ADVANCED CONVERTER TECHNOLOGY EVALUATION AND SELECTION FOR ARPS

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Abstract

The three advanced converter technologies for future potential radioisotope power sources for space were evaluated based on mission require. ments for proposed NASA planetary missions. Alkali Metal Thermal-to-Electric (AMTEC), Stirling Engines (ST) and Thermal PhotoVoltaic (TPV) technologies were the three best advanced conversion technologies candidates for low power, -100 watts, space radioisotope power source. General mission requirements were prepared for potential NASA deep space scientific missions as described in the Mission to the Solar System Roadmap, (Elachi 1996). The selection criteria for the conversion technology was prepared based on mission requirements. Safety, Performance (efficiency, specific power & lifetime), Development (cost and schedule risk), Spacecraft Interfaces and Operations and Scalability (150We to 50 We to 10 We) were the five key converter technology characteristics used to compare and make the selection. AMTEC was selected as the conversion technology for the near term advanced radioisotope power source for potential NASA deep space science missions.

INTRODUCTION

Three advanced conversion technologies, Alkali Metal Thermal-to-Electric (AMTEC), Stirling (ST) and Thermal PhotoVoltaic (TPV), were being developed and evaluated as potential converters for solar or radioisotope heated space power sources. NASA completed the Mission to the Solar System Roadmap describing several potential deep space scientific missions with significant science community interest. Advanced technology radioisotope power was identified as a potential power source needed to accomplish several of these potential deep space scientific missions. Top-level mission requirements for a radioisotope power source (RPS) were prepared for the near term proposed missions. These mission requirements, summarized in Table 1, were used to evaluate and select one conversion technology.

TABLE 1. RPS Requirements for Near Term Deep Space Science Missions

Power Level at End Of Mission (EOM) (We)	100
Power Source Lifetime (yrs)	15
Technology Power Scalable Range (We)	50 to 150
Conversion Technology Scalable Down to (We)	10
Operating Voltage (dc) (V)	28
Radioisotope Heat Source	Use Existing General purpose Heat Source (GPHS) Modules
Safety	No Negative Impact
Mass (kg)	< 8
Heat Rejection Area	Minimum
Schedule	Deliver Engineering Model by July 1999

CONVERSION TECHNOLOGIES

The conversion technologies for space radioisotope power were being developed to improve the conversion efficiency from thermal power to electric power. The major reasons for increasing conversion efficiency are:

1. To reduce the amount of radioisotope material for a given electric power.
2. To reduce the radioactive source term in the case of a very unlikely release of hazardous material.
3. To reduce the mass of the power source to provide more flexibility to the spacecraft/mission designer.

The near term high efficiency conversion technologies for a small, low mass radioisotope power source (RPS) arc AMTEC, ST, and TPV. These arc the three technologies that were considered and evaluated for the near term RPS.

AMTEC Technology

Alkali Metal Thcrn]al-to-Electric (AMTEC) converter is an electrochemical conversion device that uscs a solid electrolyte, beta alumina, and high-pressure sodium vapor on one side and low pressure sodium on the other side to produce electric power. The Beta Alumina Solid Electrolyte (BASE) under a pressure gradient passes sodium ions but not neutral sodium atoms. The inner surface of the BASE has a porous electrode that collect the electrons given up by the sodium ionized atoms and conducts the electrons via a current collector through an external load and back to an outer surface porous electrode which neutralizes the positive sodium ions. A radiator rejects heat from the sodium vapor to space which condenses the low-pressure sodium vapor. A wick pumps liquid sodium back to the heat source where the sodium is vaporized by the heat source at the high pressure and forced through the BASE, thus converting thermal power to electric power.

The AMTEC Multitube cell and it operations are described in a paper by Underwood, et. al. (1992). A conceptual design of a Multitube AMTEC cell is shown in Figure 1. The AMTEC Multitube radioisotope power source (RPS) operates with a hot-face temperature of about 1200K and a cold-face temperature of about 600K.

