RTG, both of which would be dependent on the final design of each. For the purpose of the study, the Team assumed 6.5 % efficiency for the new RTG. The new RTG could potentially incorporate the use of available segmented thermoelectric materials, which could increase the conversion efficiency. This would reduce the number of modules for both strategies, and decrease the difference between them.

Likewise, the Team assumed 25% efficiency for the Stirling RPS. This too could be off a few percent in either direction, but except in unusual circumstances would not affect the total number of modules.

Another factor affecting the number of modules is the assumed probability of the RTG Outcome in the Dual Strategy. If it were to decrease from the estimated 30% the number of estimated modules in the Dual Strategy would decrease.

If an acceptable single converter Stirling RPS were to be achieved, it might be possible to satisfy redundancy requirements with fewer GPHS modules in missions using the Stirling RPS. This would also reduce the number of estimated modules in the Dual Strategy. In both of these cases, the number of modules in the All-RTG Outcome would be unchanged, so the difference between the Strategies would increase.

4. Recommendations

The Terms of Reference explicitly tasked the Team to recommend a strategy for the provisioning of safe, reliable and affordable RPSs to enable potential NASA 2004-2011 space robotic missions, and to address a number of related issues. The following subsections present the Team's recommendations for the use of existing assets, provisioning strategy, implementation plan, and advanced RPS technology development funding.

4.1 Use of Existing Assets

The principal assets available for consideration are F-5, E-8, and the MHWs, as discussed in Section 2.3. The Team reviewed their potential use and makes recommendations as discussed in the following paragraphs. Planning for the use of existing assets must include consideration of DOE plans for potential GPHS module enhancements.

DOE has been evaluating potential enhancements of GPHS modules, which include incorporation of a reinforcement rib to provide greater strength for aerodynamic and impact loads without exceeding the module stack height of the F-5 and E-8 design. Additional enhancements are being investigated that would increase the overall module size beyond that which could be accommodated by the F-5 and E-8 design. The Team has taken these plans into account in making its recommendations.

F-5 and E-8

Since the potential schedule for the new RPSs would not support missions before 2007, the Team supports the use of F-5 and E-8 as allowed for in the PKB AO for the early PKB options (2004 through 2006). The recommended disposition of F-5 and E-8 is summarized graphically in the flow chart in Figure 4.1-1. If only one RTG were needed, the Team recommends using E-8 and fueling it with enhanced GPHS modules.

If F-5 were also required, the Team recommends upgrading F-5 with enhanced GPHS modules. These modules would be fueled using the original fueled clads from F-5. If F-5 were not required, it could be defueled and the fuel returned to the DOE inventory. Table 4.1-1 shows the estimated cost for preparing F-5 and E-8 for the potential early PKB, as well as the cost of preparing E-8 only.

The Team concluded that F-5 or E-8 should not be used for missions beyond 2006 when the new RPSs would become available. The rationale for this conclusion was that it is anticipated that the RPSs would incorporate a GPHS module design with additional enhancements. In the judgment of the Team, F-5 or E-8, which cannot accommodate the new GPHS module design, should not be launched once the new designs are available.

The Team recognizes that plans for the EO mission include the potential use of F-5 and E-8 should an early PKB mission not be flown. The costs of preparing F-5 and E-8 for a 2008 EO mission are scenario dependent. For the All-RTG Strategy, dropping PKB from Scenario A and using F-5 and E-8 for EO is estimated to result in a total cost of $367 million.

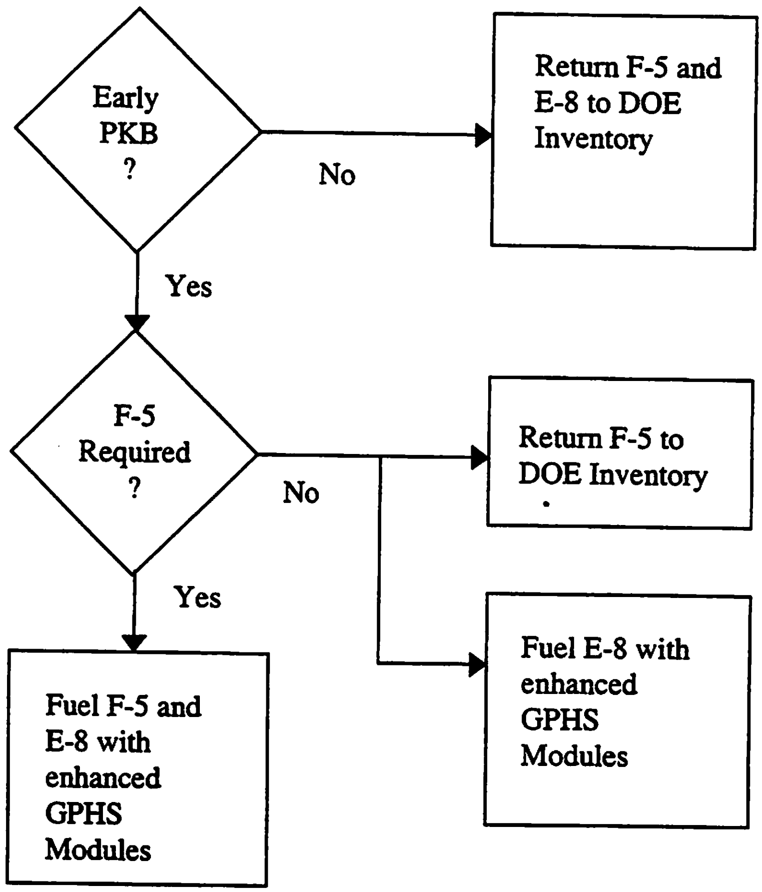


Figure 4.1-1. Potential Use of F-5 and E-8

Table 4.1-1. Delta Cost to NASA for Delivery of F-5 and E-8 ($M)

Cases	FY02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	FY 10	FY 11	FY 12	Total
F-5 and E-8 for PKB in 2004	12	11	10	38	0	0	0	0	0	0	0	71
E-8 only for PKB in 2004	10	9	9	25	0	0	0	0	0	0	0	53

Simply dropping PKB from the All-RTG Scenario A (using three new RTGs for EO) is estimated to result in a total cost of $362 million ($433 million for Scenario A from Table 3.2-1 less $71 million from Table 4.1-1). The difference in cost between using three new RTGs and F-5/E-8 for Scenario A is small. While the cost differences for other scenarios may differ somewhat, they would still be comparable.

The comparable costs and the potential opportunity to use additionally enhanced GPHS modules is the basis for the Team's recommendation to consider F-5 and E-8 only for missions flown before 2007.

MHW Generators

Given the current understanding of the likely mission scenarios, the Team recommends against the use of the MHW generators. The characteristics of these generators are described in more detail in Appendix E.

For the mission scenarios considered by the Team, MHW generators would not be needed given the availability of F-5 and E-8 for near-term missions. The Team considers the MHW generators to be a dead-end investment, which should only be considered for use if the early need for RTGs grows beyond the assumed scenarios.

4.2 Provisioning Strategy

Based on available information and after careful consideration of the criteria and factors discussed above, the Team recommends that NASA and DOE proceed with the Dual Strategy.

Rationale

This recommendation is based on the consideration of the relevant decision drivers depicted in Figure 4.2-1.

The most compelling argument for the All-RTG Strategy is that it would cost an estimated $41M less during the development phase than the Dual Strategy as illustrated in Table 3.4-1. The differences between the runout costs are small and are not judged by the Team to be a decision driver (see Tables L-5 through L-8 and Figures L-1 through L-4 in Appendix L).

There are a number of drivers for selecting the Dual Strategy. As discussed in Section 3.4.4, the Dual Strategy would require less expected fuel processing. Fuel processing would take place at LANL where a number of other critical processing activities would be going on simultaneously. The nature and complexity of the LANL activities make them susceptible to unpredictable work interruptions. Such interruptions have the potential to disrupt the normal processing of the work being done for NASA. This in turn would have the potential for reducing the schedule margin of the final RPS assembly and testing operations that occur downstream.

While it might appear that the required schedule margin would be independent of the throughput required by the different scenarios, the Team believes that an increase in required throughput would make a work interruption more likely, making the risk of schedule impact throughput dependent. Since the Dual Strategy would require less throughput than the All-RTG Strategy, it would have less potential for work interruptions. The strength of this argument is dependent on the mission scenario, being less critical with fewer missions in the scenario, and could be mitigated to a degree by providing additional staffing and schedule slack at LANL. The impact of the additional staffing on schedule margin has not been quantified.

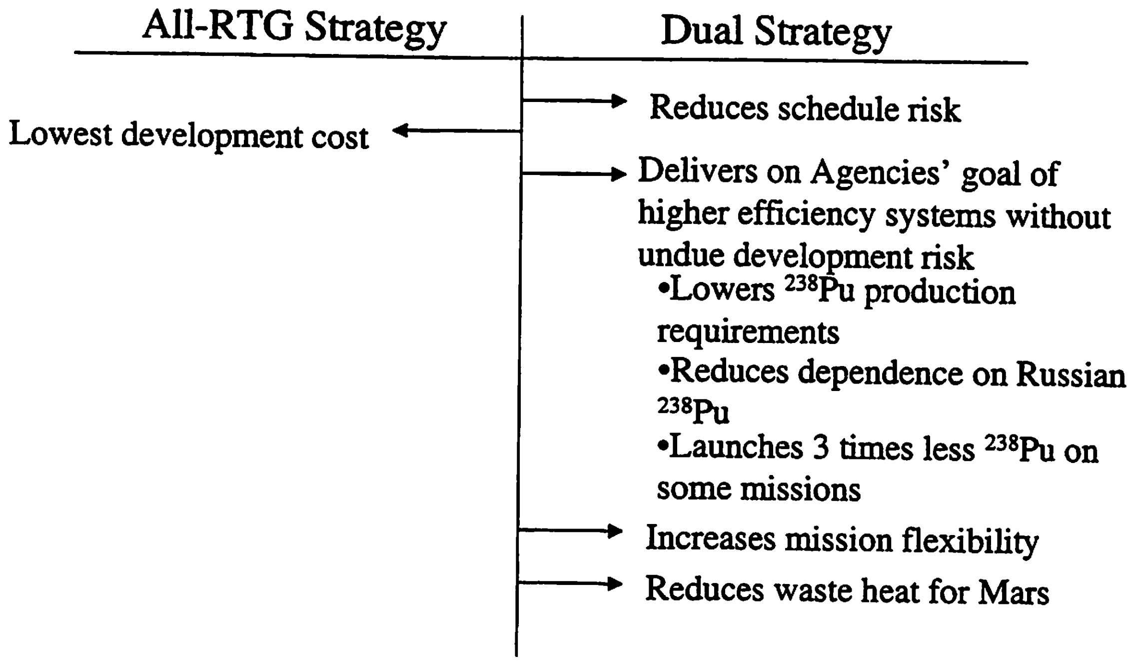


Figure 4.2-1. Decision Drivers

During the Cassini launch timeframe, both Agencies were quoted in the open literature as having the intent to develop higher efficiency systems for future missions (see References 2 through 6). The technology development uncertainty and the consequential risk of delivering a mission-qualified Stirling RPS for the highly schedule critical Mars missions was the major reason for not recommending the All-Stirling Strategy. The Dual Strategy effectively addresses this concern by incorporating the RTG design in the program as a backup to the Stirling RPS, thus decoupling the progress of the Mars mission from the development risk concerns of the Stirling RPS.

The goal of more efficient systems is to reduce the quantity of fuel required, both in total, and per flight. The total fuel includes not only fuel per mission but also the fuel required for qualification testing and for the spare flight units. The total expected fuel required would be less for the Dual Strategy, but not enough to recover the added development cost, at least over the timescale of the potential missions considered in this study. Nevertheless the reduction would be real and would continue into the future with any assumed mission model, thus promising lower recurring costs for potential future missions, and less dependence on Russian fuel.

Another advantage of the Dual Strategy would be the potential for reduction in fuel per mission for missions using Stirling RPSs. For each of the two potential Mars missions considered in the study phase, the Dual Strategy would require the launch of only six GPHS modules per mission, while the All-RTG Strategy would require sixteen modules per mission.

The Dual Strategy also offers mission planners and projects in the formulation phase the flexibility to choose between two different RPS designs, based upon the best match of the system capability with the mission requirements. This is a notable, but not significant, strategy decision driver.

The Dual Strategy also makes the Stirling RPS with its lower waste heat available for use on Mars missions. Aeroshell encapsulation of the RPS makes disposal of waste heat during cruise more difficult. Again, while notable, this is not a significant driver in the choice of strategy.

Cost and Cost Profiles

Cost estimates have been developed for the recommended strategy. These costs were developed for the four scenarios in the same manner as the other costs included in the report. The cost estimates provide for the increase in the DOE production throughput capability to support the use of new RTGs for all missions as a viable alternative to the Stirling RPS. Detailed spreadsheets for these costs are presented in Appendix N (see spreadsheets labeled 3ARS, 3BRS, 3CRS, and 3DRS).

A summary of the estimated costs for the recommended strategy is presented in Table 4.2-1 and shown graphically in Figure 4.2-2.

Table 4.2-1. Estimated Costs for Recommended Strategy ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	44	71	75	87	70	47	23	19	14	6	2	458
B (Delayed PKB)	36	65	65	64	76	63	33	20	14	6	2	444
C (Early PKB, No SP)	44	71	74	85	42	31	13	14	12	6	2	394
D (No PKB, No SP)	34	54	58	51	39	32	16	12	10	6	2	314

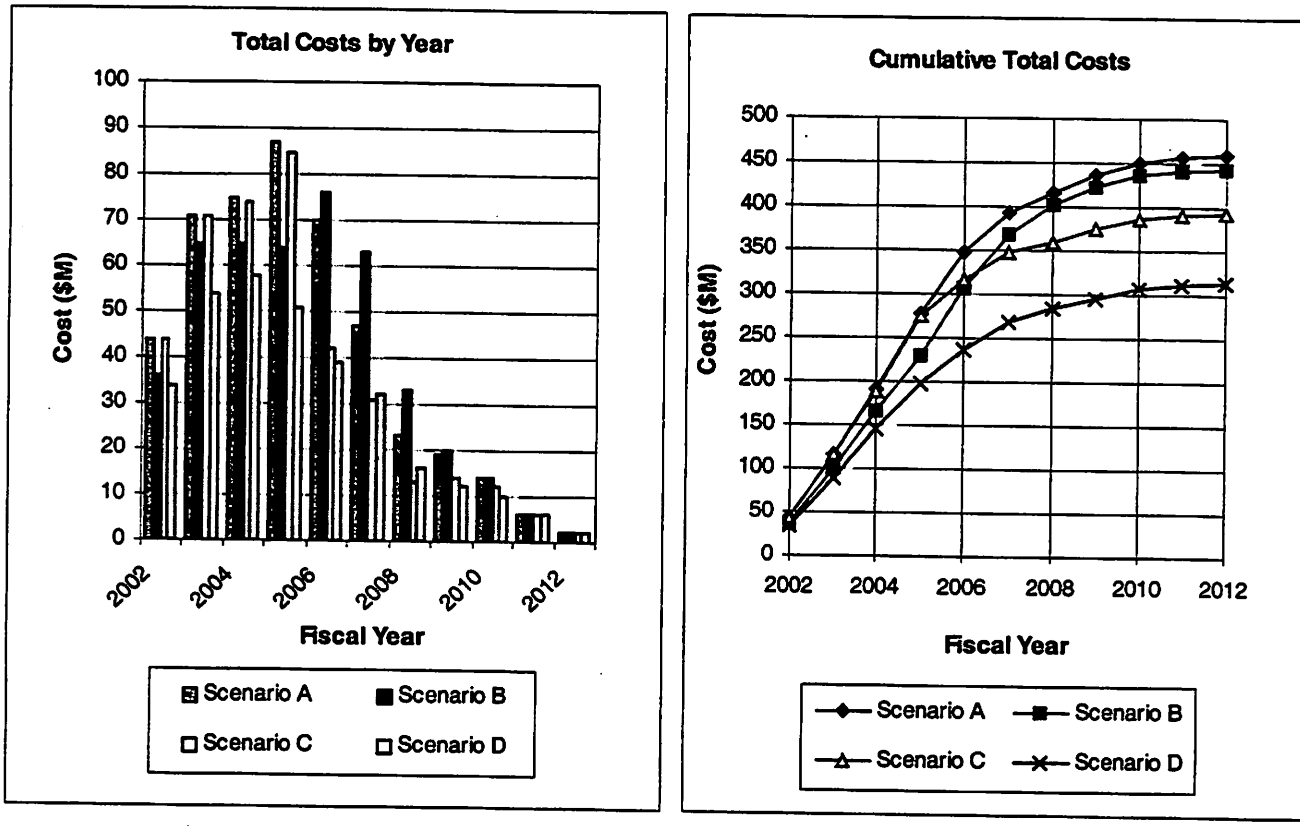


Figure 4.2-2. Estimated Costs for Recommended Strategy

This data shows the funding profiles that would be required should the recommended strategy be adopted. The figures illustrate the strong dependency of total costs on mission scenario. The costs have been split into non-recurring and recurring costs and are discussed separately in the following paragraphs.

Non-recurring costs for the recommended strategy are detailed in Table 4.2-2. These costs include only the systems contractor, material, and shipping costs involved in development of the two new RPS designs. Fuel processing and assembly and acceptance testing costs are assumed to be covered within the DOE infrastructure. ^{238}Pu fuel costs incurred in the development program are not included, as existing DOE inventory would be used to support development.

The production of the two required spare units (one each for the new RTG and Stirling RPS) is included in the second line of the table pursuant to the recommendation in Section 4.3.

Table 4.2-2. Estimated Non-Recurring Costs ($M)

	FY02	FY03	FY04	FY05	Total
Without Spares	23	31	24	0	78
Including 1 Spare RTG and 1 Spare Stirling RPS	25	48	30	8	111

Recurring costs for a typical mission under the recommended strategy have also been estimated and are presented in the following tables. The typical mission is assumed to use either two new RTGs (Table 4.2-3) or three Stirling RPSs (Table 4.2-4). Recurring costs have been detailed in each table for two limiting cases. In the first case fuel processing and assembly and acceptance testing work can be performed within the DOE infrastructure. The costs shown include fuel, materials, mission integration and transportation. In the second case fuel processing and assembly and acceptance testing work exceeds the DOE infrastructure production throughput capability and additional costs would be required to cover the increase in staffing needed to support the production requirements.

Table 4.2-3. Estimated Recurring Costs for Missions Using Two New RTGs ($M FY02)

	Year 1	Year 2	Year 3	Year 4	Total
Within infrastructure	15	20	10	6	51
Above Infrastructure	19	26	16	9	70

Table 4.2-4. Estimated Recurring Costs for Missions Using Three Stirling RPSs ($M FY02)

	Year 1	Year 2	Year 3	Year 4	Total
Within infrastructure	10	10	11	9	40
Above Infrastructure	12	14	14	12	52

The differences in the effects of infrastructure assumptions between the RTGs and the Stirling RPS cases are a result of the non-linear effects of throughput costs associated with increasing the DOE production throughput (see Section 2.5). The limiting case of the throughput work exceeding the infrastructure is representative of the concentration of work in the 2008 timeframe. In the post-2011 period a more uniform spacing of work could be accommodated within the infrastructure production throughput capability.

4.3 Implementation Plan

Development Concept

The Team recommends that the development of the new RTG and the Stirling RPS proceed on the basis that these developments would result in generic off-the-shelf designs that could operate both in space and in an atmosphere. These designs would be available to future user missions, rather than designs specifically tailored to or driven by the needs of each mission. Inherent to this notion is the concept that the design requirements would be amenable to the spectrum of missions likely to be flown with minimal adaptation to the standard design. Such adaptation if required would be funded by the using mission.

Implementation Concept

The Team strongly recommends that an implementation office for development and project coordination be established by NASA with sole responsibility for providing technical requirements and coordinating with DOE in the development and deployment of these RPSs.

Industrial Contracting

The recommended strategy would require two contracts to be awarded, one for Stirling RPS development and production and one for the new RTG development and production.

Efforts are, and have been, underway by DOE to select a Stirling RPS system contractor. This contractor would be responsible for the Stirling RPS development and subsequent flight system production. Proposals in response to the request for proposal (RFP) are currently being evaluated. Award of the contract would be expected in early summer. The Team recommends that the appropriate findings and information developed over the course of this study be incorporated in the planned contract prior to its execution.

DOE activities associated with the release of a RFP for the new RTG development and production have also begun in order to preserve schedule margin should the recommended strategy be accepted. The RFP is scheduled for release in the early summer with contract award projected for the end of calendar year 2001. The Team recommends that NASA and DOE move with all deliberate haste to establish the necessary funding arrangement so that selection of a system contractor can proceed in a timely fashion.

Plutonium Procurement

The Team recommends that an initial procurement of Russian ^{238}Pu be completed in FY01. This initial procurement would allow for early verification of Russian fuel properties and processing losses and confirm the time required to place an order and receive the material in the United States. In addition, this initial procurement would alert the Russians of the United States intention to procure material and set the stage for a new contract in December 2002 when the current contract expires.

The early verification of the Russian fuel properties and LANL processing losses is a key point. The integrated schedules presented in this report and used by the Team in forming the recommended strategy assume that LANL would use the material as received with no further processing and with consistent processing losses. Early confirmation of this assumption is required and would allow for re-planning efforts if the assumption cannot be confirmed.

Since ^{238}Pu has not been purchased from Russia in several years, there are some reservations about the procurement process. While the Team believes the procurements can still be completed and in a timely fashion, the process should be vetted as quickly as possible.

In recent discussions with the Russians, they stated a reluctance to enter into a new contract with the United States after the current contract expires. While the Russians are expending resources maintaining their capability to produce, process, package, and ship the material, the United

States has not purchased any material in several years. The Russians expressed concern regarding a new multi-year contract with the United States that would require them to continue expending their resources without having received any compensation for their efforts.

Increased DOE Production Throughput Capability

All scenarios considered would require production rates that exceed the current DOE production throughput capability. Due to the nature of the DOE activities (requirements of nuclear operations), the increase in the production throughput capability would take two years and would need to be initiated immediately. NASA must project its potential requirements sufficiently in advance for DOE to plan for the required production rate. The Team recommends that DOE and NASA agree on and commit to a production rate that would support potential future mission requirements.

Safety and Launch Approval

Because NASA requirements for RPS/RHU missions could double to triple over the next decade relative to the last ten years, the Team recommends that NASA and DOE ensure that planning, schedule considerations and selection processes provide sufficient lead times to ensure cost-effective and timely satisfaction of the environmental and nuclear launch safety approval process requirements. Appendix I provides some suggestions that NASA and DOE may wish to consider in this regard.

Redundancy

Based on the driving considerations discussed in Section 2.7, the Team recommends that a redundant unit be carried on all missions using Stirling RPSs.

Sparing

Flight spares are normally provided for all replaceable items of spacecraft flight systems as a protection against loss of equipment due to hardware failure, or damage due to mishaps. Spares are especially critical during those phases of Assembly, Test, and Launch Operations (ATLO) when minimizing downtime for repair and replacement is essential to maintaining scheduled activities. Particular instances of the latter are during spacecraft system level testing and pre-launch preparations.

Flight spare RTGs are not planned for F-5 or E-8 for use on the potential early PKB Mission. Based on the previous use and operational experience with these generators on Galileo, Ulysses, and Cassini, the Team concurs with this plan.

For any new RPS design, either Stirling or new RTG, a flight spare would be required. The use of a qualification unit would not be suitable as a flight spare because its exposure to full qualification testing would invalidate its use as a flight unit. The Team recommends that any new qualification units be put on long-term life test after completing the qualification test program.

The Team recommends a revolving spare concept, whereby the flight spare from one mission would be inherited by the next mission and nominally designated as first flight unit for that mission. Each mission would fund the recurring cost of the full set of flight units required for that mission. The last unit would normally be the designated Flight Spare, to be passed by inheritance to the next user for use as its first flight unit. The flight spare would be delivered to KSC along with the flight units, and would be returned to the Mound facility after launch.

Since the revolving spare would benefit all users, the Team recommends that the cost of the revolving spare be included in the non-recurring NASA cost for developing and qualifying a new design. This would be the most equitable funding approach. An alternate approach would be to require the first user to fund the flight spare, which subsequent users would inherit without cost. In either case, the recurring cost for the flight units and any additional spares would be born by the using project. The using project would also be responsible for repair or refurbishment requirements incurred while the unit was assigned to the using project.

RPS Power Sizing

Based on the available information, the Team recommends that the power output from a potential RPS unit be in the range of 110 W_e to 150 W_e. Two conflicting issues drive this choice. A large RPS unit power level design would be more efficient than a small RPS unit power level design in terms of output power per kilogram of power system mass, while a lesser power level would be more effective on average in matching the RPS unit power level to the power required by a mission. This tradeoff is simplified by recognizing that the efficiencies of scale from increasing RPS unit power level would be largely achieved when the power level reaches about 110 to 150 W_e, suggesting that this level is an upper bound on desirable RPS unit power level. There is also the tradeoff of the cost to assemble and test, which is independent of unit power level. Lower unit power levels require more RPSs for a given mission, thus increasing the total cost of assembling and acceptance testing the ship set of RPSs for that mission. Within this range, the optimum unit power level would depend somewhat on the characteristics of the RPS technology, and so would not necessarily be identical for RTG and Stirling RPS designs.

RTG Power System

The simplest and most practical specification of RTG size is the number of GPHS modules, not a power level. The upper range of RPS unit power level described above corresponds to about six to eight GPHS modules.

An RTG segment design having three or four GPHS modules would be very desirable if the mass penalty for combining two such segments into a six- or eight-GPHS-module RTG was small relative to an optimized larger design. The practicality of this approach should be further assessed.

Stirling Power System

The preferred Stirling RPS design has Stirling converters aligned so that piston movement dynamics can be almost totally eliminated by appropriate relative stroke phasing of opposed converters. Studies have shown that the maximum power from the present Stirling converter design is about 55 to 75 W_e (depending on details of operation), thus a two-converter RPS unit power level is quite compatible with the upper range of the RPS unit power level described above. Studies have also indicated that a single Stirling converter design with a vibration compensation mechanism is practical. The mass efficiency of this design would need to be determined early in the design phase.

Summary

Based on available information, either the RTG or the Stirling power system technology appears compatible with the recommended 110 to 150 W_e power level, that could achieve most of the efficiencies of large scale. Furthermore, both RTG and Stirling RPS technologies appear to offer promise of a "half size" power element at a tolerable mass penalty, although this needs to be verified by detailed study in both cases. Successful development of "half size" power elements described above for both power systems would provide excellent capability to match the generator element design power to potential mission power requirements.

Some interest has been expressed in power systems for post 2011 outer planet missions that could have power requirements at the 50 W_e level. The described "half size" RPS units would fill this need nicely. The Team believes that proposed missions through 2020 would be adequately supported by a combination of the "full size" and "half size" RPS unit power levels described in this section.

4.4 Advanced RPS Technology Development Funding

NASA and DOE are funding several technology development efforts to improve on existing radioisotope power converter technologies. The primary thrusts of these technology development efforts are to provide: (1) increased system specific power (watts electrical output divided by system mass) and (2) increased conversion efficiency (watts electrical output divided by watts thermal input). As promising technologies progress from the laboratory, the emphasis shifts to addressing issues such as extending lifetime, eliminating failure modes, reducing recurring cost, etc.

NASA's Office of Space Science chartered an advanced radioisotope power system (ARPS) assessment study in 2000. A draft report of that study has now been published (Reference 7) and the final report is awaiting publication. The participants included representatives of NASA, DOE, industry, and the academic community. The results of the ARPS assessment study include a comprehensive technology assessment and a recommended technology development roadmap (including funding profiles and technology evaluation "gates") for missions beyond 2011.

The results of the ARPS assessment study are applicable to several issues addressed in this report—particularly in the context of the post-2011 missions. Three advanced RPS technologies currently under development show promise and should be carried forward on a schedule compatible with identified out-year mission needs. These technologies are Thermoacoustic Stirling, AMTEC, and Advanced Segmented Thermoelectrics (AS-TE). More details on these technologies, including an assessment of their relative advantages and disadvantages, may be found in Appendix K.

It is the Team's assessment that if all of the power converter technologies were successfully developed and sitting on the shelf, the AS-TE converter technology would be the first choice. After AS-TE, AMTEC would be the next choice, with Thermoacoustic Stirling as the final choice. Since there is development risk inherent in all of these technologies, the decision on which technology should be selected for future mission use must await the completion of work now underway to achieve technology readiness levels sufficient to justify continued investment. The Team recommends that rigorous technology evaluation review gates be imposed and that technologies that continue to make progress be carried forward to a technology readiness level that would allow system issues to be fully addressed.

The following is the Team's recommendation for the RPS technology investment strategy:

1. Fund AS-TE aggressively while funding AMTEC and Thermoacoustic Stirling at minimum levels. If AS-TE achieves "an acceptable level of readiness" by the end of FY2004, then consider
   AS-TE system development for use by missions in the post-2011 time frame.

2. If AS-TE fails to make adequate progress, fund AMTEC aggressively, holding Thermoacoustic Stirling at minimum funding levels. If AMTEC passes the technology gate by the end of FY2004, consider proceeding with system development.

3. If neither AS-TE nor AMTEC make adequate progress, consider funding Thermoacoustic Stirling only if significant advantages can be achieved over conventional Stirling technology.

5. Impact of Recommended Strategy On Post-2011 Missions

The Terms of Reference direct the Team to discuss the impacts of the recommended strategy on missions in the post-2011 timeframe.

In general, the individual mission requirements and the integrated mission queue flight rates for the post-2011 period are enveloped by the baseline missions described in the previous sections. Therefore, the recommended strategy (including fuel acquisition and allocation of DOE and NASA resources) would continue to serve well in the post-2011 period.

There are a few post-2011 missions under consideration that are not within the characteristic envelope established by the baseline mission set. These include the potential for very low-power (10 W_e -class) long-duration surface missions to Mars and/or the Outer Planets, as well as higher-power (400+ W_e -class) missions for subsurface exploration. These subsurface missions might also impose new requirements on system packaging, waste heat rejection, etc.

In order to meet requirements for larger power levels, the recommended designs are up-scalable—either by adding additional like-sized RPSs or by increasing the overall size of the RPS unit. In order to avoid a new flight qualification program, the modular approach is recommended. Further discussion on module sizing is provided in Section 4.3.

Requirements for significantly lower power levels would involve a new development unless the mission is willing to accept dramatic reductions in system specific power. RPSs in the 10 W_e -class using Stirling and RTG technologies have been developed, although no space mission has used less than 40 W_e for an RPS application.

When planning NASA and DOE resources as a function of generic mission flight rate, a rate of approximately one mission per two calendar years could be accommodated without the need for augmentation to the baseline DOE production throughput capability. A flight rate of up to one mission per year could be accommodated with augmentations to the DOE baseline capability. Even higher "surge" flight rates might be able to be accommodated on an occasional basis by front-loading fuel buys, fueled clad production, etc.

At some point in the future, improvements in RPS technology would change the requirements for number of GPHS modules required to support a particular mission of "standard" (e.g., 250 W_e) size. At such time, it would be appropriate to modify the production rate accordingly.

6. Management Issues

Discussion of certain risk management, organization and funding issues, as requested in Terms of Reference (Appendix B), is contained in this section.

Basis of the Current Management Interfaces

The current MOU (Appendix N), executed in July 1991, delineates the authorities and responsibilities of DOE and NASA in RPS research, technology development, design, production, delivery, space vehicle integration, and launch. Among other items, the MOU stipulates that DOE is "… responsible for designing, developing, fabricating, evaluating, testing and delivering RPSs to meet the overall system requirements, specifications, schedules, and interface requirements as agreed to by NASA and DOE" (*MOU*, Section III.A.1). The MOU also stipulates that "funding for the research, development, design, fabrication, qualification, test, evaluation, storage, delivery, contingency planning support, and other related activities of radioisotope power systems as well as radioisotope fuel charges, as mutually agreed to by NASA and DOE will be provided for under separate Interagency Agreements to this agreement" (*MOU*, Section III.B.15).

Two supplements to the MOU (see Appendix N), one for Cassini and one for Pathfinder, were executed in 1993 and 1994, respectively. In the 1993 supplement, NASA agreed to fund all of DOE's equipment and services costs for the Cassini mission except the "costs of fuel acquisition, production and processing" which were to be covered by a non-project-specific agreement (*Agreement No. 1 to Supplement MOU,* Section III.B.2; see Appendix N). In *Agreement No. 2 to Supplement MOU*, Section III.B (see Appendix N), the DOE agreed to provide three Galileo/Ulysses flight spare LWRHUs for the Pathfinder mission to NASA without cost because "NASA provided the necessary funds to fuel and fabricate these LWRHU units during the Galileo/Ulysses mission development program phases". Except for a minor design change to the Galileo RTG (replacing the Galileo lanyard operated pressure release devices with Voyager style barometrically operated devices), there were no non-recurring costs involved for either of these missions.

The source of funds for the non-recurring cost of developing and qualifying new generators is an important element in the interagency relationship. DOE funded the non-recurring costs of such activities for all missions through Cassini. NASA funded the recurring cost of producing generators for Ulysses, Galileo, and Cassini (see Appendix O).

In 1995, as the DOE budget for nuclear energy programs became more constrained, DOE was compelled to review with NASA the manner in which the design and production of future RPSs would be funded. As a result of those discussions, NASA and DOE exchanged letters (see Appendix N) in which the agencies tacitly agreed that NASA would "pay all costs for mission-specific related technology and radioisotope power system development" while DOE would provide "funding to maintain the technology and facility infrastructure that would enable these systems to be fabricated in the future" (Lash, 1995, Appendix N).

A key point documented in the 1995 exchange of letters was that because RPS "technology and mission specific development often require longer lead times than the spacecraft development itself, NASA may be required to provide mission specific technology funding in advance of an official start of mission activities" (Lash, 1995, Appendix N).

In practice the details of this arrangement have not worked to the mutual satisfaction of the two agencies. NASA has changed direction on several occasions due to changing mission definition plans and budgets. As an example, the EO baseline mission plans have evolved from use of AMTEC, to a new RTG design, to Stirling, and most recently to the use of F-5 and E-8. With each change came new direction to DOE and new cost estimates. Likewise, the Pluto mission has evolved from Stirling to use of the same assets (F-5 and/or E-8) baselined by EO. None of these changes have been documented in supplements to the MOU, although the MOU states "Implementing Interagency Agreements, supplemental to this Memorandum of Understanding (MOU), will address the deliverables, levels of support, funding, and other program-specific items in accordance with this agreement and will be executed between DOE and NASA at the Assistant Secretary and Associate Administrator level."

Moreover, DOE has been unable to establish a stable implementation plan in the face of continuing changes in both the amount and scheduling of funding to be provided by NASA.

Management Interface Arrangement

The current organizational interface arrangement is patterned on the model used for Voyager, Galileo, and Cassini, as shown in Figure 6-1. This arrangement worked well with a single project and when the requirements and technical coordination were limited to technical interface requirements for a standard product. However the dynamic of today is much different from earlier programs. In addition to the change in the funding paradigm, i.e., NASA to fund the non-recurring costs, there are multiple NASA projects sponsored by different program offices and having different technical requirements, all operating concurrently.

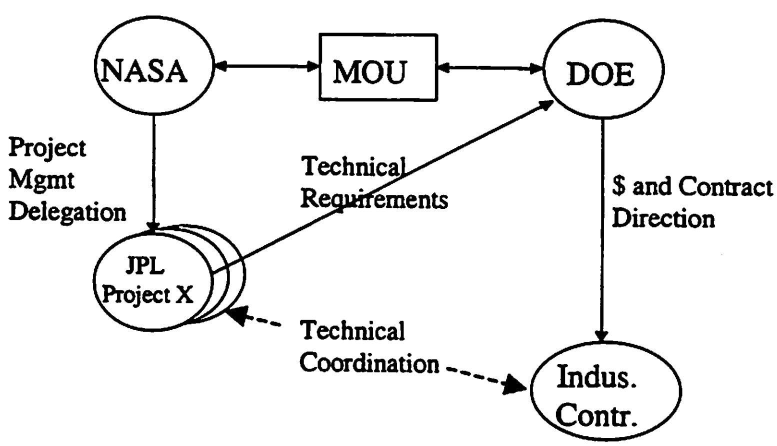


Figure 6-1. Management Interfaces

Given the change in funding, NASA expects to provide detail design, performance, and schedule requirements and not just the spacecraft technical interface specifications as provided for in the MOU. The specifics of this new interface arrangement have not yet been formalized. In the absence of established protocols and NASA HQ guidance, JPL has been providing technical direction on detail design, performance, and schedule information, which under the terms of the MOU are the responsibility of DOE. This situation contributes to frustration and a sense of irritation to both parties.

Having multiple independent projects, each providing separate funding and demanding sometimes differing technical requirements, exacerbate the situation.

Most of the foregoing problems result from the lack of a Management Interface Agreement and from the lack of a single NASA point of contact for providing requirements to the DOE, and a single funding authority at NASA, which is not subject to independent discretionary action by any one project.

Cost Risk Management

Past RPS developments were funded and managed by DOE. This arrangement limited NASA's cost risk. Since the onset of DOE's constrained budgets in 1995 (as discussed above), NASA's cost risk has increased. In the 1995 exchange of letters, NASA indicated concurrence with DOE's proposal that NASA should fund the cost of mission specific related technology and RPS development. Given that DOE will manage the development and that NASA will fund it, one way to limit NASA's cost exposure and to alleviate an intractable situation, would be for NASA to enter into a pre-negotiated fixed-price performance and fixed-schedule Supplemental Agreement with DOE for the non-recurring development activities and recurring flight unit costs. Although used in the past (see Appendix O), current planning does not contemplate this type of funding arrangement.

Timeliness of Fund Transfers and Payment Schedules

Although the details of the funding and management interface arrangements have not been developed, DOE has maintained the RPS infrastructure, and both DOE and NASA have continued technology development. However, lacking a defined management plan, the timely transfer of interagency funds has been inhibited by several factors:

- The lack of supplemental agreements to the MOU has impaired the budgeting and planning processes for both agencies.
- Frequent project changes (more than once per year) have occurred during early project planning.
- DOE internal budget requirements demand 3 months' carry over of advanced funding, which is in direct conflict with internal NASA funding practices.

Impairment of Authority

DOE has also been limited in planning for a flexible selection of RPS designs for potential future users. Potential spacecraft and/or mission specific requirements that are driven principally by a single funding project run counter to the need to develop a standard product flexible enough and sized properly for a variety of users. Single project requirements are also subject to change at any time driven by changing programmatic circumstances.

While DOE is accountable for successfully executing an RPS development, the Department's discretion to act accordingly is limited by NASA funding authority. The recent example of AMTEC is a case in point.

The funding required to develop, qualify, and provide flight units for a new RPS design typically leads and overlaps the development phase of the using spacecraft. The resulting parallel developments, wherein the requirements of one element of the system interactively drive the requirements of another element, frequently cause funding adjustments during the development cycle for both elements. A standard RPS design avoids this problem, and NASA would benefit from it as it has previously.

Appendix A. Establishment of Strategy Team

February 20, 2001

Distribution

Dear Sir:

The National Aeronautics and Space Administration (NASA) Office of Space Science (OSS) is planning several missions over the coming decades, some of which may require space nuclear power systems including radioisotope power systems (RPS) and radioisotope heater units (RHU). For acquisition of these systems, NASA defines its mission requirements to the U.S. Department of Energy (DOE). DOE in turn develops and produces these systems in accordance with the provisions of the 1991 Memorandum of Understanding (MOU) between DOE and NASA concerning RPS for Space Missions, as supplemented for specific missions. To ensure integrated planning within both agencies, there is a need to coordinate the needs of near-term missions. Therefore, a joint agency RPS Provisioning Strategy Team is being established to address the needs of missions in planning with launch dates in the 2004 to 2011 timeframe.

The RPS Provisioning Strategy Team will assess the RPS/RHU needs of OSS missions in planning for launch in the 2004 to 2011 timeframe and will provide recommendations on an RPS provisioning strategy that will be a basis for near-term decisions. This provisioning strategy will address RPS/RHU requirements as an ensemble rather than on a mission-by-mission basis and will be used to support mission planning and mission specific supplements to the MOU. Mr. John Casani will lead this activity. The team is requested to complete their review and present their initial recommendations to our offices by March 30, 2001.

NASA Headquarters, the Department of Energy, and their respective field Centers, laboratories, and contractors are requested to provide information and assistance, as appropriate and necessary, to support this effort.

Sincerely,

Earle K. Huckins III
Deputy Associate Administrator
for Space Science
National Aeronautics and Space Administration

Earl J. Wahlquist
Associate Director, Office of Space and Defense Power Systems
U.S. Department of Energy

DISTRIBUTION:
Strategy Team Members
NASA/S Distribution
DOE/NE-50 Distribution
JPL/Dr. Stone
    Dr. Elachi
    Mr. Gavin
    Dr. Naderi
    Mr. Casani
    Mr. VanDamme

Appendix B. Terms of Reference

- **Objective**

  Recommend a strategy for the provisioning of safe, reliable and affordable radioisotope power systems (RPS) that enable the NASA 2004-2011 space robotic missions. Specifically consider the 2007 Smart Lander, Europa Orbiter, Pluto-Kuiper Express, Solar Probe and 2011 Mars Sample Return missions.

- **Reporting**

  The team will report jointly to Earl Wahlquist and Earle Huckins. Status briefings will be provided incrementally at the request of either, and the final recommendation will be delivered jointly to both.

- **Stakeholders**

  Several organizational entities have a vested interest in the activities of this team and in the recommended strategy. Accordingly, the team will appraise the following organizations of their work and solicit input and advice from them in developing the recommended strategy.

  - NASA/S – individuals responsible for defining, advocating, justifying and obtaining funding for NASA space exploration priorities
  - NASA/R – individuals responsible for RPS technology/system development activities
  - DOE – managers and technical staff responsible for RPS technology and system development
  - JPL – Program/Project managers responsible for planning/implementing space exploration programs/missions, and managers and technical staff responsible for technology assessment and RPS application assessment

- **Issues to be Addressed**

  In formulating its recommendation, the team should account for issues that the decision makers will need to take into account in deciding whether to go forward with the recommended strategy. The following considerations are relevant.

  - Schedule and funding implications, including fuel, technology readiness, development, qualification and launch approval activities
  - Spacecraft system integration and accommodation issues, including configurational implications/constraints, fault tolerance/reliability, spacecraft thermal issues, handling/ground support, and waste heat management and utilization.
  - System integration and operations attributes impacting safety, environmental and safety analyses.

- Fuel availability, including domestic, foreign and mixed domestic/foreign plutonium supply options
- Launch vehicle selection, qualification, and safety databooks
- Best use of existing RPS/RHU assets
- If and for how long to maintain unicouple capability
- Need and affordability of backup options
- If and when to convert to Stirling
- Mass risk, schedule risk, and cost risk exposure
- Intra- vs. inter-agency technology/system development funding responsibilities
- Impact on mission and technology options for missions in the post 2011 time frame
- Programmatic and launch approval implications of multiple RPS designs.

- **Output**
  - Recommended strategy and rationale
  - Discussion of intra NASA funding responsibilities (which program should pay for what)
  - Discussion of risk management scenarios
  - Discussion of organization structure options for interfacing between NASA HQ and DOE and JPL

- **Constraints**
  - RHUs baselined for both of the Mars 2003 rovers
  - Inputs from current bidders for Stirling RPS contract must observe appropriate non-disclosure restrictions.
  - Near term RPS technology options consist of GPHS-RTG, new RTG, MHW-RTG, and Stirling RPS.
    (Advanced Stirling, AMTEC and segmented thermoelectrics may be options for post 2011missions.)

- **Committee Membership, Operating Mode and Schedule**
  - Members
    - Garry Burdick (JPL)
    - Bob Carpenter (OSC)
    - John R. Casani (JPL) [Chairman]
    - Tim Frazier (DOE)
    - Duncan MacPherson (JPL)
    - Art Mehner (DOE)

- Joe Parrish (NASA)
- Lyle Rutger (DOE)
- Reed Wilcox (JPL)

- Executive Secretary
  - Paul VanDamme (JPL)
- Operating Mode

  The team will function in a way analogous to a Select Committee, interviewing and gathering information from the Technical and Programmatic Information Sources listed below.
- Meeting Dates
  - January 9-11, 2001 @ JPL
  - January 22-26, 2001 @ DOE/Germantown
  - February 13, 2001 @ Mound
  - February 15, 2001 @ LANL
  - February 27, 2001 @ LMA (Valley Forge)
  - February 28, 2001 @ TES (Baltimore)
  - March 13-15, 2001 @ JPL
  - March 21-22, 2001 (Final Briefing) @ NASA HQ or DOE/Germantown

- **Technical and Programmatic Information Sources**

  The following sources within NASA and the DOE will provide information as typified below.
  - NASA
    - Code S
      - Definition of the hypothetical suite of 2004-2011 RPS mission scenarios to be considered.
      - 'Best estimate' projection of potentially available Code S RPS technology/system development funds.
    - Code R
      - 'Best estimate' projection of Code R potentially available RPS technology/system development funds
    - JPL
      - Mars Program Office
        - Definition of 'best estimate' mission RPS power (and associated RHU) requirements to satisfy NASA 2004-2011 Mars RPS mission scenarios
      - Outer Planets Program

- Definition of 'best estimate' mission RPS power (and associated RHU) requirements to satisfy NASA 2004-2011 Outer Planets RPS mission scenarios
- Sun-Earth Connection Program Office
  - Definition of 'best estimate' mission RPS power (and associated RHU) requirements to satisfy NASA 2004-2011 SEC RPS mission scenarios
- ARPS Technology Assessment Team
  - Results of assessment team findings and recommendations

- DOE
  - NE-50
    - Definition of reasonable plutonium supply scenarios
    - Definition of anticipated production throughput capability for the various RPS options
    - Description of program infrastructure and capability
  - Mound
    - Anticipated capability for assembly and related throughput activities for RPS
  - LMA
    - Assessment of capability and other relevant factors to starting the Unicouple line
    - Assessment of MHW usage and applicability to near term missions
    - Assessment of salvage and usage of MHW Unicouples
  - Stirling Study Contractors
    - Current assessment of Stirling RPS near term potential based on information gleaned as technical consultants to DOE at final briefing sessions.
  - LANL
    - Fuel processing and encapsulation
  - TES
    - Assessment of Viking type RTGs (PbTe/TAGS)

Appendix C. Mission Scenarios

A number of potential scenarios for launches in the 2004 to 2012 timeframe were used to develop the four representative scenarios presented in Section 2. These potential scenarios are shown in Figure C-1. These scenarios are grouped into classes that were taken from a presentation made to NASA HQ in late 2000 (Reference 8) discussing options for timing of outer planet missions.

These classes are defined as:

Class 1: Programs that fit within current NASA budget profile
Class 2: Programs that fit through FY06, but may exceed profile thereafter
Class 3: Programs that fit through FY02, but may exceed profile thereafter
Class 4: Programs that fit through FY01, but may exceed profile thereafter.

A number of mission options were outlined for each class, resulting in the sub-classes listed in the table. The spacing of potential launches for PKB, EO, and an as-yet-undesignated additional outer planets mission was determined for the 13 scenarios shown in Table C-1 based on the information contained in that presentation.

Additionally, a Solar Probe mission is shown in each of the scenarios. At the time this study was begun, the SP project was planning to launch in 2008. For the purposes of the scenarios developed in the table, SP launch opportunities were assumed in 2008, 2009, or 2010, adjusted to best fit the launch scenarios defined for the outer planet missions. It should be noted that a solar-powered SP mission with reduced science return is also under study. If this became the baseline there would be only four RPS missions through 2011; i.e., PKB, EO, and the two Mars missions.

Finally, each scenario assumes fixed launch dates for Mars landed missions in 2007 and 2011. This is derived from the current NASA Mars strategy of sending orbiter and lander missions on alternate launch opportunities. Those opportunities occur at roughly 26-month intervals, with Mars lander missions planned for September 2007 and November 2011 launches.

As discussed in Section 2.1 of the report, four potential scenarios were chosen by the Team to evaluate RPS provisioning strategies. For comparative purposes these have been appended to Table C-1, illustrating that they encompass most of the mission profiles.

Scenario A includes an early (2004) launch of PKB.

Scenario B is the same as Scenario A with PKB moved to 2008. This combination of two missions in 2008 (EO and PKB) is not covered in any of the defined program classes, but has emerged recently as a possible scenario that the Team decided, with input from NASA, should be considered.

Scenario C is the same as Scenario A with no SP mission, reducing the total number of missions to four during the next decade.

Scenario D is the same as Scenario C, but with no PKB through 2012.

Table C-1. Mission Scenarios

Calendar Year	2004	2005	2006	2007	2008	2009	2010	2011	2012
Class 1-1				▽ MSL 09/07	▽ EO 03/08	▽ SP 04/09		▽ ▽ PKB MSR 6/11 11/11	
Class 1-2a				▽ ▽ EO MSL 2/07 9/07		▽ SP 04/09	▽ PKB 05/10	▽ MSR 11/11	
Class 1-2b				▽ ▽ EO MSL 5/07 9/07		▽ PKB 04/09	▽ SP 05/10	▽ MSR 11/11	▽ OP 07/12
Class 1-3	▽ PKB 12/04			▽ MSL 09/07	▽ SP 03/08		▽ EO 05/10	▽ MSR 11/11	
Class 2-1				▽ MSL 09/07	▽ EO 03/08	▽ SP 04/09	▽ PKB 05/10	▽ MSR 11/11	
Class 2-2				▽ ▽ EO MSL 2/07 9/07		▽ PKB 04/09	▽ SP 05/10	▽ MSR 11/11	▽ OP 07/12
Class 2-3	▽ PKB 12/04			▽ MSL 09/07	▽ SP 03/08	▽ EO 04/09		▽ MSR 11/11	▽ OP 07/12
Class 3-1				▽ ▽ EO MSL 2/07 9/07		▽ SP 04/09	▽ PKB 05/10	▽ MSR 11/11	
Class 3-2				▽ ▽ EO MSL 5/07 9/07		▽ PKB 04/09	▽ SP 05/10	▽ MSR 11/11	▽ OP 07/12
Class 3-3	▽ PKB 12/04			▽ MSL 09/07	▽ EO 03/08	▽ SP 04/09		▽ ▽ OP MSR 6/11 11/11	
Class 4-1			▽ EO 01/06	▽ MSL 09/07		▽ PKB 04/09	▽ SP 05/10	▽ MSR 11/11	▽ OP 07/12
Class 4-2		▽ EO 09/05		▽ MSL 09/07	▽ PKB 03/08		▽ SP 05/10	▽ ▽ OP MSR 6/11 11/11	
Class 4-3	▽ PKB 12/04			▽ MSL 09/07	▽ EO 03/08		▽ SP 05/10	▽ ▽ OP MSR 6/11 11/11	
Scenario A (Early PKB)	▼ PKB 12/04			▼ MSL 09/07	▼ EO 03/08	▼ SP 04/09		▼ MSR 11/11	
Scenario B (Delayed PKB)				▼ MSL 09/07	▼ ▼ EO PKB 3/08 12/08	▼ SP 04/09		▼ MSR 11/11	
Scenario C (Early PKB, No SP)	▼ PKB 12/04			▼ MSL 09/07	▼ EO 03/08			▼ MSR 11/11	
Scenario D (No PKB, No SP)				▼ MSL 09/07	▼ EO 03/08			▼ MSR 11/11	

MSL = 2007 Mars Smart Lander; EO = Europa Orbiter; SP = Solar Probe; MSR = 2011 Mars Sample Return; PKB = Pluto Kuiper-Belt; OP = undefined outer planet mission

RPS Assumptions

To evaluate competing strategies, four representative mission scenarios were developed, as discussed above. The potential RPS requirements for the three strategies defined in Section 3 are shown for each of the four representative mission scenarios in Tables C-2 through C-5.

Note that the requirements of RPS units to these missions reflects the potential need for delivery of a flight spare for the first mission to use each type of RPS as discussed in Section 4.3, as well as the potential assignment of one additional RPS unit for redundancy for any mission using Stirling RPSs.

Table C-2. Mission Scenario A (Early PKB launch)

Mission	Launch Date	Potential RPS Requirements		
		All-RTG	All-Stirling	Dual
PKB	12/04	F-5 and/or E-8	F-5 and/or E-8	F-5 and/or E-8
Mars Smart Lander	09/07	2 RTGs + spare	3 Stirling RPSs + spare	3 Stirling RPSs + spare
Europa Orbiter	03/08	3 RTGs	4 Stirling RPSs	3 RTGs + spare
Solar Probe	04/09	2 RTGs	3 Stirling RPSs	2 RTGs *
Mars Sample Return	11/11	2 RTGs	3 Stirling RPSs	3 Stirling RPSs

* NOTE: RTGs were assigned to these potential missions on the basis of lifetime and other mission issues. Depending on future resolution of these issues, Stirling RPS may be a better choice.

Table C-3. Mission Scenario B (EO in '08, PKB in '08)

Mission	Launch Date	Potential RPS Requirements		
		All-RTG	All-Stirling	Dual
Mars Smart Lander	09/07	2 RTGs + spare	3 Stirling RPSs + spare	3 Stirling RPSs + spare
Europa Orbiter	03/08	3 RTGs	4 Stirling RPSs	3 RTGs + spare
PKB	12/08	2 RTGs	3 Stirling RPSs	2 RTGs *
Solar Probe	04/09	2 RTGs	3 Stirling RPSs	2 RTGs *
Mars Sample Return	11/11	2 RTGs	3 Stirling RPSs	3 Stirling RPSs

* NOTE: RTGs were assigned to these potential missions on the basis of lifetime and other mission issues. Depending on future resolution of these issues, Stirling RPS may be a better choice.

Table C-4. Mission Scenario C (Early PKB launch, No SP)

Mission	Launch Date	Potential RPS Requirements		
		All-RTG	All-Stirling	Dual
PKB	12/04	F-5 and/or E-8	F-5 and/or E-8	F-5 and/or E-8
Mars Smart Lander	09/07	2 RTGs + spare	3 Stirling RPSs + spare	3 Stirling RPSs + spare
Europa Orbiter	03/08	3 RTGs	4 Stirling RPSs	3 RTGs + spare
Mars Sample Return	11/11	2 RTGs	3 Stirling RPSs	3 Stirling RPSs

Table C-5. Mission Scenario D (No PKB or SP)

Mission	Launch Date	Potential RPS Requirements		
		All-RTG	All-Stirling	Dual
Mars Smart Lander	09/07	2 RTGs + spare	3 Stirling RPSs + spare	3 Stirling RPSs + spare
Europa Orbiter	03/08	3 RTGs	4 Stirling RPSs	3 RTGs + spare
Mars Sample Return	11/11	2 RTGs	3 Stirling RPSs	3 Stirling RPSs

Appendix D. Mission Requirements

Introduction

The following sections address the key requirements associated with the potential missions in Section 2. In some cases, the requirements are direct; e.g., power levels and durations that must be met by the RPS baselined for that mission. In other cases, the requirements are indirect; e.g., limitations on EMI, vibration levels, etc. imposed by a particular instrument. These requirements are collected and summarized as a group in the final subsection.

Mars Missions

The Mars Exploration Program has adopted a strategy of alternating landed and orbiting missions in subsequent opportunities. Therefore, the two 2003 launches and the planned 2007 and 2011 launches would be surface missions. The goal of the 2007 mission would be to demonstrate precise, safe landing which could be used as a foundation for further surface exploration. The 2011 mission would be targeted at landing sample collection, packaging and launch hardware to return a sample of Martian surface materials back to Earth in 2014. The selection of power system hardware has a direct effect on the lifetime of the mission and the accessible latitudes. RPSs enable multi-year missions anywhere on the planet.

The current reference RPS requirement for the 2007 mission has an estimated average power of 135 W_e. Applying appropriate conservatism for the lack of maturity of this mission design, the power system should be sized at ≥200 W_e for a 2 to 5 year surface mission following a 7 to 13 month cruise phase. Other concepts under consideration might need a RPS as small as 110 W_e. In an effort to reduce non-recurring costs, the surface asset design considered for the 2007 mission should be as common as possible with the surface asset that would perform the sample collection in 2011.

These missions would be launched off an EELV-class vehicle (Delta IV or Atlas V), although options exist for downsizing to an Atlas III. Because of planetary protection concerns, the RPS would have to be compatible with a Level IV-A sterilization that may be as simple as an alcohol wipe down. However, for the sample return mission, a Level IV-B or higher sterilization would be required, typically a hydrogen peroxide gaseous bath. These sterilizations would occur as late in the launch site processing as possible but before pad integration. The RPS would have to be installed off-pad due to the nested nature of Mars entry vehicles where the surface asset is located inside an aeroshell, which could be inside a bioshield. Appropriate measures would have to be taken to insure personnel safety during the operations following RPS mating to the spacecraft. These considerations and the entire launch site flow should be considered when selecting a RPS design.

The location of the RPS inside the aeroshell for cruise and entry would make rejection of waste heat more difficult. High efficiency systems may be able to radiate heat passively to the aeroshell but low efficiency systems would require active thermal fluid loops to move the heat from the RPS to a radiator. Solar power could be used to supplement cruise power needs so optimum RPS efficiency would not be needed during this mission phase.

The Mars entry profile has a variety of loading conditions that may be design drivers. The supersonic entry phase can result in sustained (quasi-static) 10 G loading, followed by a jerk when the parachute inflates. Landing could be by a derivative of the Mars Pathfinder airbags that might result in 20 G landing loads. Once on the surface, the RPS would have to be able to accommodate the Martian environment. The atmosphere is mostly CO_2 at a pressure of 6 to 10 torr. Daily atmosphere and surface temperatures range from 170 to 270K. The atmosphere suspends and deposits a significant amount of dust that effects insolation and thermal surface emissivity. The RPS would be expected to produce close to full power day and night on a stationary or moving platform. As the science complement for these missions has not been determined, it is possible that some instruments could be sensitive to radioactive emissions from the RPS.

Outer Planet Missions

The outer planet missions currently have three proposed missions within their scenario mix; Pluto Kuiper-Belt (PKB), Europa Orbiter (EO), and a third mission yet to be determined. A NASA Announcement of Opportunity (AO) is currently under consideration by Code S for a possible early launch of PKB. Such a launch, if it were to occur, could occur in December 2004 or January 2006. The Europa Orbiter mission is to investigate the ice surrounding the moon of Jupiter, Europa. Launch date for this mission could be 2008 or later.

Due to the unique nature of deep space exploration, RPS is an enabling technology. The cruise period for such missions is normally in the range of 5 to 10 years (depending on trajectory), with the encounter phases being much less. Unfortunately, the encounter phase is normally the highest power mode required. Thus, requirements for outer planet missions are normally stated at end of mission (EOM) when the critical science data is acquired.

For outer planet missions, the power required ranges between 200 W_e for Pluto type (flyby) missions to 340 W_e for Europa Orbiter. This power range should bracket future missions. The EOM condition would be 8 or more years for PKB and 6 or more years for EO with a 30-day encounter.

There are also unique spacecraft integration issues for the RPS. In the case of EO or other proposed orbiter missions, the large propulsion system would require heat input for proper operation. Up to 150 W_{th} would be required. This could either be accomplished by electric heaters (thus increasing the power requirement substantially above the 340 W_e; by Radioisotope Heater Units; or from waste heat from the RPS. In the latter case, the heat rejection temperature from the RPS is a critical parameter, with higher temperatures providing easier integration. For Cassini, this implementation was performed by GPHS-RTGs.

There are also specific launch vehicle requirements to be considered. Due to the large injection energy required for outer planet missions, EELV-class launch vehicles would probably be needed. The dynamic environments for these vehicles both during launch and kick stage burns could be a driver in the RPS selection. The Delta IV H and Atlas V vehicles are being considered for EO and PKB at this time. If the EELV class of vehicle were not certified in time for the early outer planet missions, trajectories that require Earth and Venus gravity assists might be needed. In this case, the RPS would have to withstand the additional albedo and sun heating such a trajectory would impose upon the power source.

All presently planned proposed outer planet missions would operate in space only, although there is a potential Titan atmosphere mission in the post 2011 timeframe.

There are a number of other RPS design requirements driven by potential outer planet missions. For EO, a strong radiation environment would be encountered during the course of the mission. A total dose of up to 6.5 Mrad would need to be endured.

Due to the science nature of outer planet missions, there would also be mild requirements on microphonics and magnetic cleanliness. Microphonic requirements occur due to pixel smear that could occur during imaging. Magnetic requirements may be placed upon the RPS due to the magnetometer and other sensitive magnetic instruments that might be selected as part of an instrument suite for these missions.

Sun-Earth Connection Missions

At this time, the only potential Sun-Earth Connection mission within the 2004-2011 period with a potential RPS requirement is the Solar Probe mission. The purpose of the Solar Probe mission would be to enter the atmosphere of the Sun and to investigate the solar corona and winds. The spacecraft would approach within three solar radii of the Sun's surface, but also ventures as far away as Jupiter.

The power requirements for the mission would include a launch/transorbit injection requirement of 191 W_e, a cruise requirement of 156 W_e over 3 to 5 years, and an encounter requirement of 282 W_e for 59 hours. The higher power requirement during launch would be due to the command and data handling and attitude control systems of the spacecraft providing the guidance and control function for the upper stage. Batteries could meet the launch and encounter power requirements, so the driving requirement for RPS sizing is 156 W_e. It should be noted that a possibility of two passes is under consideration by mission planners, which would effectively double the mission duration requirement.

The launch vehicle for this mission has not yet been selected, but could be one of the following: Delta III, Delta IVH, Atlas IIIB, or Atlas V. No special launch environments or launch vehicle integration issues exist.

A number of indirect requirements would affect the RPS design and implementation for this mission. The first is that RPS could be seen as enabling a two-pass mission, as solar arrays would not survive the close solar encounter. Solar insolation would be a strong driver in terms of both range and magnitude. The flux ratio is over 75000:1, based on maximum insolation of 3000 Suns and minimum insolation of 0.037 Suns. There could also be some significant instrument-based constraints, including a need to keep background radiation low, minimize the magnetic field ($\leq$25 nT), and minimize the AC EMI interference with the spacecraft's plasma wave and search coils.

In general, the Solar Probe mission would fit within the design driving parameters established by the other potential 2004 to 2011 missions, with some additional requirements to meet the extreme range/magnitude of solar insolation and instrument sensitivities to radiation and EMI.

Mission Requirements Summary Table

	Potential Outer Planet Missions		Potential Mars Missions		Potential Sun-Earth Connection Missions
Baseline Missions	Europa Orbiter	Pluto-Kuiper	Mars Smart Lander	Mars Sample Return	Solar Probe
Launch Timeframe					
	2007+	2004+	2007	2011+	2005-2009
Launch Phase					
Power Required	80% of mission req't				≥191W.
Cruise Phase					
Duration	~5 yrs	10+ yrs	0.6-1.1 yrs	0.6-1.1 yrs	3-5+ yrs
Power Required					≥156W.
Encounter/Mission Phase					
Duration	0.1 yrs	fly-by	2.0 yrs	2.0 yrs	59 hrs
Power Required	≥340 W.	TBD	≥200 W.	≥200 W.	≥282W.
Launch Environment					
Acceleration	17.5G		per Delta IV or Atlas V	per Delta IV or Atlas V	
Vibration	per Delta IVH		•	•	
Acoustic	144.9 dB		•	•	
Operational Environment					
Atmosphere	Vacuum	Vacuum	6-10 torr CO_2; dust	6-10 torr CO_2; dust	Vacuum
Temperature			170-270 K	170-270 K	
Radiation	10 Mrad				
Loads	-	-	20G landing	20G landing	
Insolation	3 Suns				3000 Suns
Spacecraft/Payload Accommodation					
Waste Heat	≥150 W				
Radiation			Instruments?	Instruments?	Instruments?
EMI/EMC					Sensitive
Magnetic	•25 nT				•25 nT
Vibration/Microphonics		•35 Nm on 1m arm			
Fairing Access	3 doors				
Sterilization			4A	4B	

Appendix E. Existing Assets

F-5 Issues

History

F-5 was fueled at the Mound facility in December 1984. Acceptance tests were in June 1985. F-5 was the designated flight spare for the Cassini mission. After the Cassini launch, F-5 was returned to Mound and placed in long-term storage. It has remained in long-term storage until only recently. The unit was removed from long-term storage to support upcoming testing.

Preliminary Inheritance Review and System Requirements Review

In support of NASA and JPL, DOE initiated a preliminary inheritance review and a system requirements review held in October 2000. The purpose of this activity was to determine the adequacy of the test and analysis plan, and results to date demonstrate that F-5 will meet the requirements to which it was previously accepted for the Cassini mission. The review will focus on design, qualification, and test history, as well as test and analysis planned to validate F-5 acceptability.

The preliminary inheritance review and system requirements review determined that the tests and analysis plans are adequate to address and provide resolution to the issues. DOE concurrence was provided to proceed with the test and analysis.

Testing

F-5 is currently undergoing testing to determine its suitability for potential future flight applications and in support of the preliminary inheritance review and the system requirements review. While these tests are not for "acceptance" of the unit, they will provide valuable information to evaluate structural integrity of power performance of the unit. The testing is expected to be completed by mid-summer

Case Length Measurement

The case length of F-5 will be measured to determine the amount the case length has changed due to creep and the data used in conjunction with the data from the radiography to support a determination whether or not acceptable pre-load exists on the 18 GPHS module stack. The case length will measure the creep in the aluminum case of the unit.

Radiography

Radiography of the unit will be used in conjunction with the case length measurement. Specifically the radiography will attempt to determine the dimensions of the internal components associated with applying the pre-load to the 18 GPHS module stack.

Vibration Testing

A vibration test of F-5 is currently planned. The test will be performed at the Cassini flight acceptance levels.

Thermal Vacuum

Thermal vacuum testing will be performed on the unit after completion of the vibration test. The thermal vacuum test will provide a performance data point for the unit in simulated space conditions.

Power Predictions

Power predictions for the F-5 indicate a power of 220.2 W_e in December 2004 and power of 176.9 W_e 10.5 years later. The power predictions will be updated after the unit has been through thermal vacuum testing.

Final Inheritance Review and System Requirements Review

The final inheritance review and system requirements review is scheduled for September 2001. The final inheritance review and system requirements review will confirm adequacy of the tests and analysis activities and confirm the flight worthiness of F-5.

E-8

History

E-8 is currently a partially assembled Electrically-heated Thermoelectric Generator (ETG), hence the designation E-8. DOE initiated an E-8 inheritance review and E-8 maintenance activities in September 2000. The inheritance review will verify that E-8 would meet the Cassini mission requirements. The maintenance activities include verification that the E-8 hardware, assembly tooling, planning, personnel, and facilities are acceptable (i.e., capable of producing a flight qualified E-8).

Schedule

If LMA were to get direction from DOE they could be ready to begin assembly of E-8 in October 2001. According to current plans, E-8 could be accepted and delivered to Mound in mid-July 2003.

MHW Generators

Background

Multi-hundred watt (MHW) radioisotope thermoelectric generators (RTGs) were flown on the two Voyager spacecraft and the two LES 8/9 spacecraft. There are six flight-capable MHW generators in storage at Mound. Four of the generators are in shipping containers and two are not. One of the MHW generators suffered some superficial damage when the cover gas was inadvertently released and displaced by air with its associated oxygen content and humidity. This caused internal discoloration of some surfaces and unknown effects on the long-term performance of this generator. The remaining generators are capable of being fueled and readied for flight with few liens, if necessary. Additional safety tests and analyses would likely be required if these generators were to be considered for use by a potential mission. They would need to be modified to use the GPHS module configuration. Lockheed Martin has developed a configuration concept that would accommodate nine GPHS modules as an option.

MHW DOE Costs as Compared to New RTGs

The estimated non-recurring and recurring cost of retrofitting the first and second MHW for flight would be about $71M. The cost of fueled clads would be a significant driver to this cost. If two more MHW generators were needed, the cost would be about $62M more. The estimated recurring cost of the first two new RTGs would be about $70M. Add to this the estimated cost for two more new RTGs at about $59M, and it becomes clear that MHW RTGs are not significantly cheaper than the alternative that could be available during the period of interest.

Possible Uses of MHW Generators

For the mission scenarios considered by the Team, MHW generators are not needed given the availability of F-5 and E-8 GPHS-based SiGe RTGs for near-term missions. The Team considers the MHW generators to be a dead-end investment that should only be considered for use if the early need for RTGs grows beyond the assumed scenarios.

If SiGe were to be chosen over PbTe for a new RTG design, and if a SiGe line could not be qualified in time, the MHW RTGs could be dismantled and their unicouples salvaged for use in a new RTG. This could be a plausible scenario if new RTGs were needed in the 2004 timeframe, but there should not be a problem in the requalification of a SiGe line for 2007.

In summary, the MHW RTGs should be considered a deep backup for the provisioning of near-term missions over and above the scenarios considered by the Team. Alternatively, they could be used as a source of unicouples to build up GPHS-based RTGs if new unicouples were not available in time for deep space missions launched before 2007.

Radioisotope Heater Units

There are 87 fueled and qualified Light Weight Radioisotope Heater Units (LWRHUs) available at LANL and 200 sets of hardware required for assembly. LWRHUs require a small quantity of fuel and therefore are not a factor in the planning options addressed in this study.

Unicouples

There are potentially 2381 SiGe unicouples available for use. There are 873 flight unicouples in bonded storage at LMA, 936 flight-worthy unicouples in Multi-Hundred Watt converters in storage at Mound, and 572 unicouples available in the fueled F-5 also in storage at Mound.

Fine Weave Pierced Fabric Components

There are 19 billets of flight quality fine weave pierced fabric (FWPF) in bonded storage at Mound. These billets will conservatively produce 38 complete sets of FWPF components.

Iridium Clad Vent Sets

There are currently 67 flight quality clad vent sets (CVSs) in bonded storage at Oak Ridge National Laboratory (ORNL) and LANL.

Appendix F. Fuel Availability

Existing Inventory

As of January 2001, in addition to the fuel in F-5 there are 9.2 kg of ^{238}Pu available in the U.S. inventory for use by NASA in space applications. The available ^{238}Pu is a combination of the domestically produced material from the mid-1980s and material from the first and second Russian purchases in 1993 and 1995. The material is currently in storage at the Los Alamos National Laboratory (LANL), and is available for use in NASA missions. After accounting for process losses, the existing inventory is sufficient to produce 18 General Purpose Heat Source (GPHS) modules. The cost of this fuel will be charged to NASA upon delivery of the flight unit at the established price of $2M/kg (or ~$15.84M).

F-5 was fueled in 1985. In keeping with the decay rate of ^{238}Pu, approximately 6.7 kg will remain in F-5 in 2004.

There is an additional 0.153 kg of ^{238}Pu contained in Light Weight Radioisotope Heater Units (LWRHUs). These LWRHUs are spares produced during the Cassini and Galileo missions.

The quantity of ^{238}Pu available for potential NASA missions requiring RPSs is insufficient to meet the projected needs through 2011, thus more would need to be procured or produced in the very near term.

Sources of ^{238}Pu

Domestic Production

On January 26, 2001, the DOE issued a Record of Decision in accordance with the National Environmental Policy Act. The Record of Decision documents the DOE's decision to implement the Preferred Alternative as identified in the Final Nuclear Infrastructure Environmental Impact Statement (NI EIS). The Record of Decision indicated that DOE would reestablish a domestic production capability utilizing existing facilities and operating nuclear reactors. The domestically produced ^{238}Pu would be available for use in space applications in late 2008 or early 2009, too late to be used for any mission prior to 2012. Therefore it is imperative that NASA provides immediate funding to permit the purchase of an adequate supply of fuel for potential missions in the 2007 through 2012 timeframe as recommended in Section 4.3.

The domestic production is intended to produce 5 kg per year of ^{238}Pu for use in space applications. Utilizing an additional operating DOE reactor would complement the production rate by an additional 2 kg.

Russian Procurement

Contract

The DOE has a contract is place with the Russian Federation's MAYAK Production Agency (MAYAK). The contract is a delivery order contract for up to 40 kg of ^{238}Pu. To date, approximately 9.1 kg of ^{238}Pu has been purchased and delivered to the U.S. Under the existing contract the U.S. may purchase up to 30.9 kg of ^{238}Pu. However, limits on the quantity that can be ordered and delivered during the remaining duration of the contract effectively limit the amount purchased to 15 kg. The contract expires in December 2002.

It is worth noting that the cost of domestic fuel, when available, will be more than the current cost of procurement from Russia. Since these costs will be fully chargeable to NASA under the current funding assumptions, it is in NASA's interest to have the DOE acquire and stockpile the needed fuel from Russia at the best possible price.

Contractual Requirements

The ^{238}Pu is provided in the form of PuO_2. The oxide is required to meet a stringent specification set forth in the contract. The specification establishes requirements for ^{238}Pu content, ^{236}Pu content, actinide impurities, and non-actinide impurities. PuO_2 that meets the requirements of the contract's specification would satisfy the current flight specification.

The contract limits the orders of ^{238}Pu to a maximum of 5 kg per six-month period not to exceed 10 kg/year.

The order is due, Freight On Board, at a DOE designated U.S. port of entry, 6 months after the order is placed.

Costs are set at $2K/gram ^{238}Pu isotope in FY01 and are escalated in future years.

Russian Procurements after December 2002

As of December 1997, the current contract was extended for 5 years, i.e., to December 2002. DOE procurement regulations do not allow the contract to be extended again. Consequently, if fuel must be procured after December 2002, a new contract would need to be put into place.

Appendix G. DOE Infrastructure

The DOE has a mandate from the Administration to maintain the infrastructure necessary to design, build, test and deliver radioisotope power supplies for NASA and other users. In keeping with this mandate, the DOE maintains a minimum cadre of skilled and trained personnel at each of the relevant laboratories. This cadre regularly exercises the required processes in order to assure their timely and safe availability as required for NASA or other users.

When a need arises, this cadre is able to step forward immediately and begin the required processing. The customer provides funding for the cost of the materials used in the process, but not the recurring costs of services that can be provided within the resource capability of the infrastructure.

If the need of the customer exceeds the throughput capability of the infrastructure, the DOE can readily staff up and/or provide the added facility capability as required. The cost of labor and facilities, which is in excess of the minimum required by the DOE to maintain the infrastructure, must be mutually agreed to by DOE and the customer and, in the case of NASA, provided for under supplemental agreements to the interagency MOU between the DOE and NASA concerning RPSs for space missions.

Appendix H. Process and Process Limitations

Certain activities and processes conducted at the DOE laboratories are key to the production and rate of production of RPSs. The following sections describe those processes and their throughput limitations based on the existing infrastructure capability.

Oak Ridge National Laboratory

Iridium Clad Vent Sets (CVS)

ORNL procures iridium powder from a commercial source. This iridium is used to make a special iridium alloy (DOP-26) by an arc-melting process. This alloy is rolled into sheets for foils and blanks. Thin foils are used to make vent covers, vent housings and weld shields. Thicker blanks are used to form the two cup components of the iridium clad. The iridium powder is also used to make the frit material used in the helium vent.

The infrastructure staff at ORNL can make up to 10 CVSs per year (including blanks, foils and frits).

Carbon-Bonded Carbon Fiber Insulators

ORNL also produces the carbon-bonded carbon fiber (CBCF) insulator sleeves and disks used around the Graphite Impact Shells in the GPHS module. Two sets of CBCF insulators are required per module. The CBCF is a special 10% dense graphite material with a very low thermal conductivity. It was developed by ORNL.

The infrastructure staff at ORNL can make up to 10 CBCF insulator sets per year.

Los Alamos National Laboratory (LANL)

Scrap Recovery

The Bench-Scale Scrap Recovery Process is operational and can produce up to 300 g of ^{238}Pu per month in the form of fresh purified oxide powder.

The Full-Scale Scrap Recovery Process is scheduled to be operational in April 2002. The Full-Scale process will produce up to 500 g of ^{238}Pu per month as purified oxide powder. The full-scale operation will require two additional staff members.

Bench-Scale and Full-Scale Scrap Recovery operations could be run concurrently to produce up to 800 g of ^{238}Pu per month; but would require four additional staff members.

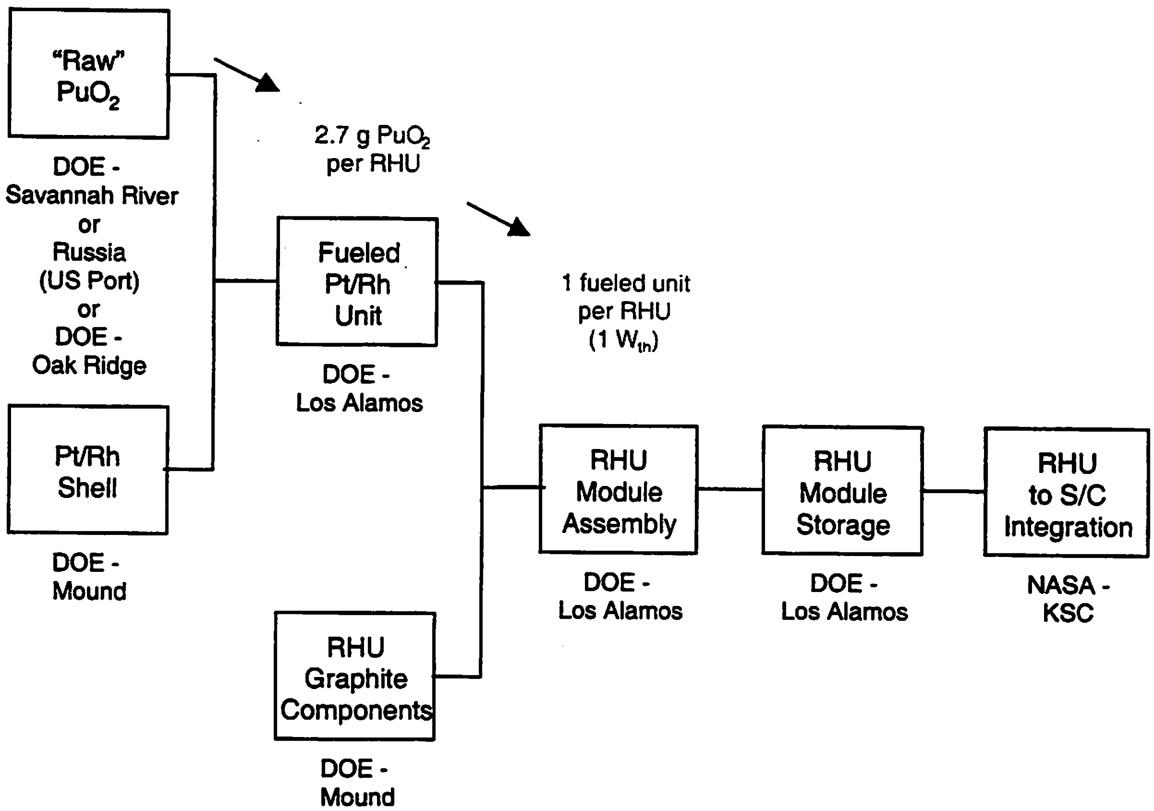
Fueled Clads

The current infrastructure staff at LANL can produce fueled clads at the rate of 4 per month (10 months/CY).

Radioisotope Heater Units (RHUs)

LANL produces fuel pellets for the 1-Watt RHUs, encapsulates them in Pt 30 Rh clad components made by Mound, and then assembles them in graphite (FWPF and pyrolitic graphitic) components from Mound. The assembled RHUs are stored at LANL until needed by NASA for a mission.

There are 87 RHUs in stock at LANL. Over 200 sets of RHU components are also available. The current LANL staff can press 16 RHU pellets at a time.



Radioisotope Heater Unit Production Process

Mound – GPHS Assembly, Generator Fueling, and Testing

Mound is responsible for the assembly of the GPHS modules, the assembly and test of the RPS, shipment of the RPS to the user launch site, and care of the units while at the launch site.

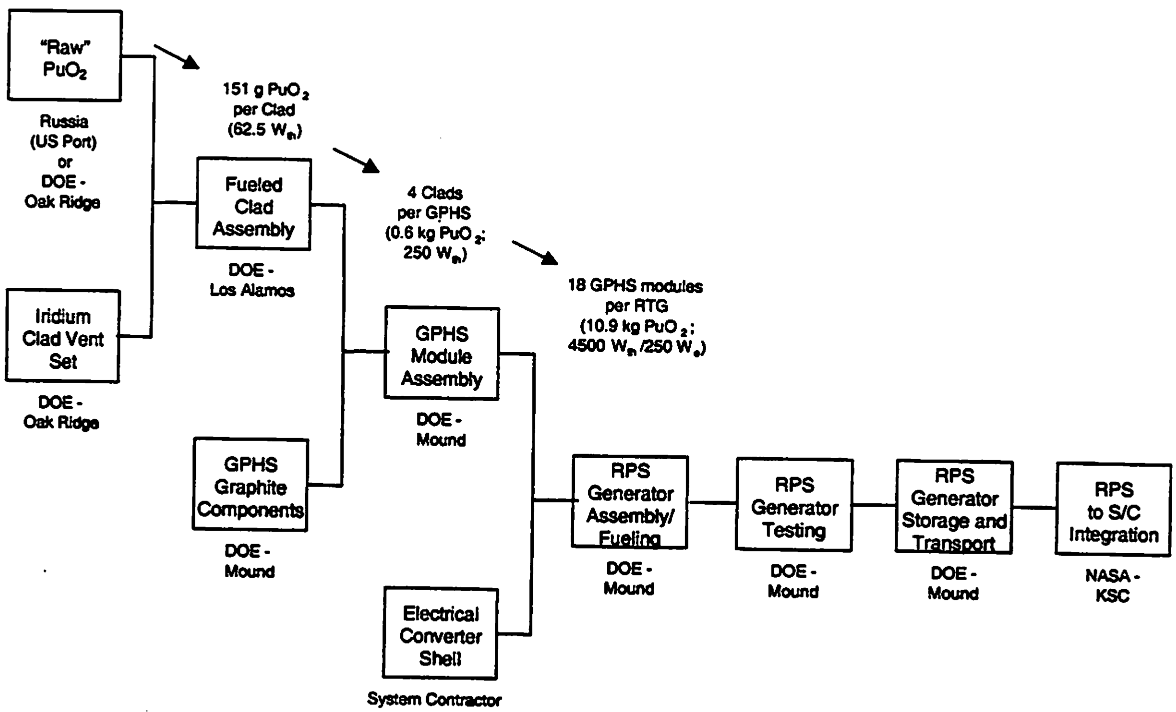
GPHS Module Assembly

The infrastructure at Mound supports the assembly of up to 18 GPHS modules a year. These modules can be assembled into an RPS unit in one month. GPHS module assembly is not considered to be driving the schedule at Mound or hold any schedule risk. With additional staffing, increased production rates of GPHS modules, assuming fueled clads are available from LANL, can be easily achieved.

Once the modules are assembled they go through the oxygen reduction treatment in the module reduction and monitoring facility (MRMF) at Mound. The MRMF is capable of holding up to 100 modules, well above any projected requirements, and the process takes three months.

RPS Assembly and Acceptance Testing

The infrastructure at Mound supports the assembly and acceptance testing of one RTG per year. This is broken into two months for assembly of the unit and four months for acceptance testing. In addition, there are two months allotted at the end of the acceptance testing for data package preparations, buy-off meetings, and final acceptance by DOE.



Radioisotope Power Source Production Process

RPS Testing

Vibration

Mound is maintaining the capability to perform vibration acceptance testing and low-level shock testing for RPSs. The vibration testing system is functional and maintained at regular intervals. Software upgrades are being maintained and serviced.

Thermal Vacuum

Mound maintains the capability to perform thermal vacuum testing for RPSs. Mound has two identical thermal vacuum chambers that are capable of performing the testing function, used for long-term storage or for life testing. Recently one of these two thermal vacuum chambers held the F-5 unit in long-term storage.

Magnetic Field Determination

The magnetic field determination capability is being maintained at Mound. The magnetometers used in the actual testing belong to NASA and are provided to Mound when required.

Mass Properties

The mass properties capability is being maintained.

Radiation Field Determination

Capability exists at Mound and is being maintained.

RPS Transportation

Mound is the custodian of the USA/9904/B(U)F-85 RTG Shipping Container. The shipping container is being maintained in a certified condition and could be used to ship RPSs when needed.

Appendix I. Safety and Launch Approval

Safety is an integral element in the design of all space RPSs and the safety of each RPS design is driven by the safety attributes of its heat source. The General Purpose Heat Source (GPHS) module provides multiple layers of fuel containment for the impact, ablation, overpressure, fragment and fire environments associated with launch vehicle accidents and atmospheric reentry scenarios. In the event a release does occur, the mobility of the fuel is limited. The fuel is a tough, highly insoluble ceramic oxide.

The response of GPHS modules to these accident environments was evaluated through testing and modeling over the course of the Galileo, Ulysses, and Cassini development programs. The test data and response modeling indicated low mission risks.

System Safety

For this study, the systems under consideration are the GPHS-RTG, the new RTG, the GPHS version of the MHW-RTG, and the Stirling RPS. While there are some differences in the failure modes and accident response modes of these systems, their safety is not expected to be a discriminator in terms of recommending a RPS provisioning strategy for the reasons discussed below.

1. All the systems would be expected to exhibit a similar performance for reentry accidents. For reentry, the GPHS modules would separate from the spacecraft and from the housing of the GPHS-RTG. The GPHS module is designed to withstand an Earth orbital reentry, and also is expected to provide containment in reentry scenarios even for hyperbolic Earth swingby trajectories. Similarly, the outer structure of the new RTG would be expected to release the GPHS modules. Lockheed Martin has performed analyses indicating that the MHWs would also release their GPHS modules. For the Stirling RPS, it is a contractual requirement that the Stirling structure be designed to release the modules during reentry.

2. The response of these RPS concepts is expected to be similar for exposures to fragments and fire environments.

3. For conventional ELV launches, the predicted accident overpressure environments have been low and do not represent a threat to the GPHS modules. The response of all RPS designs to overpressure should be similar because the RPS casings are expected to accelerate with the modules rather than into them as projectiles.

4. Testing and hydrocode modeling has demonstrated that for GPHS-RTGs, during the low probability scenarios of an end-on impact of a stack of modules on a hard surface, only the first few modules absorb sufficient energy to result in damage to a few of the clads. These scenarios have been analyzed for past missions and were found to have acceptably low risks. The new RTG would be expected to respond in a manner similar to the GPHS-RTG during an impact scenario. Also, hydrocode analysis of GPHS version of the MHW-RTGs indicates that their safety performance for impact scenarios would be similar to that of the GPHS-RTG.

5. A Stirling RPS has components that are mounted adjacent to the GPHS modules to facilitate heat transfer. The proximity of these components to the GPHS modules might affect the fuel clad containment in an impact. As the design matures, the testing of the Stirling RPS design,

as appropriate, would follow. After the Stirling RPS is developed, some additional safety testing and limited system design modifications may be appropriate depending upon the outcome of impact modeling. A preliminary hydrocode analysis of one Stirling converter/GPHS configuration indicated a response similar to a GPHS-RTG.

6. Each GPHS-RTG has hundreds of thermocouples, so a failure of a few thermocouples has an insignificant impact on the thermal environment of the fuel clads. With Stirling, a single failure could produce a larger change in the fuel clad thermal environment. The design of the Stirling RPS must ensure that this thermal condition does not compromise the containment capabilities of the fuel clads.

While differences exist between the concepts under consideration, most of the safety features of the systems are intrinsic in the design of the GPHS module and the GPHS module is common to all concepts. For this reason, the environmental and launch approval processes associated with each of these power systems is expected to be comparable.

Environmental and Launch Approval Considerations

Program Definition and Implementation

- Baseline the use of RPSs/RHUs only in applications that enable accomplishing mission science objectives or for missions that lack reasonable non-nuclear alternatives.
- Baseline inner solar system swingby trajectories [for missions using RPS/RHUs] only when they enable accomplishing mission science objectives.
- Select launch vehicle 60 months prior to launch. Allow for early procurement of launch vehicles for missions potentially requiring RPSs/RHUs to avoid having to prepare multiple nuclear launch safety approval process databooks (i.e., extensive documents that describe in detail a launch system including its potential accident scenarios, environments and probabilities).

RPS Design

- Develop increased electrical conversion efficiency, modularized RPS that allows for the optimal sizing of spacecraft power and thermal control systems such that PuO_2 requirements are minimized.

Launch System/Mission Design Risk Mitigation

- Develop and maintain launch system (i.e., mission, launch vehicle, and space vehicle) safety implementations that reduce or mitigate the threats from credible accident scenarios, e.g.,
    - Systems that mitigate environments presented by solid propellant upper stage
    - Systems that enhance Range Safety monitoring of launches involving RHUs or RPSs (e.g., Laser Illumination System and Telemetry Advisory System).

- o Systems that reduce the potential for reentry accidents (e.g., Sufficiently High Orbit Capabilities).

Radiological Contingency Planning

- In concert with other federal, state and local government agencies, maximize multi-mission coordination and continuity in the development and implementation of launch and mission radiological contingency plans.

Safety Analysis

- Initiate preparation of environmental impact statement-supporting launch system databooks at the earliest indication of a launch system's consideration for launching a RPS/RHU mission.
- Identify and exploit opportunities for coordinating multi-mission databooks, environment test programs, safety analyses and safety testing.
- Develop and maintain the expertise, methods and data to allow parallel preparation of multiple environmental document supporting studies and SARs.

Launch Nuclear Safety Review

- Initiate early coordination with U.S. international partners (in missions involving RPSs/RHUs) to align and satisfy U.S. and foreign partner 'launch approval' requirements.

Risk Communication

- Develop and implement a proactive risk communication plan to address potential executive branch, congressional, international and public concerns about RPSs/RHUs.

Appendix J. Redundancy

Background

Redundancy is not intended to deal with wearout modes, and the following discussion assumes that wearout modes have been shown to not be a factor. Wearout modes can exist when there are no moving mechanical parts, and are a primary concern in devices with moving elements. The concern over spacecraft component wearout modes is usually removed by implementing a test program demonstrating large margins against required lifetime. Known characteristics of the power systems (e.g., the reduction in RTG output power with time) are modeled in selecting the power system design for the mission.

The following discussion assumes a very sound quality control process is implemented in all phases of development from part manufacture through final power system testing. This is mandatory, and redundancy is in no way a substitute for it.

RTG Power System

Redundancy in RTG designs is provided by use of series-parallel string thermocouples, so significant loss of power occurs only when both thermocouples in a two-couple element fail. Since the probability of a thermocouple failure is very low (of the order of 10^{-4} during a mission), the probability of both thermocouples in any of the many two-couple elements failing is very low ($<<10^{-4}$). As a result, redundancy at the RTG level does not provide a substantive increase in the probability of mission success and is not an effective use of resources. Experience on several past space missions (and in other RTG designs) support this conclusion.

Stirling Power System

A Stirling RPS requires control electronics and the converter has moving elements; both of these characteristics introduce potential failure modes. A Stirling RPS is therefore conceptually similar to other spacecraft electromechanical devices having these two characteristics (e.g., reaction wheels, momentum wheels, and inertial measurement units). The failure modes of these spacecraft elements require redundancy to achieve adequate reliability unless the failure probability is low enough to be ignored (which is not a realistic assumption).

Units with both control electronics and moving parts typically require redundancy to provide adequate reliability for control electronics failures only (which are more easily estimated); proper implementation of this redundancy then also provides some protection against mechanical failures (whose rate is harder to quantify). While a Stirling RPS control electronics design has not been finalized, the functional complexity is similar to other spacecraft electromechanical units that require a redundant element independent of mechanical failures.

The typical Stirling RPS would probably consist of two controller and converter assemblies with a vibration compensator to be used if one converter fails. Single controller and converter assemblies with integrated vibration compensators also appear practical. This combination would enable "n+1 for n" converter and controller assembly redundancy in all missions. One redundant converter and controller assembly would be required to provide RPS reliability ≥ 0.99 for all potential missions in the reference set if the Stirling converter/controller MTBF were at least 500 to 1000 years.

At the present time there is insufficient data available to provide a useful estimate of the failure rate of a Stirling RPS. Note that the n+1 for n redundancy is satisfactory only when the failure rate is relatively small; multiple spare elements could be required if a Stirling RPS MTBF greater than 500 years could not be assured. Therefore, a Stirling RPS development effort should include getting such data as a critical element of the development program.

A representative Stirling converter design has a nominal power rating of 55 watts (actual power output would depend on operating conditions). Then the "n+1 for n" converter and controller assembly redundancy would imply an "all converters operating" power level about 55 watts above the mission requirement. However, the probable operating condition would usually be a reduced power output from each converter with an associated decrease in operating temperature to minimize stress on the Stirling converter. The characteristics of a Stirling RPS (as with some types of electronics units) make this active redundancy more practical than standby (i.e., non-operating) redundancy. This standby redundancy implementation can lead to misunderstanding of the redundancy because there is no non-operating converter, but the concept is to concentrate on the fact that a mission would be successful even if one converter failed, and to not be confused by how many converters would operate in the absence of failure.

Appendix K. RPS Converter Technologies

RPS Technologies for Near Term

The Terms of Reference given to the Team preclude consideration of advanced Stirling, i.e., thermoacoustic Stirling, AMTEC, and advanced segmented thermoelectrics converter technologies as options for missions in the 2004 through 2011 timeframe. Given the current status of these technologies, and the uncertainties in the projected cost and schedule estimated to bring them to flight readiness status, this constraint is prudent and the Team is in full agreement with it. Therefore the technology options considered for potential missions through 2011 are limited to use of the existing assets (F-5, E-8, and MHWs), a new RTG (either SiGe or PbTe/TAGS), and the current Stirling RPS concept.

The inherent attributes and the attendant advantages and potential limitations of SiGe, PbTe/TAGS, and Stirling technologies are described in the following sections.

SiGe Thermoelectrics

SiGe thermoelectric material has a high melting point, low vapor pressure, and a modest figure-of-merit. This combination of properties allows SiGe thermoelectric converters to operate over a wide temperature range, e.g. 1000 C to 300 C, producing a thermoelectric efficiency of 7.7%. The low vapor pressure allows the SiGe thermocouple to operate in a vacuum with an acceptably low power degradation rate over very long lifetimes.

The ability to operate in a vacuum allows the use of multifoil insulation if the converter is sealed prior to launch and opened to space vacuum via a highly reliable pressure relief device. A new sealed SiGe RTG, with provisions for venting the helium generated by the fuel decay, would be needed for operation in a planetary atmosphere, such as on Mars.

The relatively high cold junction temperature leads to small, light-weight radiators making SiGe RTGs attractive for higher-powered units for use in deep space missions.

The last 19 RTGs flown on U.S. space missions over the last 25 years were based on the SiGe unicouple technology. Table K-1 contains the characteristics of the SiGe RTGs that have been used successfully in space.

A major attribute of all RTGs is the large number of thermocouples that can be wired in series-parallel strings to provide a high level of reliability and a graceful power loss if individual thermocouples should fail. RTGs are completely static conversion units with no rotating or oscillating components. They are low voltage, high direct current devices that can be easily integrated with spacecraft power systems.

The low conversion efficiency requires a larger fuel inventory which produces more waste heat to either reject to space or to supply to the spacecraft for thermal control. The larger heat source is heavier and costlier, and emits a higher level of gamma and fast-neutron radiation.

To date, efforts to segment or cascade SiGe thermocouples with other materials have not demonstrated performance advantages. Since SiGe reacts with most metals at its high hot junction temperature, a SiMo hot shoe is used and a radiation gap is required between it and the heat source. This necessitates cantilevering the unicouples from the cold end. A spring-loaded thermocouple, such as in lower-temperature telluride converters, provides the potential for a more robust converter to withstand higher shock and vibration loads.

Table K-1. RPS System Characteristics

Characteristics	PbTe/TAGS RTGs			SiGe RTGs		Candidate Systems	
	SNAP 19 (Pioneer Class)	SNAP 19 (Viking Class)	HPG-150	MHW RTG	GPHS RTG	New RTG	Stirling RPS
History							
Missions Flown	Pioneer 10 (1972-) Pioneer 11 (1973-95)	Viking Lander I (1975-80) Viking Lander II (1975-78)	Not flown (Qual unit)	LES 8 (1976-) LES 9 (1976-) Voyager 1 (1977-) Voyager 2 (1977-)	Galileo (1989-) Ulysses (1990-) Cassini (1997-)	(Outer Planets) (Mars Surface) (Solar Probe)	(Outer Planets) (Mars Surface) (Solar Probe)
Power							
Power Output (BOM)	41.2 W_e	42.5 W_e	169 W_e	157 W_e	285 W_e	~120-175 W_e	~110-130 W_e
Voltage	4.4 V_{dc}	4.4 V_{dc}	15 V_{dc}	28-30 V_{dc}	28 V_{dc}	28 V_{dc}	28 V_{dc}
Size							
Mass	13.6 kg	15.2 kg	36.3 kg	38 kg	56 kg	~24-44 kg	~18-33 kg
Dimensions	50.8 D x 28.4 L (cm)	58.4 D x 39.6 L (cm)	84 D x 54 L (cm)	(in MHW report)	40.6 D x 112 L (cm)	TBD	TBD
Fuel							
Configuration	IRHS	IRHS	IRHS	MHW	18 GPHS	8-10 GPHS	2 GPHS
^{238}Pu Mass	1.1 kg	1.2 kg	4.3 kg	4.1 kg	8.0 kg	3.5-4.4 kg	0.9 kg
Thermal Energy	645 W_{th}	685 W_{th}	2414 W_{th}	2350 W_{th}	4250 W_{th}	2000-2500 W_{th}	500 W_{th}
Figures of Merit							
Specific Power	3.0 W_e/kg	2.8 W_e/kg	4.6 W_e/kg	4.1 W_e/kg	5.1 W_e/kg	~4-5 W_e/kg	~4-6 W_e/kg
System Efficiency	6.4%	6.2%	7.0%	6.7%	6.7%	~6-7%	~23-25%
Operational Environment							
Atmosphere	Vacuum	Mars Surface	Vacuum	Vacuum	Vacuum	Vacuum/ Mars Surface	Vacuum/ Mars Surface
Sterilization Level	n/a	Heat 150°C for 60 hours	n/a	n/a	n/a	4A/4B	4A/4B

PbTe/TAGS Thermoelectrics

TAGS, a p-type thermoelectric material, when used with an n-type PbTe material forms a telluride couple which has a relatively high figure-of-merit. The hot junction operating temperature of the telluride material is limited to ~550°C (for low degradation over long lifetimes). Thermoelectric efficiencies of at least 8% can be achieved with a cold junction temperature of 165°C. This lower cold-side temperature requires larger and heavier radiators for use in deep space missions and tends to limit optimum power levels for telluride RTGs.

More efficient (~10%) telluride converters can be made by segmenting BiTe cold segments with the PbTe/TAGS thermoelements, as has been done for commercial generators. Since BiTe is limited to <250°C, the radiator size and weight must be traded-off against the added power to determine if use of the BiTe segment is worthwhile.

Telluride converters require a cover gas to control sublimation/evaporation and vapor transfer. This permits the use of a bulk insulation and provides a means for power flattening and helium management within a telluride RTG.

All 28 of the RTGs flown on US space missions between 1961 and 1975 were based on telluride thermoelectrics. Table K-1 contains the characteristics of the PbTe/TAGS RTGs used on Pioneer 10/11, Viking Landers 1 and 2, and the HPG-150 RTG that was tested under flight qual levels, but not used in space.

Both SiGe and PbTe/TAGS RTGs have demonstrated reliable operation for over 20 years in space. The telluride RTGs operated for several years on Mars.

Stirling

The Stirling RPS offers significant advantages in terms of thermal conversion efficiency (reducing the amount of ^{238}Pu required for a given power level), and the development of a working system is technologically feasible. However, the development uncertainties existing at this time could easily manifest themselves as mass impacts and the possibility of significant spacecraft impact from dealing with the existence of failure modes.

Advantages

The advantage of a Stirling RPS is in conversion efficiency; a Stirling RPS would require much less plutonium than an RTG requires to produce the same power. While there are uncertainties in the final system performance of a Stirling RPS, the improvement would be about a factor of four. This would represent a reduction in fuel costs that is very significant in the long run and desirable for all scenarios, although the difference in total RPS costs in the near term (i.e., through 2011) appears to be too small to be critical to the affected programs.

Characteristics/Design Issues

The Stirling RPS has much less waste heat than an RTG of similar power; this could be an advantage or disadvantage, depending on the mission.

The safety issues associated with the Stirling RPS have not been worked in detail and are somewhat uncertain. Any Stirling RPS design characteristic that presents a new hazard to the GPHS modules would be addressed in the development phase.

It appears that vibration from the Stirling converters could be eliminated as a significant concern through active compensation. This compensation is normally achieved by synchronized running of the converters in pairs, but could be implemented on a single converter with a separate vibration compensator.

Spacecraft interface issues with a Stirling RPS have received only limited attention, so it is possible that there are significant unknown implementation issues.

The recovery to normal operations after an internal RPS failure is an issue that would require close attention during the architecture design phase. The fault protection problems that can arise from power loss can probably be dealt with if the Stirling RPS controller configuration were properly selected.

Significant Risks and Concerns

It is not now clear whether wearout modes are a concern for the Stirling converter, although preliminary results are encouraging. Significant wearout modes would pose a very significant threat to the viability of a Stirling RPS.

The Stirling RPS requires control electronics and the converter has moving elements; both of these features introduce potential failure modes.

The Stirling converter, as a component of the Stirling RPS, has had considerable development, but the Stirling RPS design is relatively immature at the system level. Since only about one-third of the total system mass is in the converters with about two-thirds in other system elements, the assessment of Stirling RPS system specific power (w/kg) has significant uncertainty at this time. Preliminary designs indicate that a Stirling RPS would at best have little or no specific power advantage over an RTG, and adequate accommodation of failure modes may make specific power a disadvantage. This lack of specific power improvement does not appear to be a significant problem for the proposed Mars landers, but is a concern for most proposed missions, and so is a significant lien on the Stirling RPS as a long term RPS solution. Since most of the mass of a Stirling RPS would not be in the Stirling converter, this solution is unlikely to be much improved by converter technology advances.

RPS Technologies for 2011 and Beyond

A number of advanced power conversion technologies are being pursued for potential application to space missions for 2011 and beyond. A team of NASA, DOE, industry, and university technologists assessed advanced RPS converter technologies for far-term NASA missions (see Reference 7). These technologies are focused on improving several performance issues associated with existing RPS technologies, particularly on increasing system specific power (W_e/kg) and increasing conversion efficiency (W_e output/W_{th} input) (See Table K-2, taken from Reference 7). As reported in Reference 7, a total of six technologies were examined with the conclusion that three are promising for further development. The technologies are advanced Stirling, advanced segmented thermoelectrics (AS-TE), and Alkali Metal Thermal-to-Electric Conversion (AMTEC). The descriptions of these advanced technologies in the following subsections are based on the information in Reference 7.

Table K-2. Specific Power and Conversion Efficiency

	TRL	Specific Power (W/kg)	System Efficiency (%)
Baseline RPS Technologies			
PbTe/TAGS RTG	8	3.0	6.4
SiGe RTG	8	4.5	6.5
Stirling RPS	4	4.1-6.0	23-25
Advanced RPS Technologies			
Advanced Stirling	2	7.5	25
Segmented Thermoelectric	2	8.9-10.2	13-15
AMTEC	3	5.6-8.8	14.5-16.7

Advanced Stirling

The advanced Stirling converter would use thermoacoustic or other advanced dynamic energy conversion methods to reduce system mass in order to increase system specific power. The technology would still involve a Stirling heat converter and AC/DC converter, and would require a linear alternator to convert mechanical energy into electrical energy. However, the need for a physical piston could be obviated through the use of thermoacoustics. Further improvements in mass and efficiency could be possible through improved design of radiators and control electronics.

While the advanced Stirling technology potentially represents a significant improvement in specific power over the baseline Stirling technology, the basic spacecraft integration and reliability issues of Stirling remain. These include the lack of graceful degradation, the need for an active controller, and potential vibration associated with the mechanical cycle.

AMTEC

AMTEC involves an electrochemical cell in which electrical power is produced by the conduction of sodium ions through a solid electrolyte under a pressure differential. Although fluid moves through the system, there are no mechanical moving parts and the system produces DC power with no vibration. Relatively small radiators are required and waste heat is delivered at approximately 300 C, which may be of benefit to spacecraft thermal design.

The major emphasis is on increasing specific power and conversion efficiency. Specific power is projected to be better than baseline Stirling RPS but worse than AS-TE, while conversion efficiency is better than AS-TE but worse than Stirling RPS (see Table K-2). Both specific power and efficiency will need to be demonstrated convincingly in the technology development phase.

AMTEC cells have not yet met their predicted efficiency ratings in laboratory tests. It is not clear that this phenomenon is localized to AMTEC or if all advanced RPS technologies will have descoped actual performance in comparison to predicted performance. Material compatibility is a major challenge and concerns about AMTEC fluid recirculation in a 0-G environment have not yet been resolved, although a flight demonstration on the Space Shuttle is under consideration.

Advanced Segmented Thermoelectrics (AS-TE)

The advanced segmented thermoelectric converter would build upon the current unicouple RTG design approach, but using instead a series of advanced materials tailored for particular temperature ranges. Short lengths of different materials are bonded together in series forming segments, such that each segment is at its peak efficiency temperature band between the hot side and the cold side. This approach is analogous to multi-junction cells in photovoltaic solar arrays. The major obstacles for AS-TE technologies are production-related, particularly in bonding dissimilar materials and ensuring that diffusion does not occur across material boundaries.

AS-TE offers improved conversion efficiency and specific power while retaining the advantages of existing thermoelectric systems. The efficiency improvements are somewhat more modest than those of the advanced Stirling systems while the specific power is significantly better (see Table K-2, taken from Reference 7). AS-TE technologies promise easy integration into existing spacecraft architectures, as they produce DC power and have no moving parts. It may even be possible to perform direct replacement of existing unicouples with AS-TE unicouples. The graceful degradation associated with existing thermoelectric technologies would also be expected from AS-TE.

Appendix L. Cost Estimate and Schedule Data

A cost estimate and schedule was developed for each of the three candidate provisioning strategies for each of the four mission scenarios with total costs per fiscal year shown Tables L-1 through L-4).

The estimated costs required for the System Integration Contractor were based on past experience and engineering judgment. The System Integration Contractor cost and schedule estimates are the least developed, especially the non-recurring costs and schedules for developing the Stirling RPS and the new RTGs.

The recurring costs for fabricating a Stirling RPS were estimated to be at $6 million per unit and $8 million per unit for a new RTG. Project integration costs including costs for spacecraft integration, management, quality and reliability assurance, laboratory coordination, and launch site activities were estimated to be $12 million per mission. The cost for the System Integration Contractor will become firm when the Stirling RPS and new RTG procurements are completed.

The number of heat source components needed for each of the mission scenarios and strategic paths in excess of the number that can be provided by the DOE's infrastructure base program was determined. The costs for providing these additional components above those produced within the infrastructure base program were estimated assuming a levelized production rate starting at the beginning of fiscal year 2002. The levelized production rates are especially important at LANL to reduce fluctuations in staffing requirements. It takes 1 ½ to 2 years to bring new personnel on board at LANL due to the need to obtain Q clearances and to be enrolled in the Personnel Security Assurance Program before being allowed to work in plutonium processing facilities.

The training costs for staff increases are included and therefore changes in plans and requirements may incur significant costs even if they can be accommodated. Therefore, it is important to limit fluctuations in plans and requirements. This difficulty of staffing changes has two consequences. The first is that it represents additional costs. The second is that changes in plans and requirements may be difficult or impossible to accommodate.

The spreadsheets include all costs above the infrastructure program for fabricating clad vent sets and insulator sets at ORNL. The DOE infrastructure can provide only one fueled clad per mo during a 3 1/2 year period (2004 to 2007). At other times the infrastructure program produces a rate of four fueled clads per month. The cost of any fueled clads required above the capabil described above are included.

The largest strain on the DOE infrastructure occurs at Mound, which must assemble, test, and ship up to 14 RPS units in a 3 ½ year time period starting in late 2006 through early 2009. Si the infrastructure staffing level can produce one RPS per year, funding augmentation to the b program infrastructure is required to accommodate this higher volume production. To accommodate any of the mission scenarios and strategic paths currently proposed requires increased staffing level. The costs associated with the one-year lead time for hiring and training of Mound personnel are included. Costs above the infrastructure program were assessed to NASA.

As a first-order validation of these estimates, the cost and staffing levels required to meet each mission scenario and strategic path requirements were compared to the actual costs and staffing levels required for the Cassini mission. The estimated costs and staffing levels compared favorably and, in general, were lower than those for Cassini. This decrease in cost was expected since DOE has maintained a core of trained staff and has maintained the facilities in operation by continuing a low level of production while improving production processes.

Estimated Total Cost by Outcome

Estimated total cost profiles for the All-RTG Strategy and the three possible outcomes of the Dual Strategy were developed from the spreadsheets in this appendix and are presented in the following tables. The tables include projected total annual costs for each potential outcome for the four illustrative scenarios.

Table L-1. Estimated Total Costs for All-RTG Strategy ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	31	56	60	92	65	58	32	17	14	7	2	433
B (Delayed PKB)	23	46	48	61	82	71	47	19	13	6	2	418
C (Early PKB, No SP)	31	55	61	86	43	37	22	15	11	6	2	369
D (No PKB, No SP)	22	39	41	56	41	38	31	14	11	6	2	301

* Same as Table 3.2-1

Table L-2. Estimated Total Costs for Dual Strategy/RTG Outcome ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	44	74	74	91	67	58	32	17	14	6	2	479
B (Delayed PKB)	38	65	61	61	82	71	37	26	12	6	2	461
C (Early PKB, No SP)	44	74	74	86	43	37	22	15	11	6	2	414
D (No PKB, No SP)	35	57	56	56	41	38	30	14	11	6	2	346

Table L-3. Estimated Total Costs for Dual Strategy/Hybrid Outcome ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	44	71	75	87	70	47	23	19	14	6	2	458
B (Delayed PKB)	36	65	65	64	76	63	33	20	14	6	2	444
C (Early PKB, No SP)	44	70	74	85	42	31	14	14	12	6	2	394
D (No PKB, No SP)	34	54	58	51	39	32	16	12	10	6	2	314

* Same as Table 3.3-1

Table L-4. Estimated Total Costs for Dual Strategy/Stirling Outcome ($M)

Scenario	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
A (Early PKB)	42	65	57	69	50	41	25	17	14	6	2	388
B (Delayed PKB)	27	40	40	50	73	58	34	18	15	6	2	363
C (Early PKB, No SP)	42	62	55	66	35	30	14	15	13	6	2	340
D (No PKB, No SP)	27	40	39	45	35	33	18	13	12	6	2	270

Comparative Total Costs by Scenario

The estimated cost profiles for the All-RTG Strategy and each of the three potential outcomes of the Dual Strategy are compared for each mission scenario in Tables L-5 through L-8. In addition, the estimated costs are presented graphically in Figures L-1 through L-4, both by year and cumulatively.

For Scenario A the total estimated costs for the possible outcomes vary by $91M with the lowest total cost being for the Stirling Outcome of the Dual Strategy and the highest for the RTG Outcome of the Dual Strategy. The All-RTG Strategy falls in the middle range of total cost, comparable to and slightly lower than the Hybrid Outcome of the Dual Strategy. The effect of developing both systems can be seen in the chart of total costs by year, in which the All-RTG Strategy incurs a significantly lower annual cost in the first three years, reflecting the absence of Stirling RPS development. These relative costs form the same pattern for all of the scenarios, although the absolute costs vary (see Tables L-6 through L-8).

Table L-5. Scenario A (Early PKB) Estimated Costs ($M)

Strategy/Outcome	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
All-RTG/RTG	31	56	60	92	65	58	32	17	14	6	2	433
Dual /RTG	44	73	74	91	67	58	32	17	14	6	2	478
Dual /Hybrid	44	71	75	87	70	47	23	19	14	6	2	458
Dual /Stirling	42	65	57	69	50	41	25	17	14	6	2	388

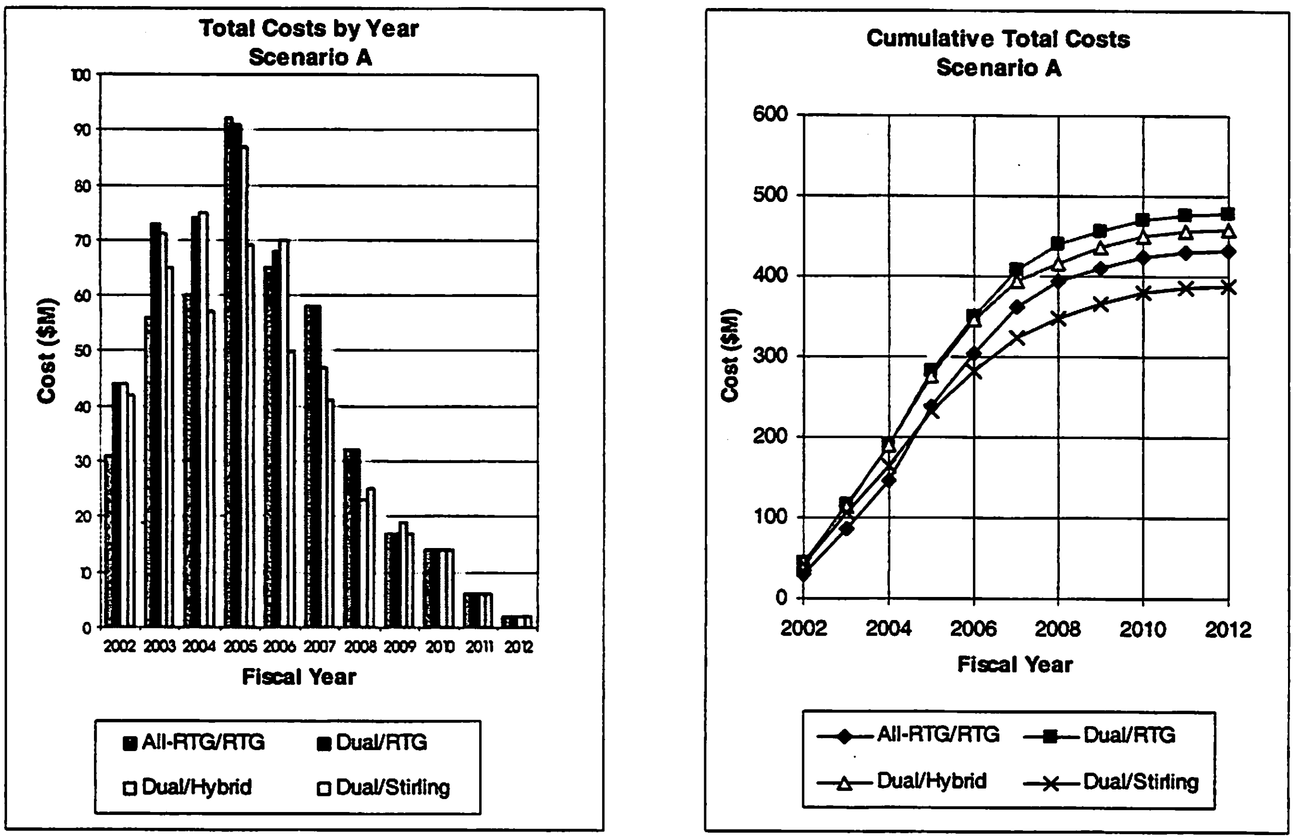
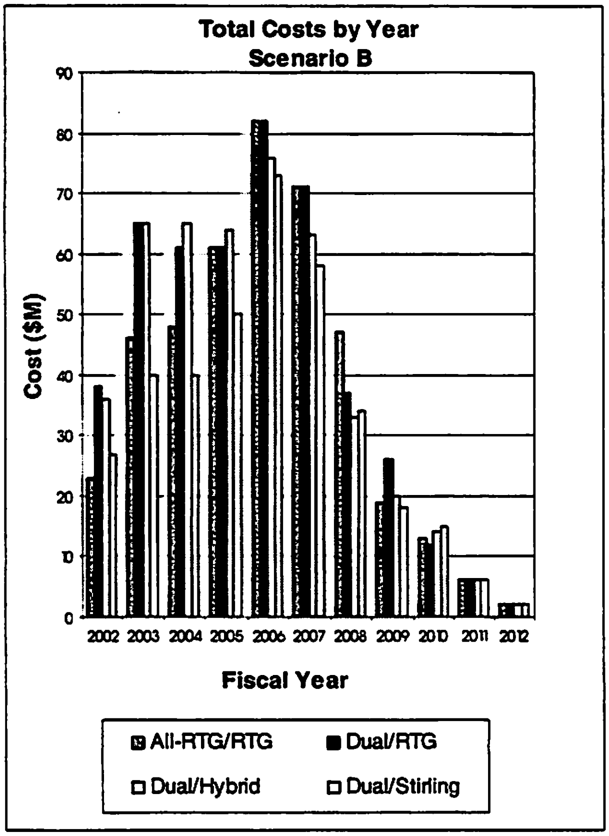


Figure L-1. Scenario A (Early PKB) Estimated Costs ($M)

Table L-6. Scenario B (Delayed PKB) Estimated Costs ($M)

Strategy/Outcome	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
All-RTG/RTG	23	46	48	61	82	71	47	19	13	6	2	418
Dual /RTG	38	65	61	61	82	70	37	26	12	6	2	460
Dual /Hybrid	36	65	65	64	76	63	33	20	14	6	2	444
Dual /Stirling	27	41	42	50	73	58	34	19	15	7	2	368



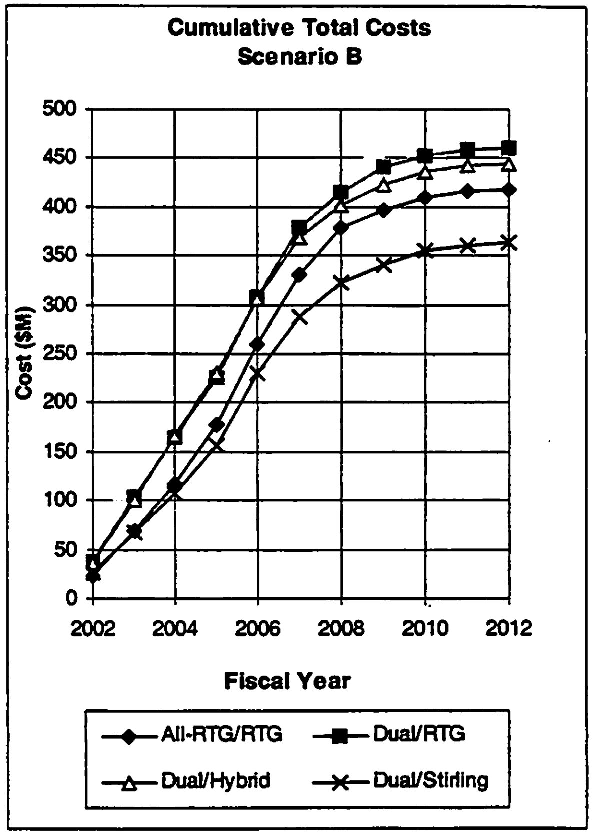
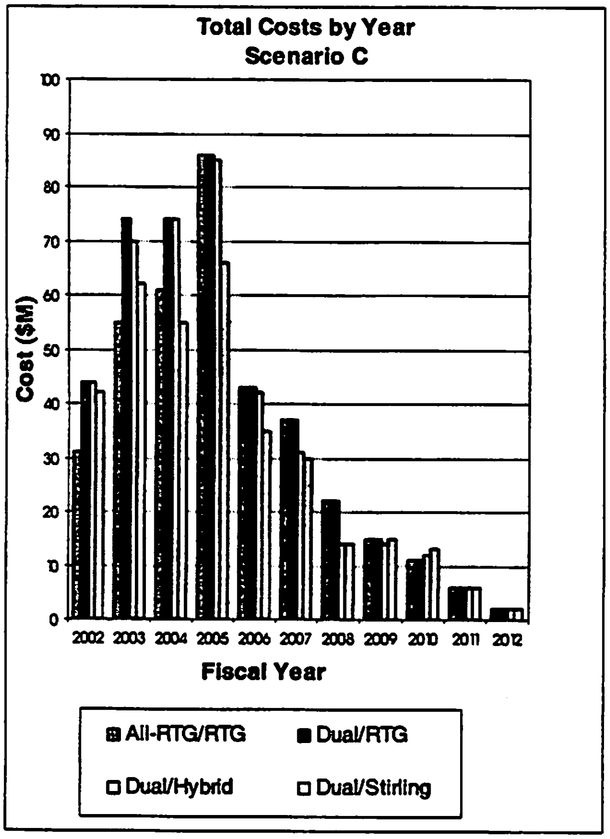


Figure L-2. Scenario B (Delayed PKB) Estimated Costs ($M)

Table L-7. Scenario C (Early PKB, No SP) Estimated Costs ($M)

Strategy/Outcome	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
All-RTG/RTG	31	55	61	86	43	37	22	15	11	6	2	369
Dual /RTG	44	74	74	86	43	37	22	15	11	6	2	414
Dual /Hybrid	44	70	74	85	42	31	14	14	12	6	2	394
Dual /Stirling	42	62	55	66	35	30	14	15	13	6	2	340



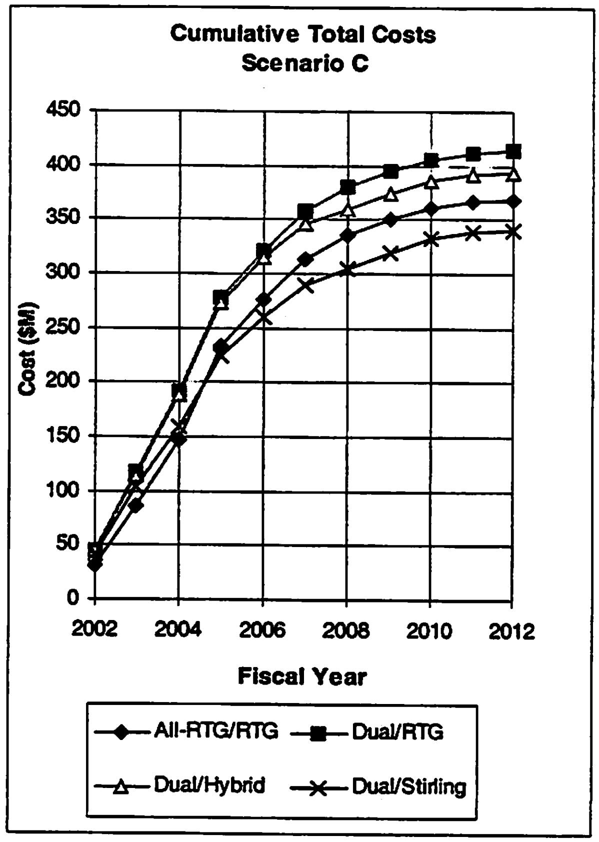
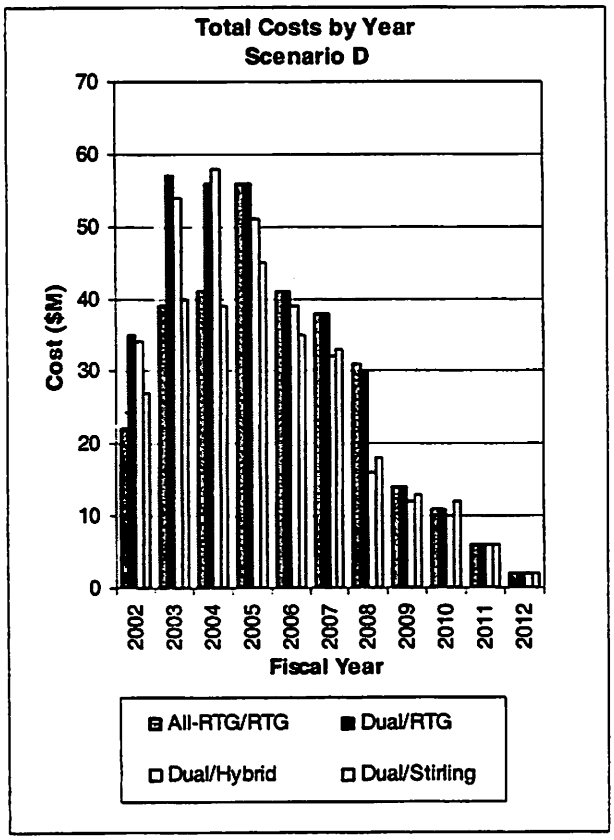


Figure L-3. Scenario C (Early PKB, No SP) Estimated Costs ($M)

Table L-8. Scenario D (No PKB, No SP) Estimated Costs ($M)

Strategy/Outcome	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total
All-RTG/RTG	22	39	41	56	41	38	31	14	11	6	2	301
Dual /RTG	35	57	57	56	41	38	30	14	11	6	2	346
Dual /Hybrid	34	54	58	51	39	32	16	12	10	6	2	314
Dual /Stirling	27	40	39	45	35	33	18	13	12	6	2	270



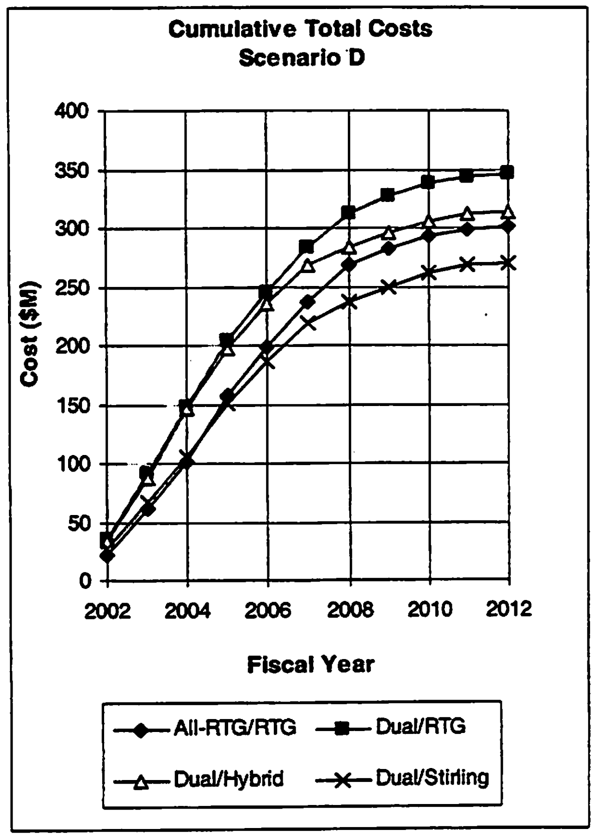


Figure L-4. Scenario D (No PKB, No SP) Estimated Costs ($M)

1ART

All RTG
Mission Scenario A
PKB early, Mars 07, EO 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Small RTG Development	8.0	12.0	10.0									30.0	8
Small RTG Flight Units												0.0	
Spare Unit			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
SP 09 (2)					6.0	8.0	2.0					16.0	16
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	124
Project Integration	2.0	2.0	2.0	6.0	10.0	12.0	6.0	5.5	4.0	4.0	0.5	54.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.5	2.6	2.7	2.8	2.9	2.6						16.1	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	3.2	5.3	5.1	4.2						22.9	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	5.4	5.4	5.8	3.0	2.0			37.5	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aeroshells/FWPF	0.6	2.4	0.7	2.3	0.7	2.5	0.1	0.5	1.5	0.1	0.0	11.4	
Other	0.0	0.7	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.8	
Shipping (9516 hardware, 9904, OTS)	0.3	0.5	0.7	0.2	0.4	1.4	1.3	0.3	0.2	0.6	0.3	6.2	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7)				13.4								13.4	
F8 (8 kg)				8.9								8.9	
												0.0	
Russian Purchases (44 kg)	6.0	16.6	21.6	22.5	11.7	12.2	7.6					98.2	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1				3.6	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	30.4	54.3	57.9	89.6	63.1	56.2	30.8	16.9	13.2	6.3	1.7	420.4	
DOE Added Factor	0.9	1.7	1.8	2.8	2.0	1.7	1.0	0.5	0.4	0.2	0.1	13.0	
TOTAL	31.3	56.0	59.7	92.4	65.1	57.9	31.7	17.4	13.6	6.5	1.8	433.4	

* assumes no startup cost or upgrades for thermoelectric production line startup

2AST
All Stirling
Mission Scenario A
PKB early, Mars 07, EO 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare Unit			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
SP 09 (3)					6.0	8.0	4.0					18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	66
Project Integration	2.0	2.0	2.0	6.0	10.0	12.0	6.0	5.5	4.0	4.0	0.5	54.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	0.9	0.9	1.0	1.0	1.1	0.6						5.5	
												0.0	
Fueled Clad Assemblies (LANL)	1.0	1.7	1.8	1.9	1.9	0.2						8.5	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	6.0	6.0	5.8	3.0	2.0			38.7	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aeroshells/FWPF	0.6	0.2	2.1	0.5	0.3	0.4	0.0	0.0	0.0	0.0	0.0	4.1	
Other	0.0	0.3	0.2	0.4	0.1	0.1	0.1	0.1	0.2	0.0	0.0	1.5	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4	0.5	0.0	1.0	1.0	0.3	0.0	0.6	0.3	4.6	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7)				13.4								13.4	
F8 (8 kg)				14.2								14.2	
												0.0	
Russian Purchases (15 kg)	6.0	6.2	6.5	6.7		7.3						32.8	
												0.0	
Shipping	0.5	0.3	0.3	0.3		0.3	0.1					1.8	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	29.7	40.8	41.5	73.5	43.7	43.2	24.4	16.3	13.6	6.1	1.6	334.5	
DOE Added Factor	0.9	1.3	1.3	2.3	1.4	1.3	0.8	0.5	0.4	0.2	0.0	10.3	
TOTAL	30.6	42.1	42.8	75.8	45.1	44.5	25.2	16.8	14.0	6.3	1.6	344.8	

RTGs for OP/Stirling for Mars
Mission Scenario A
PKB early, Mars 07, EO 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
												0.0	
Stirling Flight Units												0.0	
Spare			2.0	2.0	2.0							6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
Small RTG Flight Units												0.0	
Spare			2.0	3.0	3.0							8.0	8
EO 08 (3)			4.0	8.0	8.0	4.0						24.0	24
SP 09 (2)					6.0	8.0	2.0					16.0	16
												0.0	108
												0.0	
Project Integration	4.0	4.0	4.0	6.0	10.0	12.0	6.0	5.5	4.0	4.0	0.5	60.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.3	2.4	2.5	2.6	2.7	0.6						13.1	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	3.2	5.3	4.7	3.3						21.6	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	5.4	5.4	5.8	3.0	2.0			37.5	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aeroshells/FWPF	0.6	0.3	2.4	0.9	2.6	0.4	0.0	1.7	0.0	0.0	0.0	8.9	
Other	0.3	0.2	0.1	0.9	0.2	0.2	0.2	0.2	0.1	0.1	0.0	2.5	
Shipping (9516 hardware, 9904, OTS)	0.4	0.6	0.9	0.6		1.3	1.0	0.7	0.0	0.6	0.3	6.4	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7)				13.4								13.4	
F8 (8 kg)				7.1								7.1	
												0.0	
Russian Purchases (36 kg)	6.0	16.6	17.3	18.0	14.0	7.3						79.3	
												0.0	
Shipping	0.5	0.5	0.5	0.5	0.5	0.3	0.1					2.9	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	42.6	68.6	73.1	83.9	67.4	46.1	22.5	18.5	13.5	6.2	1.6	444.1	444.1
DOE Added Factor	1.3	2.1	2.3	2.6	2.1	1.4	0.7	0.6	0.4	0.2	0.0	13.7	
TOTAL	43.9	70.8	75.4	86.5	69.5	47.5	23.2	19.1	13.9	6.4	1.6	457.8	

* assumes no startup cost or upgrades for thermoelectric production line startup

Pre-Decisional Working Papers, For Internal Review Only

1ART-B

All RTG with Backup
Mission Scenario A
PKB early, Mars 07, EO 08, SP 09, Mars 11

		FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor														
F8		6.0	5.9	5.8	1.5								19.2	18
F5		1.0	2.0										3.0	18
													0.0	
Stirling Development		10.0	15.0	10.0									35.0	2
													0.0	
Small RTG Development*		8.0	12.0	10.0									30.0	8
Small RTG Flight Units													0.0	
Spare Unit**				2.0	3.0	3.0							8.0	8
Mars 07 (2)				2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)					10.0	10.0	4.0						24.0	24
SP 09 (2)						6.0	8.0	2.0					16.0	16
Mars 11 (2)								6.0	6.0	4.0			16.0	16
													0.0	126
Project Integration		4.0	4.0	4.0	6.0	10.0	12.0	6.0	5.5	4.0	4.0	0.5	60.0	
													0.0	
Clad Vent Sets and Insulators (ORNL)		2.5	2.6	2.7	2.9	3.0	2.6						16.3	
													0.0	
Fueled Clad Assemblies (LANL)		2.1	3.0	5.0	5.3	5.1	4.2						24.7	
													0.0	
Assembly and Test (Mound)													0.0	
													0.0	
Labor			4.9	5.2	5.8	5.4	5.4	5.8	3.0	2.0			37.5	
													0.0	
Materials													0.0	
F5 Aeroshell Caps/Bodies		0.2											0.2	
Aeroshells/FWPF		0.6	2.4	0.7	2.3	0.7	2.5	0.1	0.5	1.5	0.1	0.0	11.4	
Other		0.3	0.2	0.1	0.9	0.2	0.2	0.2	0.2	0.1	0.1	0.0	2.5	
Shipping (9516 hardware, 9904, OTS)		0.3	0.5	0.7	0.2	0.4	1.4	1.3	0.3	0.2	0.6	0.3	6.2	
													0.0	
													0.0	
^{238}Pu Acquisition													0.0	
													0.0	
Domestic													0.0	
F5 (6.7)					13.4								13.4	
F8 (8 kg)					7.1								7.1	
													0.0	
Russian Purchases (45 kg)		6.0	16.6	21.6	22.5	14.0	12.2	7.6					100.6	
													0.0	
Shipping (9516 hardware,OTS)		0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.1				3.2	
													0.0	
Technical Support and QA Support		1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total		42.7	70.8	71.5	88.7	65.6	56.1	30.7	17.0	13.2	6.3	1.6	484.3	
DOE Added Factor		1.3	2.2	2.2	2.7	2.0	1.7	0.9	0.5	0.4	0.2	0.0	14.4	
TOTAL		44.0	73.0	73.7	91.4	67.7	57.8	31.6	17.5	13.6	6.5	1.6	478.6	

* assumes no startup cost or upgrades for thermoelectric production line startup
**under this scenario, the cost of a fueled and flight accepted spare small RTG is ???

2AST-B

All Stirling with Backup
Mission Scenario A
PKB early, Mars 07, EO 08, SP 09, Mars 11

System Integrator Contractor	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Small RTG Development	8.0	12.0	10.0									30.0	8
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare Unit			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
SP 09 (3)					6.0	8.0	4.0					18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	74
Project Integration	4.0	4.0	4.0	6.0	10.0	12.0	6.0	5.5	4.0	4.0	0.5	60.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	1.1	1.2	1.3	1.3	1.4	0.6						6.9	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	2.7	1.9	1.9	0.2						11.8	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	5.4	5.4	5.8	3.0	2.0			37.5	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aeroshells/FWPF	0.6	0.2	2.1	0.5	0.3	0.4	0.0	0.0	0.0	0.0	0.0	4.1	
Other	0.0	0.3	0.3	0.4	0.1	0.1	0.1	0.1	0.2	0.0	0.0	1.6	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4	0.5	0.0	1.0	1.0	0.3	0.0	0.6	0.3	4.6	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7)				13.4								13.4	
F8 (8 kg)				7.1								7.1	
												0.0	
Russian Purchases (19 kg)	6.0	12.5	6.5	6.7	4.7	4.9						41.3	
												0.0	
Shipping	0.5	0.5	0.3	0.3	0.3	0.3	0.1					2.3	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	41.0	62.9	54.8	66.7	48.4	40.2	24.4	16.3	13.6	6.1	1.6	376.0	
DOE Added Factor	1.3	1.9	1.7	2.1	1.5	1.2	0.8	0.5	0.4	0.2	0.0	11.6	
TOTAL	42.3	64.8	56.5	68.8	49.9	41.4	25.2	16.8	14.0	6.3	1.6	387.6	

1BRT

All RTG
Mission Scenario B
Mars 07, EO 08, PKB 08, SP 09, Mars 11

		FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor														
Small RTG Development*		8.0	12.0	10.0									30.0	8
Small RTG Flight Units													0.0	
Spare unit				2.0	3.0	3.0							8.0	8
Mars 07 (2)				2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)					10.0	10.0	4.0						24.0	24
PKB 08 (2)						6.0	8.0	2.0					16.0	16
SP 09 (2)						6.0	8.0	2.0					16.0	16
Mars 11 (2)								6.0	6.0	4.0			16.0	16
													0.0	104
													0.0	
Project Integration		2.0	2.0	2.0	6.0	13.5	16.0	10.0	6.0	4.0	4.0	0.5	66.0	
													0.0	
Clad Vent Sets and Insulators (ORNL)		2.4	2.5	2.6	2.7	2.8	2.6						15.6	
													0.0	
Fueled Clad Assemblies (LANL)		2.1	3.0	3.2	3.3	3.5	5.1						20.2	
													0.0	
Assembly and Test (Mound)													0.0	
													0.0	
Labor			4.9	5.2	5.8	6.0	6.0	6.0	4.0	2.0			39.9	
													0.0	
Materials													0.0	
Aeroshells/FWPF		0.0	1.6	0.1	2.1	0.4	2.2	0.4	0.6	1.1	0.1	0.0	8.6	
Other		0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.3	
Shipping (9516 hardware, 9904, OTS)		0.0	0.2	0.3	0.5	1.2	0.7	0.7	0.3	0.2	0.5	0.3	4.9	
													0.0	
^{238}Pu Acquisition													0.0	
													0.0	
Domestic (9 kg)								8.9					8.9	
													0.0	
Russian Purchases (43 kg)		6.0	16.6	17.3	18.0	18.7	12.2	7.6					96.4	
													0.0	
Shipping (9516 hardware,OTS)		0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.1				3.2	
													0.0	
Technical Support and QA Support		1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total		22.3	44.8	46.5	59.3	79.0	68.5	45.4	18.5	12.8	6.2	1.7	405.0	
DOE Added Factor		0.7	1.4	1.4	1.8	2.4	2.1	1.4	0.6	0.4	0.2	0.1	12.5	
TOTAL		23.0	46.2	47.9	61.1	81.5	70.6	46.8	19.1	13.2	6.4	1.8	417.6	

* assumes no startup cost or upgrades for thermoelectric production line startup

2BST
All Stirling
Mission Scenario B
Mars 07, EO 08, PKB 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare unit			2.0	2.0	2.0							6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
PKB 08 (3)					8.0	8.0	2.0					18.0	6
SP 09 (3)					6.0	8.0	4.0					18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	36
Project Integration	2.0	2.0	2.0	6.0	13.5	16.0	10.0	6.0	4.0	4.0	0.5	66.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	0.5	0.5	0.5	0.5	0.6	0.6						3.2	
												0.0	
Fueled Clad Assemblies (LANL)				1.9	1.9							3.8	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	6.0	6.0	5.8	3.0	2.0			38.7	
												0.0	
Materials												0.0	
Aerochells/FWPF	0.0	0.4	1.9	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0	3.7	
Other	0.0	0.2	0.5	0.4	0.1	0.1	0.1	0.1	0.2	0.0	0.0	1.7	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4		0.2	0.1	0.1		0.8	0.8	0.3	3.2	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic (8 kg)						5.0	5.0	4.2				14.2	
												0.0	
Russian Purchases (9 kg)	2.0			6.7	7.0	4.9						20.6	
												0.0	
Shipping	0.5			0.3	0.3	0.3	0.1					1.5	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	16.5	24.4	25.7	42.1	64.1	56.5	34.7	20.9	14.6	6.5	1.6	307.6	
DOE Added Factor	0.5	0.8	0.8	1.3	2.0	1.7	1.1	0.6	0.5	0.2	0.0	9.5	
TOTAL	17.0	25.2	26.5	43.5	66.1	58.2	35.8	21.5	15.1	6.7	1.6	317.1	

1BRT-B

All RTG with Backup
Mission Scenario B
Mars 07, EO 08, PKB 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
Small RTG Flight Units**												0.0	
Spare unit			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
PKB 08 (2)					6.0	8.0	2.0					16.0	16
SP 09 (2)					6.0	8.0	2.0					16.0	16
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	106
												0.0	
Project Integration	4.0	4.0	4.0	6.0	13.5	16.0	10.0	6.0	4.0	4.0	0.5	72.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.5	2.6	2.7	2.8	2.9	2.6						16.1	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	3.2	3.3	3.5	5.1						20.2	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.8	6.0	6.0	6.0	4.0	2.0			39.9	
												0.0	
Materials												0.0	
Aeroshells/FWPF	0.1	2.1	0.6	2.1	0.6	2.4	0.2	0.3	0.1	0.1	0.0	8.6	
Other	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6	
Shipping (9516 hardware, 9904, OTS)	0.0	0.2	0.3	0.5	1.2	0.7	0.7	0.3	0.2	0.5	0.3	4.9	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic (8 kg)								7.1				7.1	
												0.0	
Russian Purchases (44 kg)	8.0	16.6	17.3	18.0	18.7	12.2	7.6					98.4	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.1				3.2	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	36.5	62.7	59.1	59.4	79.3	68.7	36.3	25.3	11.8	6.2	1.7	447.0	
DOE Added Factor	1.1	1.9	1.8	1.8	2.5	2.1	1.1	0.8	0.4	0.2	0.1	13.8	
TOTAL	37.6	64.7	60.9	61.2	81.8	70.8	37.4	26.1	12.2	6.4	1.8	460.8	

* assumes no startup cost or upgrades for thermoelectric production line startup
**Under this scenario, the cost of a fueled and flight accepted spare Small RTG is

2BST-B

All Stirling with Backup
Mission Scenario B
Mars 07, EO 08, PKB 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Small RTG Deviopment	8.0	12.0	10.0									30.0	8
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units													
Spare unit			2.0	2.0	2.0							6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
PKB 08 (3)					8.0	8.0	2.0					18.0	6
SP 09 (3)					6.0	8.0	4.0					18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
													44
Project Integration	4.0	4.0	4.0	6.0	13.5	16.0	10.0	6.0	4.0	4.0	0.5	72.0	
Clad Vent Sets and Insulators (ORNL)	0.8	0.8	0.8	0.8	0.9	0.6						4.7	
Fueled Clad Assemblies (LANL)				2.9	3.1	1.6						7.6	
Assembly and Test (Mound)													
Labor		4.9	5.2	5.8	6.0	6.0	5.8	3.0	2.0			38.7	
Materials													
Aerochells/FWPF		0.6	2.1	0.4	0.4	0.2	0.2	0.3	0.1	0.1	0.1	4.5	
Other		0.2	0.5	0.4	0.1	0.1	0.1	0.1	0.2			1.7	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4		0.2	0.1	0.1		0.8	0.8	0.3	3.2	
^{238}Pu Acquisition													
Domestic (8 kg)						3.0	3.0	1.1				7.1	
Russian Purchases (13 kg)	2.0			11.2	11.7	4.9						29.8	
Shipping	0.5			0.3	0.3	0.3	0.1					1.5	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	351.8
Mission Total	26.8	38.9	38.2	48.1	70.5	56.1	32.7	17.9	14.5	6.4	1.7	351.8	351.8
DOE Added Factor	0.8	1.2	1.2	1.5	2.2	1.7	1.0	0.6	0.4	0.2	0.1	10.9	10.9
TOTAL	27.6	40.1	39.4	49.6	72.7	57.8	33.7	18.5	14.9	6.6	1.8	362.7	362.7

3BRS

RTGs for OP/Stirling for Mars
Mission Scenario B
Mars 07, EO 08, PKB 08, SP 09, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
												0.0	
Stirling Flight Units												0.0	
Spare unit			2.0	2.0	2.0							6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
Mars 11 (3)							6.0	6.0	6.0			18.0	6
Small RTG Flight Units												0.0	
Spare unit			2.0	3.0	3.0							8.0	8
EO 08 (3)			2.0	10.0	10.0	2.0						24.0	24
PKB 08 (2)					6.0	8.0	2.0					16.0	16
SP 09 (2)					6.0	8.0	2.0					16.0	16
												0.0	88
												0.0	
Project Integration	4.0	4.0	4.0	6.0	13.5	16.0	10.0	6.0	4.0	4.0	0.5	72.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.2	2.3	2.4	2.5	2.6	0.6						12.6	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	3.2	3.3	3.5	2.7						17.8	
												0.0	
Assembly and Test (Mound)												0.0	
Labor		4.9	5.2	5.8	6.0	6.0	6.0	4.0	2.0			39.9	
												0.0	
Materials												0.0	
Aeroshells/FWPF	0.1	2.1	0.6	2.1	0.6	2.4	0.2	0.3	0.1	0.1	0.0	8.6	
Other	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6	
Shipping (9516 hardware, 9904, OTS)	0.4	0.6	0.7	0.7		1.3	1.2	0.3	0.5		0.3	6.0	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic (8 kg)						3.0	3.0	1.1				7.1	
												0.0	
Russian Purchases (35 kg)	6.0	16.6	17.3	18.0	11.7	7.3						76.9	
												0.0	
Shipping	0.5	0.5	0.5	0.5	0.3	0.3	0.1					2.7	
												0.0	
Russian Purchases (13 kg)	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	34.6	62.8	63.2	62.3	73.6	61.0	32.0	19.2	14.1	5.7	1.7	430.2	
DOE Added Factor	1.1	1.9	2.0	1.9	2.3	1.9	1.0	0.6	0.4	0.2	0.1	13.3	
TOTAL	35.7	64.8	65.2	64.2	75.9	62.9	33.0	19.8	14.5	5.9	1.8	443.5	

* assumes no startup cost or upgrades for thermoelectric production line startup

1CRT

All RTG
Mission Scenario C
Early PKB, Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
Small RTG Flight Units												0.0	
Spare			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	108
												0.0	
Project Integration	2.0	2.0	2.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	42.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.5	2.6	2.7	2.9	2.5							13.2	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	5.0	5.3	4.3							19.7	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
F5	0.2											0.2	
Aeroshells/FWPF	0.0	2.1	0.6	2.5	0.4	1.9	0.1	0.4	0.4	0.0	0.0	8.4	
Other	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.3	
Shipping (9516 hardware, 9904, OTS)	0.3	0.4	0.7	0.2	0.4	1.0	0.8	0.0	0.2	0.6	0.3	4.9	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7 kg)				13.4								13.4	
F8 (8 kg)				8.9								8.9	
												0.0	
Russian Purchases (36 kg)	6.0	16.6	21.6	15.7		12.2	7.6					79.8	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.5	0.5	0.5		0.3	0.3	0.1				2.7	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	29.9	53.5	59.4	82.9	41.6	36.2	21.5	14.0	11.1	6.2	1.7	358.1	
DOE Added Factor	0.9	1.7	1.8	2.6	1.3	1.1	0.7	0.4	0.3	0.2	0.1	11.1	
TOTAL	30.8	55.2	61.3	85.5	42.9	37.3	22.2	14.4	11.4	6.4	1.8	369.2	

* assumes no startup cost or upgrades for thermoelectric production line startup

All Stirling
Mission Scenario C
Early PKB, Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	60
Project Integration	2.0	2.0	2.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	42.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	1.0	1.0	1.1	1.1	0.6							4.8	
												0.0	
Fueled Clad Assemblies (LANL)	1.0	1.7	1.8	3.2								7.7	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
F5	0.2											0.2	
Aeroshells/FWPF	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.5	0.0	0.0	0.0	1.4	
Other	0.0	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.1	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4	0.4	0.0	1.0	0.5	0.0	0.0	0.6	0.3	3.7	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7 kg)				13.4								13.4	
F8 (8 kg)				5.0	5.0	4.2						14.2	
												0.0	
Russian Purchases (12 kg)	6.0	6.2	6.5			7.3						26.0	
												0.0	
Shipping	0.5	0.3	0.3			0.3	0.1					1.5	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	29.4	40.9	39.6	57.8	37.7	33.6	13.3	14.0	12.5	6.2	1.6	288.6	
DOE Added Factor	0.9	1.3	1.2	1.8	1.2	1.0	0.4	0.4	0.4	0.2	0.0	8.9	
TOTAL	30.3	42.2	40.8	59.6	38.9	34.6	13.7	14.4	12.9	6.4	1.6	295.5	

1CRT-B

All RTG with Backup
Mission Scenario C
Early PKB, Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Small Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
Small RTG Flight Units												0.0	
Spare			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	110
												0.0	
Project Integration	4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	2.7	2.8	2.9	3.0	2.5							13.9	
												0.0	
Fueled Clad Assemblies (LANL)	2.1	3.0	5.0	5.3	4.3							19.7	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aeroshells/FWPF	0.6	2.3	0.6	2.5	0.4	1.9	0.1	0.4	0.4	0.0	0.0	9.2	
Other	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6	
Shipping (9516 hardware, 9904, OTS)	0.3	0.4	0.7	0.2	0.4	1.0	0.8	0.0	0.2	0.6	0.3	4.9	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic												0.0	
F5 (6.7 kg)				13.4								13.4	
F8 (8 kg)				7.1								7.1	
												0.0	
Russian Purchases (37 kg)	6.0	16.6	21.6	18.0		12.2	7.6					82.0	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.5	0.5	0.5		0.3	0.3	0.1				2.7	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	42.7	71.2	71.6	83.5	41.6	36.2	21.5	14.0	11.1	6.2	1.7	401.3	
DOE Added Factor	1.3	2.2	2.2	2.6	1.3	1.1	0.7	0.4	0.3	0.2	0.1	12.4	
TOTAL	44.0	73.4	73.8	86.1	42.9	37.3	22.2	14.4	11.4	6.4	1.8	413.7	

* assumes no startup cost or upgrades for thermoelectric production line startup

2CST-B

All Stirling with Backup
Mission Scenario C
Early PKB, Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5								19.2	18
F5	1.0	2.0										3.0	18
												0.0	
Small RTG Development	8.0	12.0	10.0									30.0	8
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	68
Project Integration	4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	1.3	1.4	1.4	1.5	0.6							6.2	
												0.0	
Fueled Clad Assemblies (LANL)	1.8	2.7	2.8	2.0	1.3							10.6	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.2	
Aerochells/FWPF	0.6	0.2	0.4	0.4	0.1	0.0	0.0	0.5	0.0	0.0	0.0	2.2	
Other	0.0	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.3	
Shipping (9516 hardware, 9904, OTS)	0.3	0.2	0.4	0.4	0.0	1.0	0.5		0.0	0.6	0.3	3.7	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
F5 (6.7)				13.4								13.4	
F8 (8 kg)				7.1								7.1	
												0.0	
Russian Purchases (16 kg)	6.0	10.4	6.5	4.5		7.3						34.7	
												0.0	
Shipping	0.5	0.3	0.3	0.3		0.3	0.1					1.8	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	40.9	60.5	53.3	64.1	34.0	29.4	13.3	14.0	12.5	6.2	1.6	329.8	
DOE Added Factor	1.3	1.9	1.6	2.0	1.1	0.9	0.4	0.4	0.4	0.2	0.0	10.2	
TOTAL	42.2	62.4	54.9	66.1	35.1	30.3	13.7	14.4	12.9	6.4	1.6	340.0	

3CRS

RTGs for OP/Stirling for Mars
Mission Scenario C
Early PKB, Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
F8	6.0	5.9	5.8	1.5									
F5	1.0	2.0										19.2	18
												3.0	18
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
Stirling Flight Units												0.0	
Spare			3.0	3.0								0.0	
Mars 07 (3)			2.0	7.0	7.0	2.0						6.0	2
Mars 11 (3)							6.0	6.0	6.0			18.0	6
Small RTG Flight Units												18.0	6
Spare			2.0	3.0	3.0							0.0	
EO 08 (3)			2.0	10.0	10.0	2.0						8.0	8
												24.0	24
												0.0	92
												0.0	
Project Integration	4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
Clad Vent Sets and Insulators (ORNL)	2.3	2.4	2.5	2.6	0.6							0.0	
												10.4	
Fueled Clad Assemblies (LANL)	2.1	3.0	3.2	5.3	4.3							0.0	
												17.9	
Assembly and Test (Mound)												0.0	
												0.0	
												0.0	
Labor		4.9	5.2	5.8	5.8	5.8	3.0	2.0				32.5	
Materials												0.0	
F5 Aeroshell Caps/Bodies	0.2											0.0	
Aeroshells/FWPF	0.6	0.1	2.3	0.8	0.6	2.0	0.0	0.7	0.1	0.0	0.0	0.2	
Other	0.3	0.2	0.1	0.9	0.1	0.1	0.1	0.1	0.1	0.1	0.0	7.2	
Shipping (9516 hardware, 9904, OTS)	0.3	0.6	0.9	0.5		1.0	0.5	0.4	0.0	0.6	0.3	2.1	
												5.1	
^{238}Pu Acquisition												0.0	
												0.0	
F5 (6.7)				13.4								0.0	
F8 (8 kg)				7.1								13.4	
												7.1	
												0.0	
Russian Purchases (28 kg)	6.0	16.6	17.3	13.5		7.3						60.7	
												0.0	
Shipping	0.5	0.5	0.5	0.5		0.3	0.1					2.4	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	42.5	68.4	72.0	82.2	40.7	29.8	13.1	14.1	11.6	6.2	1.6	382.2	
DOE Added Factor	1.3	2.1	2.2	2.5	1.3	0.9	0.4	0.4	0.4	0.2	0.0	11.8	
TOTAL	43.8	70.6	74.2	84.7	42.0	30.7	13.5	14.5	12.0	6.4	1.6	394.1	

* assumes no startup cost or upgrades for thermoelectric production line startup

1DRT

All RTG
Mission Scenario D
Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Small RTG Development*	8.0	12.0	10.0									30.0	8
Small RTG Flight Units												0.0	
Spare			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	72
												0.0	
Project Integration	2.0	2.0	2.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	42.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	1.8	1.9	2.0	2.1	2.5							10.3	
												0.0	
Fueled Clad Assemblies (LANL)	1.8	2.7	2.8	3.3	2.6							13.2	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
Aeroshells/FWPF	0.0	1.5	0.6	2.5	0.3	2.0	0.1	0.4	0.4	0.0	0.0	7.8	
Other	0.2	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.4	
Shipping (9516 hardware, 9904, OTS)	0.0	0.2	0.5	0.2	0.4	1.0	0.8	0.0	0.2	0.6	0.3	4.2	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
F8 (8 kg)							8.9					8.9	
												0.0	
Russian Purchases (27 kg)	6.0	10.4	10.8	13.5		12.2	7.6					60.5	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.3	0.3	0.5		0.3	0.3	0.1				2.3	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	21.5	37.5	39.5	54.1	39.8	36.3	30.4	14.0	11.1	6.2	1.6	292.0	
DOE Added Factor	0.7	1.2	1.2	1.7	1.2	1.1	0.9	0.4	0.3	0.2	0.0	9.0	
TOTAL	22.2	38.7	40.7	55.8	41.0	37.4	31.3	14.4	11.4	6.4	1.6	301.0	

* assumes no startup cost or upgrades for thermoelectric production line startup

2DST
All Stirling
Mission Scenario D
Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	24
Project Integration	2.0	2.0	2.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	42.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	0.3	0.3	0.3	0.3	0.3							1.5	
												0.0	
Fueled Clad Assemblies (LANL)												0.0	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
												0.0	
Labor		4.9	5.2	5.2	5.2	5.2	3.0	1.0	0.0	0.0	0.0	29.7	
												0.0	
Materials												0.0	
Aerochells/FWPF	0.0	0.1	0.4	0.2	0.0	0.0	0.0	0.5	0.0	0.0	0.0	1.2	
Other	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.1	
Shipping (9516 hardware, 9904, OTS)	0.0	0.3	0.8	0.4	0.0	1.0	0.5	0.4	0.0	0.6	0.3	4.3	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
F8 (8 kg)						7.1	7.1					14.2	
												0.0	
Russian Purchases (3 kg)						7.3						7.3	
												0.0	
Shipping						0.4						0.4	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	13.6	24.0	25.0	33.5	31.9	36.4	20.1	12.9	11.5	6.2	1.6	216.7	
DOE Added Factor	0.4	0.7	0.8	1.0	1.0	1.1	0.6	0.4	0.4	0.2	0.0	6.7	
TOTAL	14.0	24.7	25.8	34.5	32.9	37.5	20.7	13.3	11.9	6.4	1.6	223.4	

1DRT-B

All RTG with Backup
Mission Scenario D
Mars 07, EO 08, Mars 11

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
System Integrator Contractor													
Stirling Development	10.0	15.0	10.0									35.0	2
												0.0	
Small RTG Development*	8.0	12.0	10.0									30.0	8
Small RTG Flight Units												0.0	
Spare			2.0	3.0	3.0							8.0	8
Mars 07 (2)			2.0	6.0	6.0	2.0						16.0	16
EO 08 (3)				10.0	10.0	4.0						24.0	24
Mars 11 (2)							6.0	6.0	4.0			16.0	16
												0.0	74
												0.0	
Project Integration	4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	1.9	2.0	2.1	2.1	2.5							10.6	
												0.0	
Fueled Clad Assemblies (LANL)	1.8	2.7	3.2	3.3	2.6							13.6	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.6	5.6	5.4	3.2	2.5	1.0			33.4	
												0.0	
Materials												0.0	
Aeroshells/FWPF	0.0	2.3	0.6	2.5	0.3	2.0	0.1	0.4	0.4	0.0	0.0	8.6	
Other	0.2	0.7	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.7	
Shipping (9516 hardware, 9904, OTS)		0.2	0.5	0.2	0.4	1.0	0.8		0.2	0.6	0.3	4.2	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic (8 kg)							7.1					7.1	
												0.0	
Russian Purchases (28 kg)	6.0	10.4	13.0	13.5		12.2	7.6					62.6	
												0.0	
Shipping (9516 hardware,OTS)	0.5	0.3	0.5	0.5		0.3	0.3	0.1				2.5	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	33.6	55.7	54.4	54.1	39.8	36.3	28.6	14.0	11.1	6.2	1.6	335.3	
DOE Added Factor	1.0	1.7	1.7	1.7	1.2	1.1	0.9	0.4	0.3	0.2	0.0	10.4	
TOTAL	34.6	57.4	56.1	55.8	41.0	37.4	29.5	14.4	11.4	6.4	1.6	345.7	

* assumes no startup cost or upgrades for thermoelectric production line startup

2DST-B
All Stirling
Mission Scenario D
Mars 07, EO 08, Mars 11

System Integrator Contractor	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHSs
Small RTG Development	8.0	12.0	10.0									30.0	8
												0.0	
Stirling Development	10.0	15.0	10.0									35.0	2
Stirling Flight Units												0.0	
Spare			3.0	3.0								6.0	2
Mars 07 (3)			2.0	7.0	7.0	2.0						18.0	6
EO 08 (4)				10.0	10.0	4.0						24.0	8
Mars 11 (3)							6.0	6.0	6.0			18.0	6
												0.0	32
Project Integration	4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
												0.0	
Clad Vent Sets and Insulators (ORNL)	0.6	0.6	0.6	0.6	0.7							3.1	
												0.0	
Fueled Clad Assemblies (LANL)				2.9	2.2							5.1	
												0.0	
Assembly and Test (Mound)												0.0	
												0.0	
Labor		4.9	5.2	5.2	5.2	5.2	3.0	1.0				29.7	
												0.0	
Materials												0.0	
Aerochells/FWPF	0.0	0.2	0.5	0.2	0.0	0.0	0.0	0.5				1.4	
Other	0.1	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	1.3	
Shipping (9516 hardware, 9904, OTS)		0.3	0.8	0.4		1.0	0.5	0.4		0.6	0.3	4.3	
												0.0	
^{238}Pu Acquisition												0.0	
												0.0	
Domestic (8 kg)						3.1	4.0					7.1	
												0.0	
Russian Purchases (7 kg)	2.0			6.7		7.3						16.0	
												0.0	
Shipping	0.5			0.3		0.3	0.1					1.2	
												0.0	
Technical Support and QA Support	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total	26.4	38.5	37.5	43.7	34.5	32.3	17.1	12.9	11.5	6.2	1.6	262.2	
DOE Added Factor	0.8	1.2	1.2	1.4	1.1	1.0	0.5	0.4	0.4	0.2	0.0	8.1	
TOTAL	27.2	39.7	38.7	45.1	35.6	33.3	17.6	13.3	11.9	6.4	1.6	270.4	

3DRS

RTGs for OP/Stirling for Mars
Mission Scenario D
Mars 07, EO 08, Mars 11

		FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	Total	Total GPHS
System Integrator Contractor														
Stirling Development		10.0	15.0	10.0									35.0	2
													0.0	
Small RTG Development*		8.0	12.0	10.0									30.0	8
													0.0	
Stirling Flight Units													0.0	
Spare				3.0	3.0								6.0	2
Mars 07 (3)				2.0	7.0	7.0	2.0						18.0	6
Mars 11 (3)								4.0	4.0	4.0			12.0	6
Small RTG Flight Units													0.0	
Spare				2.0	3.0	3.0							8.0	8
EO 08 (3)				2.0	10.0	10.0	2.0						24.0	24
													0.0	56
													0.0	
Project Integration		4.0	4.0	4.0	6.0	8.0	8.0	2.0	3.5	4.0	4.0	0.5	48.0	
													0.0	
Clad Vent Sets and Insulators (ORNL)		1.2	1.2	1.3	1.3	0.6							5.6	
													0.0	
Fueled Clad Assemblies (LANL)		1.8	2.7	2.8	2.9	2.2							12.4	
													0.0	
Assembly and Test (Mound)													0.0	
													0.0	
Labor			4.9	5.2	5.8	5.8	5.8	3.0	2.0				32.5	
													0.0	
Materials													0.0	
Aeroshells/FWPF		0.2	0.5	0.5	0.7	0.3	0.0	0.6					2.8	
Other		0.3	0.2	0.1	0.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	2.2	
Shipping (9516 hardware, 9904, OTS)			0.3	0.8	0.4		1.0	0.5	0.4		0.6	0.3	4.3	
													0.0	
^{238}Pu Acquisition													0.0	
													0.0	
Domestic (8 kg)							3.0	4.1					7.1	
													0.0	
Russian Purchases (19 kg)		6.0	10.4	10.8	6.7		7.3						41.3	
													0.0	
Shipping		0.5	0.3	0.3	0.3		0.3	0.1					1.8	
													0.0	
Technical Support and QA Support		1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5	0.8	14.0	
Mission Total		33.2	52.7	56.0	49.3	38.3	30.8	15.8	11.4	9.5	6.2	1.7	305.0	
DOE Added Factor		1.0	1.6	1.7	1.5	1.2	1.0	0.5	0.4	0.3	0.2	0.1	9.4	
TOTAL		34.2	54.3	57.7	50.9	39.5	31.8	16.3	11.8	9.8	6.4	1.8	314.4	

* assumes no startup cost or upgrades for thermoelectric production line startup

Appendix M. Evaluation of Outcomes

A comparison of the various outcomes needs to be made in order to arrive at a recommended strategy. As an aid in this evaluation, the distinguishing attributes of each of the three Dual Strategy Outcomes were contrasted individually with the outcome of the All-RTG Strategy as shown in Table M-1. The attributes in Table M-1 are organized in three groups and discussed in the following three subsections.

Table M-1. Outcome Attributes

All-RTG Strategy	Dual Strategy		
RTG Outcome	**RTG Outcome**	**Stirling Outcome**	**Hybrid Outcome**
PuO_2 and DOE Infrastructure Related			
Lowest PuO_2 during development			
Highest PuO_2 during production	Highest PuO_2 during production	Lowest PuO_2 during production	Intermediate PuO_2 during production
Highest DOE infrastructure during production	Highest DOE infrastructure during production		
Potential for assembly and acceptance test schedule risk due to stochastic variations in fueled clad production rate	Potential for assembly and acceptance test schedule risk due to stochastic variations in fueled clad production rate	Minimum potential for assembly and acceptance test schedule risk due to stochastic variations in fueled clad production rate	Potential for assembly and acceptance test schedule risk due to stochastic variations in fueled clad production rate
		Highest assembly and test cost per mission	
Cost and Management Related			
Lowest development cost			
Lowest development cost risk			
			Multiple RPS designs are more expensive to maintain
Least management oversight			
No post-contract-award competition			
Single vendor dependency for development			
			Some protection against vendor failure during production
Mission Flexibility and Technical Constraints			
Highest near term certainty for MSL and EO planners			
			Two RPSs in production provides flexibility
		Requires successful radiation hardened controller development	

PuO_2 and DOE Infrastructure Related

Discussion of the production throughput and RPS assembly and acceptance testing capability is contained in Section 3.4.5.

Cost and Management Related Criteria

Several cost and management related criteria must be considered when comparing the All-RTG Strategy with the Dual Strategy.

As shown in Tables L-5 through L-8 and Figures L-1 through L-4 in Appendix L, the estimated cumulative costs through 2011 for both potential strategies are not significantly different (<10%), and are well within cost estimating uncertainties.

The All-RTG Strategy development cost estimate is approximately $50M lower, and the potential costs of maintaining a production capability for two RPS designs would be avoided. However, the Dual Strategy, albeit more expensive, offers the possibility of reduced ^{238}Pu requirements, which would reduce cost and provide greater schedule margin in the long run. If the Stirling RPS development was successful and depending on the mission model in the post-2011 years, there could be significantly reduced costs in the years after 2011.

Although the All-RTG Strategy would require management oversight on only one development and production activity, this is not considered a major driver. Another minor consideration for the Dual Strategy would be the enhanced contractor motivation by having competing RPS designs being considered.

Mission Flexibility and Technical Constraints

In the Dual Strategy, the outcome would not be known until three years into the development phase. The All-RTG Strategy would remove the near-term ambiguity for mission planners of not having to accommodate two RPS designs. However, it is not clear that a RTG would be well suited for all mission concepts—particularly those which cannot tolerate excessive waste heat and/or are sensitive to radiation effects from the RTG itself.

The Stirling Outcome would require a successful radiation hardened controller electronics development to accommodate a mission to Europa.

The Hybrid Outcome would provide additional mission flexibility by providing mission planners with two different RPS designs with different characteristics.

Comparative Analysis

To reach a consensus on a recommended RPS provisioning strategy, the Team considered the attributes discussed above in this section and included in Table M-1. These attributes can be summarized into five major factors (shown in Table M-2), two of which favor the All-RTG Strategy and three of which favor the Dual Strategy.

Some of these factors are qualitative, and are therefore difficult to compare directly against quantitative factors such as development cost. Furthermore, most of the quantitative factors are estimates with significant potential for errors, so the Team had to exercise considerable judgment in arriving at a recommendation based on the available information.

Table M-2. Summary of Key Strategy Attributes

Attributes Favoring All-RTG Strategy	Attributes Favoring Dual Strategy
All-RTG Strategy non-recurring cost would be approximately $41M lower than the Dual Strategy	Stirling Outcome offers potential runout cost reduction post 2011
A single RPS design would eliminate additional cost and management oversight of multiple contractors, and would eliminate the need for future mission planners to accommodate two designs	Potential for two available RPS designs, which would provide future mission planners with flexibility
	Potential reduction in total fueled clad requirement reduces risk from stochastic variations in fueled clad production rate

When balancing the factors favoring the All-RTG Strategy against the Dual Strategy, probably the most significant is the one of initial development cost against the promise of reduced ^{238}Pu requirements.

Recurring cost is not seen to be a discriminator in the postulated strategy path downselect shown in Tables L-5 through L-8 and Figures L-1 through L-4 in Appendix L.

The potential for having up to two available RPS designs in one or more of the outcomes of the Dual Strategy is a significant issue. On one hand, carrying two RPS designs would incur additional costs and DOE/NASA management oversight responsibilities to accommodate the second contractor. Furthermore, the need for future mission designers to carry two designs until an outcome decision would also increase cost and schedule risk.

On the other hand, mission designers would benefit from having two RPS designs from which to choose. In some cases, for instance, mission designers could desire waste heat for thermal control of spacecraft systems—favoring RTG designs. In other cases, waste heat rejection is difficult and a Stirling design could be favored. Also, the Dual Strategy would have the potential to reduce dependency on one supplier for all missions during the 2007 through 2011 time period.

Given the offsetting advantages and disadvantages and the dependencies on particular outcomes, single vs. dual RPS designs is not seen to be a discriminator in the postulated development path downselect.

Project development and production schedules for the various RPS strategies show that fueled clad production would be a pacing activity at LANL. The LANL facility is a unique resource for this activity, and is subject to operational perturbations and other factors that may limit the production rate of fueled clads. Replication of the LANL capabilities is not seen as a viable mitigation path for these risks.

Fueled clad production schedule margin (PuO_2 availability, LANL throughput) is seen to be a discriminator in the postulated strategy downselect process. This is an important factor that favors the Dual Strategy.

Appendix N. Memorandum of Understanding, Supplements, and Related Letters

MEMORANDUM OF UNDERSTANDING
BETWEEN THE
DEPARTMENT OF ENERGY
AND THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONCERNING
RADIOISOTOPE POWER SYSTEMS
FOR SPACE MISSIONS

I. Purpose

The purpose of this agreement is to delineate the authorities and responsibilities of the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) (the parties) in the research, technology development, design, production, delivery, space vehicle integration, and launch phases with respect to certain radioisotope power systems, including Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs), and to establish an agreement pursuant to which DOE and NASA will perform certain functions and provide funds for certain portions of the undertakings covered hereby. DOE is acting pursuant to the Atomic Energy Act of 1954 as amended and the Department of Energy Organization Act, 42 U.S.C. 7101, et seq. NASA is acting pursuant to the National Aeronautics and Space Act of 1958 as amended, 42 U.S.C. 2473 (c) (6). As used in this document, "space vehicle" shall mean the launch vehicle and the spacecraft.

II. General

DOE and NASA recognize that Radioisotope Power Systems (RPS) offer performance advantages over other space-power concepts when applied to certain space missions. They recognize that the use of radioisotope power systems will require their cooperative efforts to ensure effective system development and space vehicle integration as well as to ensure that the statutory responsibilities of each agency are properly fulfilled. Both agencies agree that NASA will furnish to DOE its requirements as to specifications, scheduling, interface, and management controls; and DOE will be responsible for managing the RPS development and production program to meet NASA requirements.

This agreement covers the general provisions for radioisotope power systems to be used by NASA and such other power units as may be mutually agreed to in writing in the future for inclusion under these provisions. Implementing Interagency Agreements, supplemental to this Memorandum of Understanding (MOU), will address the deliverables, levels of support, funding, and other program-specific items in accordance with this agreement and will be executed between DOE and NASA at the Assistant Secretary and Associate Administrator level.

DOE will be responsible for development, production, and delivery of the radioisotope power systems, and NASA shall provide the launch vehicle and spacecraft. DOE will retain title to the radioisotope power systems at all times. DOE shall have the necessary means to enable it to fulfill its responsibility with respect to the radiological health and safety and to safeguards and security aspects of the radioisotope power systems program.

Those facilities and services normally furnished by the Department of Defense (DOD) as range operators or by agreement with NASA will be considered to be furnished by NASA insofar as this agreement is concerned.

III. Agency Responsibilities

A. DOE will be responsible for:

1. Designing, developing, fabricating, evaluating, testing, and delivering the radioisotope power systems to meet the overall system requirements, specifications, schedules, and interface requirements as agreed to by NASA and DOE. DOE will also provide thermal and mechanical models (including software and hardware) for space vehicle integration and test purposes, ground support and test equipment, prelaunch operations support, and documentation as agreed to by NASA and DOE.

2. Retaining custody of the fueled radioisotope power systems at all times, except when the devices are in NASA's custody pursuant to B.2 below.

3. Providing (with the assistance of NASA and any other appropriate agencies) an evaluation of hazards involved for credible nuclear incidents (e.g., Safety Analyses Report). As used in this agreement, the term "nuclear incident" shall have the meaning ascribed to it in the Atomic Energy Act of 1954 as amended and, in addition, shall mean in regard to subparagraph "10" and "12" of this paragraph and subparagraph "14" of paragraph "B," damage or possible damage to the radioisotope power systems.

4. Specifying, in consultation with NASA, the minimum radiological, occupational/public health, safety procedures/criteria, and providing guidance with respect to safeguards and security requirements related to NASA facilities and services associated with the radioisotope power systems.

5. Providing such information concerning the radioisotope power systems as may be required for use in: (1) NASA operational plans and other documents required as part of the mission definition, environmental analysis, and launch approval process; (2) advising the Department of State and the Office of Science and Technology Policy, National Space Council, and United Nations (as appropriate); and (3) operational planning and safety analyses concerning DOD controlled range facilities, including radiological safety in the event of a launch accident.

6. Cooperating with NASA concerning the radioisotope power systems with respect to international, national, State, or other governmental bodies as may be necessary or advisable.

7. Preparing, with NASA, joint public information plans for applications involving radioisotope power systems.

8. Providing technical observation, advice, and assistance to NASA during various operations involving the radioisotope power systems including, but not limited to: (1) prelaunch storage, monitoring, handling, transportation, and preparations for launch; (2) installation on the space vehicle; (3) prelaunch acceptance testing aboard the space vehicle; and (4) launch and mission operations.

9. Affirming to NASA the operational use and flight readiness of the radioisotope power systems with respect to nuclear safety, and participating in the nuclear launch safety approval process.

10. Advising NASA (in the event of a ground or mission accident or flight termination) of DOE's determination of whether a nuclear incident has occurred and determining the extent of any off-site radiological releases. In the event of a nuclear incident, providing technical guidance to NASA and, if applicable, DOD range forces and others, as may be required, for the recovery of the radioisotope power systems and necessary decontamination and disposal operations.

11. Assuming, as between DOE and NASA and to the extent consistent with applicable law, legal responsibility for damages to life and property resulting from a nuclear incident in accordance with Appendix "A" attached hereto.

12. Jointly investigating and reporting (with NASA) nuclear incidents.

13. Funding for the research, development, design, fabrication, qualification, test, evaluation, storage, delivery, contingency planning support, and other related activities of the radioisotope power systems included under subparagraph III.A, as well as radioisotope fuel charges as mutually agreed to by DOE and NASA, will be provided for under separate Interagency Agreements to this agreement.

B. NASA will be responsible for:

1. Providing DOE with necessary details and continuing technical support to satisfy the mission and the technical interface requirements between the space vehicle or other mission applications and the radioisotope power systems, space vehicle trajectory information, mission operational and termination procedures, the configuration of the radioisotope power systems as governed by the application of the space vehicle and mission, the electrical and thermal operating characteristics, the reliability required by the mission, and such other technical requirements as may pertain to the successful execution of the mission. Providing DOE with the necessary technical data and continuing technical support to conduct the required safety tests and analyses associated with satisfying the requirements of the

environmental and safety analyses and the nuclear launch safety approval process.

2. Accepting custody of the radioisotope power systems when turned over to NASA by DOE or a DOE contractor and retaining custody, for the purpose of carrying out the requirements of this agreement, at all times except when transferring custody to DOE or a DOE designated recipient.

3. Complying with the minimum radiological occupational and public health and safety procedures and criteria specified or otherwise approved by DOE for the particular radioisotope power systems.

4. Providing adequate facilities, in conjunction with prelaunch and launch operations, which meet criteria mutually acceptable to DOE and NASA for storage, assembly, checkout, servicing, and/or repair of the radioisotope power systems while in NASA custody, including safeguards and security protection.

5. Providing tracking, command, and data acquisition and reduction facilities and services including those required to monitor the radioisotope power systems.

6. Advising the Department of State, in cooperation with DOE, of the proposed launch of the space vehicle with the radioisotope power systems aboard.

7. Coordinating, in cooperation with DOE, with the Office of Science and Technology Policy on the proposed use of a particular radioisotope power system.

8. Taking such cooperative action with DOE concerning the radioisotope power systems with respect to international, national, State, or other government bodies as may be necessary or advisable.

9. Preparing with DOE joint public information plans for applications involving radioisotope power systems.

10. Installing and testing of the radioisotope power systems in the space vehicle or other mission applications and conducting prelaunch testing in accordance with specifications or instructions agreed to by DOE and NASA.

11. Making overall operational command decisions relating to a launch involving radioisotope power systems aboard and launching the space vehicle consistent with radiological health and safety procedures and criteria specified or otherwise agreed to by DOE and NASA provided, however, that in any event, the DOE instructions or directions respecting radiological health and safety, safeguards, security, and handling of the radioisotope power systems shall be complied with.

12. Providing DOE with available data or information concerning operation, performance, and location of the radioisotope power systems in space.

13. Conducting recovery, monitoring and security operations in the event of ground or mission accident or mission abort and providing personnel and equipment in support of the DOE for recovery of the radioisotope power systems and associated decontamination and disposal operations, as necessary.

14. Jointly investigating and reporting (with DOE) nuclear incidents.

15. Funding for research, development, design, fabrication, qualification, test, evaluation, storage, delivery, contingency planning support, and other related activities of radioisotope power systems as well as radioisotope fuel charges, as mutually agreed to by NASA and DOE will be provided for under separate Interagency Agreements to this agreement.

IV. Additional Provisions

A. This agreement is effective upon signature by both parties. The agreement shall continue in effect until terminated by either party by at least thirty (30) days advance written notice to the other. This agreement succeeds prior Interagency Agreements, and in the event of any potential conflicts, this agreement supersedes prior agreements.

B. Each of the parties shall utilize its contract policies and procedures when contracting with others in furtherance of its undertakings under this agreement.

C. Freedom of Information Act (5 U.S.C. 552), decisions on disclosure of information to the public regarding projects and programs implemented under the memorandum of understanding and supplemental interagency agreements will be made following consultation between DOE and NASA representatives.

Richard H. Truly
Vice Admiral, U.S. Navy
Administrator
National Aeronautics and
Space Administration

Date: July 26, 1991

James D. Watkins
Admiral, U.S. Navy (Retired)
Secretary
Department of Energy

Date: 7/26/91

Appendix A

Nuclear Hazards Indemnity

DOE hereby indemnifies NASA for liability for nuclear incidents under Section 170d. of the Atomic Energy Act of 1954 as amended including the amendments made thereto by the Price-Anderson Amendments Act of 1988, Public Law 100-408 (the Act). The provisions of the clause set forth in 48 C.F.R. 952.250-70, Nuclear Hazards Indemnity, shall apply to this agreement provided, however, that in the event of inconsistency between the provisions of the clause and those of the Act, the latter shall prevail. For purposes of this Appendix and the clause set forth in 48 C.F.R. 952.250-70, the term "contract location" means the property and facilities owned and/or operated by NASA and the Jet Propulsion Laboratory whereon radioisotope power systems are present. NASA agrees to modify this Appendix to include herein any Nuclear Hazards Indemnity clause promulgated by DOE to implement the Act.

AGREEMENT NO. 1 TO SUPPLEMENT
MEMORANDUM OF UNDERSTANDING
DATED JULY 26, 1991
BETWEEN THE

U.S. DEPARTMENT OF ENERGY

AND THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONCERNING RADIOISOTOPE POWER SYSTEMS FOR SPACE MISSIONS

ARTICLE I. This Agreement No. 1 supplements Subparagraphs A.1, A.13, and B.15 of Article III of the Memorandum of Understanding Concerning Radioisotope Power Systems for Space Missions dated July 26, 1991 (MOU) between the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

ARTICLE II. This Agreement No. 1 applies to the radioisotope power systems and supporting services, exclusive of fuel and fuel-related services, for the Cassini mission to Saturn.

ARTICLE III. With regard to DOE's provision of the radioisotope power systems and supporting services for the Cassini mission to Saturn, DOE, and NASA agree to the following:

A. EQUIPMENT AND SERVICES

1. Equipment. The delivered radioisotope power systems shall consist of four (4) General Purpose Heat Source Radioisotope Thermoelectric Generators (GPHS-RTGs). Three newly fueled GPHS-RTGs (F-2, F-6, and F-7) will be provided, each having a minimum power output of approximately 272 watts, on October 6, 1997, with the exact value specified in the Cassini Spacecraft Radioisotope Thermoelectric Generator (RTG) Requirements Specification (JPL equipment specification 515802). The spare flight unit (F-5) from the Galileo/Ulysses missions will be retained in monitored storage and will be available as a spare flight unit. All GPHS RTGs will contain a barometrically actuated pressure relief device.

   DOE shall also provide 157 Light Weight Radioisotope Heater Units (LWRHUs). Unused flight RTGs, LWRHUs, and spare components will be returned to DOE for disposition, as mutually agreed to by NASA and DOE.

2. Services. Ground support and test equipment will be provided by DOE for the RTGs and LWRHUs. DOE will also provide support for space vehicle integration and testing of the RTGs and LWRHUs, provide prelaunch operation support, conduct safety activities, and provide documentation as agreed to by NASA and DOE to meet established specifications, schedules, and interface requirements.

B. FUNDING

1. Estimated Funding Profile. The estimated funding for the equipment and services provided for in Article III.A.1. and 2. of this Agreement No. 1 are cited below. This funding profile supports hardware delivery by July 13, 1997. The actual cost of providing these goods and services may require funding levels which exceed those specified in this agreement. Furthermore, budget constraints imposed on either party may alter funding availability in a given fiscal year. In the event either of these should occur, adjustments to the funding levels provided by either party or the scope and content of the goods and services to be provided by DOE may be made contingent upon mutual resolution by both affected parties. It is understood that DOE will not provide equipment and services in excess of those specified in Article III A.1 and 2 without mutual consent by both parties and the provision of additional funds by NASA to support these new requirements.

GPHS-RTGs

Fiscal Year

(in millions of dollars)

	1990	1991	1992	1993	1994*	1995	1996	1997	1998	Total
DOE	4.1	24.1	25.6	20.4	19.95	19.0	15.5	10.5	2.5	141.65
NASA	0.5	18.9	20.0	22.3	23.65	17.2	8.5	4.6	0.6	116.25
Total	4.6	43.0	45.6	42.7	43.60	36.2	24.0	15.1	3.1	257.90

* FY 1994 funding includes costs to perform low level vibration testing of the flight spare RTG, F-5. If the F-5 tests are not required, funding levels will be reduced accordingly.

LWRHUs

Fiscal Year

(in millions of dollars)

	1992	1993	1994**	1995	1996	1997	Total
DOE	0.3	0.3	0.65	1.2	0.7	0.2	3.35
NASA	0.0	0.7	1.01	1.0	0.4	0.1	3.21
Total	0.3	1.0	1.66	2.2	1.1	0.3	6.56

** FY 1994 funding includes costs to perform LWRHU qualification vibration tests to qualify the LWRHUs for higher dynamic loads.

2. Fuel Production and Processing Costs. The funding requirements identified above are solely for the equipment and services covered under this Agreement No. 1, including pelletization and encapsulation costs, and specifically do not include the costs of fuel acquisition, production and processing, which costs will be covered by a nonproject specific agreement on Pu-238 supplementing the MOU. Agreements as set forth in this supplement are independent of the finalization of the specific agreement on Pu-238.

3. Transfer of Funds. Annually NASA will transfer funds to the DOE for conduct of tasks for the current year. NASA will be charged full costs for its share of the work conducted under this Agreement No. 1.

4. Terms. Individual agency funding for this program is subject to the availability of appropriated funds. NASA funds for the full year of activity must be provided to DOE at the beginning of the fiscal year consistent with annual appropriations.

5. Full Cost Definition. As used in this Agreement No. 1, "full cost" includes added factor.

6. Miscellaneous Terms. If either agency is unable to meet the funding commitments in the profile provided in subparagraph 1. of this paragraph B. for any particular year, the other agency is not required to adjust its commitments so as to maintain the total annual funding, with the recognition that there will be resulting impacts to program schedule and scope.

7. Notification. Prior to the start of each Fiscal Year, DOE will confirm to NASA that the cost estimates for that year and subsequent years are still considered accurate or will inform NASA of any projected increases. In addition, timely notification will be given to NASA at any time during the year that DOE becomes aware of projected increases in the NASA share of the project costs.

ARTICLE IV. This Agreement No. 1 to supplement the MOU is effective upon the date of the last signature by the parties.

Wesley T. Huntress, Jr.
Associate Administrator for
Space Science
National Aeronautics and
Space Administration

Date: 22 Oct 1993

Daniel A. Dreyfus
Acting Director
Office of Nuclear Energy
U.S. Department of Energy

Date: 11·9·93

AGREEMENT NO. 2 TO SUPPLEMENT

MEMORANDUM OF UNDERSTANDING

DATED JULY 26, 1991

BETWEEN THE

U.S. DEPARTMENT OF ENERGY

AND THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONCERNING RADIOISOTOPE POWER SYSTEMS FOR SPACE MISSIONS

ARTICLE I. This Agreement No. 2 supplements Subparagraphs A.1, A.13, and B.15 of Article III of the Memorandum of Understanding Concerning Radioisotope Power Systems for Space Missions dated July 26, 1991 (MOU) between the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

ARTICLE II. This Agreement No. 2 applies to the radioisotope power systems and supporting services for the Mars Pathfinder mission.

ARTICLE III. With regard to DOE's provision of the radioisotope power systems and supporting services for the Mars Pathfinder mission, DOE and NASA agree to the following:

A. EQUIPMENT AND SERVICES

1. Equipment. DOE shall deliver three (3) Light Weight Radioisotope Heater Units (LWRHUs) to the Kennedy Space Center, Florida. These 3 LWRHUs will be provided (by August 1996) from the existing spares from the Galileo mission.

2. Services. As necessary, ground support and test equipment will be provided by DOE for the LWRHUs. DOE will provide prelaunch operation support, as necessary, conduct safety activities, and provide documentation as agreed to by NASA and DOE to meet established specifications, schedules, and interface requirements.

B. FUNDING

NASA provided the necessary funds to fuel and fabricate these LW RHU units during the Galileo/Ulysses mission development program phases. Therefore, no additional funds are required to provide these units from existing flight spare units.

ARTICLE IV. This Agreement No. 2 to supplement the MOU is effective upon the date of the last signature by the parties.

Wesley T. Huntress, Jr.
Associate Administrator for
Space Science
National Aeronautics and
Space Administration

July 29 1994
Date

Terry R. Lash
Director
Office of Nuclear Energy
U.S. Department of Energy

July 6, 1994
Date

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

MAY 9 1995

Reply to Attn of: S

Dr. Terry R. Lash
Director
Office of Nuclear Energy
Department of Energy
Washington, DC 20585

Dear Dr. Lash:

Thank you for your letter of March 17, 1995. The enclosure to your letter, which highlights proposed funding arrangements for new converter technology for radioisotope power systems, has received favorable response within NASA.

NASA's current plans are to launch the "Pluto Express" mission in year 2003. I understand that you currently estimate DOE funding in support of radioisotope power systems to be approximately $30M annually. At this time, we anticipate a NASA investment in radioisotope power systems of approximately $60M through FY 2003 for Pluto Express. I suggest we now allow our staffs to proceed further to coordinate in more detail the schedules and funding arrangements for the required radioisotope power system, so that this can be incorporated into our respective FY 1997 budget submissions. Please have the appropriate member of your staff contact Ms. Mary Kicza at (202) 358-0735 to initiate this dialogue.

NASA looks forward to continuing its strong partnership with DOE as together we embark on this next phase of space exploration.

Sincerely,

Wesley T. Huntress, Jr.
Associate Administrator
for Space Science

cc:
OMB/EOO2/Ms. S. Horrigan
Dr. J. Fellows

Department of Energy
Washington, DC 20585

March 17, 1995

Dr. Wesley T. Huntress, Code S
National Aeronautics and Space
Administration
300 E Street, SW
Washington, DC 20546

Dear Dr. Huntress:

The enclosure summarizes discussions between our staffs regarding future funding for Radioisotope Power Systems. My understanding is that you intend to present this summary to senior NASA management. We look forward to NASA's response regarding this matter.

Please call me or Robert Lange of my staff (301) 903-4362 if we can be of further assistance.

Sincerely,

Jerry R. Lash

Jerry R. Lash, Director
Office of Nuclear Energy

Enclosure

FUNDING OF NEW CONVERTER TECHNOLOGY FOR RADIOISOTOPE POWER SYSTEMS

The Department of Energy recognizes the importance of maintaining the capability of producing radioisotope power systems (RPSs) to support future space exploration conducted by the National Aeronautics and Space Administration. In the past, all research and design activities had been funded by DOE whereas funding for specific mission flight hardware was provided by NASA. However, as the Department's budget for nuclear energy programs becomes more constrained, it has become necessary to review the manner in which the design and production of future RPSs will be funded. Early in the FY 1996 budget process, the Department participated in several discussions with NASA staff focused on determining an equitable manner to fund future activities while maintaining the integrity of the July 1991 Memorandum of Understanding (MOU) between the Department and NASA concerning radioisotope power systems for space missions.

The concurrence of those staff discussions is that for missions beyond Cassini, NASA will pay all costs for mission-specific related technology and radioisotope power system development. Moreover, since the technology and mission specific development often requires longer lead times than the spacecraft development itself, NASA may be required to provide mission-specific technology funding in advance of an official start of mission activities.

In turn, DOE will provide--based upon NASA projections that such capabilities will be required--funding to maintain the technology and facility infrastructure that would enable these systems to be fabricated in the future. The essential expertise, training programs, enhanced efficiency developments, and all other key aspects of radioisotope power systems development and production will be sustained such that they are available when a request is received by DOE from NASA for a mission specific system. DOE will then be able to make technology selections and utilize the existing facilities without the expense and delay associated with restart. NASA's funding for mission specific activities will build upon this DOE-maintained infrastructure.

DOE funding required to retain this capability is currently estimated to be approximately $30 million annually. DOE will review this estimate to determine if further efficiencies can be achieved.

It is anticipated that this approach will be reflected in each agency's future budget requests, beginning with FY 1997.

Appendix O. Funding Arrangements – A Historical Perspective

As stated in the Memorandum of Understanding Between the Department of Energy and the National Aeronautics and Space Administration Concerning Radioisotope Power Systems for Space Missions (Appendix N, *MOU*, Section III.A.13 and III.B.15), "funding for the research, development, design, fabrication, qualification, test, storage, delivery, contingency planning support, and other related activities of the radioisotope power systems as well as radioisotope fuel charges, as mutually agreed to by DOE and NASA, will be provided for under separate Interagency Agreements to this agreement." These arrangements may be modified or restructured in any mutually acceptable way from mission to mission, or from time to time, at the discretion of the executive offices of the two agencies.

As documented in the Cassini supplement to the MOU (Appendix N), NASA agreed to fund the DOE at a specified level of $116.25 million to cover "the full costs for its share of the work conducted under this Agreement No. 1." Although not specifically defined in the supplement, NASA's share mainly funded the recurring cost of providing four flight ready Galileo/Ulysses GPHS-RTGs, modified only to incorporate a barometrically actuated pressure relief device to replace the lanyard release device used on Galileo. It is important to note that the DOE funded the full non-recurring cost for the development of these RTGs under the funding arrangements relevant during the Galileo program. NASA defined the spacecraft related requirements for these RTGs, and the DOE funded the full non-recurring cost. As with the Cassini agreement, NASA funded DOE only for the recurring cost of the Galileo and Ulysses RTGs.

For earlier missions different arrangements have been employed, including some in which the DOE (then the Atomic Energy Commission) funded both the recurring and non-recurring costs (see Figure O-1).

		Non Recur Devel	Qual Test	Flight Units	Spares
Viking	Mgmt Funding	DOE DOE	DOE DOE	DOE DOE	DOE DOE
Voyager	Mgmt Funding	DOE DOE	DOE DOE	DOE DOE	DOE NASA*
Galileo	Mgmt Funding	DOE DOE	DOE NASA*	DOE NASA*	DOE NASA*
Cassini	Mgmt Funding	N/A N/A	N/A N/A	DOE NASA	DOE NASA
95 Exch	Mgmt Funding	DOE NASA	DOE NASA	DOE NASA	DOE NASA

* Pre-Negotiated Capped Cost vs Fully Cost Reimbursable

Figure O-1. Paradigm Shift

Voyager used the MHW, which had been developed by DOE for use by the Air Force on the LES 8 and 9 missions. For Voyager, the MHW was basically an off-the-shelf device. Only very minor modifications were made to accommodate Voyager spacecraft interface requirements. These changes were defined by the project, but funded by the DOE.

This was also the case for Pioneer 10 and Viking, which used slightly modified versions of the pre-existing SNAP-19 design. It was also true for Cassini, which used a slightly modified version of the pre-existing GPHS-RTG design. In each case the modifications were modest enough to include in the agreed to recurring costs for each of these mission requirements. Because the DOE funded the changes, the project had to make a convincing case for the need, the DOE demanding to understand and accept the need before agreeing to fund it.

Glossary and Acronyms

AMTEC	Alkali Metal Thermal-to-Electric Conversion
AO	Announcement of Opportunity
ARPS	advanced radioisotope power system
AS-TE	advanced segmented thermoelectrics
ATLO	Assembly, Test, and Launch Operations
BOM	Beginning of Mission
CBCF	carbon-bonded carbon fiber
CVS	clad vent set
CY	calendar year
DOE	Department of Energy
EELV	evolved expendable launch vehicle
EIS	Environmental Impact Statement
ELV	expendable launch vehicle
EMI	electro-magnetic interference
EO	Europa Orbiter
EOM	End of Mission
ETG	electrically-heated thermoelectric generator
FC	fueled clad
FWPF	fine weave pierced fabric
FY	fiscal year
GPHS	General Purpose Heat Source
HQ	Headquarters
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LES	Lincoln Experimental Satellite
LMA	Lockheed Martin Astronautics
LWRHU	Light Weight Radioisotope Heater Unit
MAYAK	Russian Federation's MAYAK Production Agency
MHW	Multi-Hundred Watt

MOU	Memorandum of Understanding
Mound	DOE Mound Facility
MSL	2007 Mars Smart Lander
MSR	2011 Mars Sample Return
MTBF	mean time between failures
NASA	National Aeronautics and Space Administration
NE-50	Office of Space and Defense Power Systems, DOE
OP	outer planets
ORNL	Oak Ridge National Laboratory
OSS	Office of Space Science, NASA
PKB	Pluto Kuiper-Belt
PG	pyrolytic graphitic
RFP	Request for Proposal
RHU	radioisotope heater unit
RPS	radioisotope power system
RTG	radioisotope thermoelectric generator
SP	Solar Probe
TAGS	alloy of tellurium, antimony, germanium, and silver
TES	Teledyne Energy Systems
W_e	Watts-electric
W_{th}	Watts-thermal

References

1. U.S. National Space Policy (9/96)
2. Magwood Statement to Subcommittee on Energy and Environment, House Science Committee, February 25, 1998
3. America's Nuclear Technology Future, A Strategic Plan, U.S. Department of Energy, July 2000.
4. Space Exploration - Power Sources for Deep Space Probes, Report to the Honorable Barbara Boxer, U.S. Senate, B-279348, GAO, National Security and International Affairs Division, 29 May 1998
5. Space Exploration: Power Sources for Deep Space Probes, Letter Report, GAO/NSIAD-98-102, 29 May 1998.
6. Letter to Allen Li, U.S. GAO from J.R. Dailey, NASA, 23 April 1998.
7. Advanced Radioisotope Power System (ARPS) Team 2001 Technology Assessment and Recommended Roadmap for Potential NASA Code S Missions Beyond 2011, April 2001
8. JPL Viewgraph Presentation to Code S on Outer Planet Mission Options, December 2000
9. MHW/F-5/E8 Assessment Study, Final Report, LMSP-7269, 30 June 2000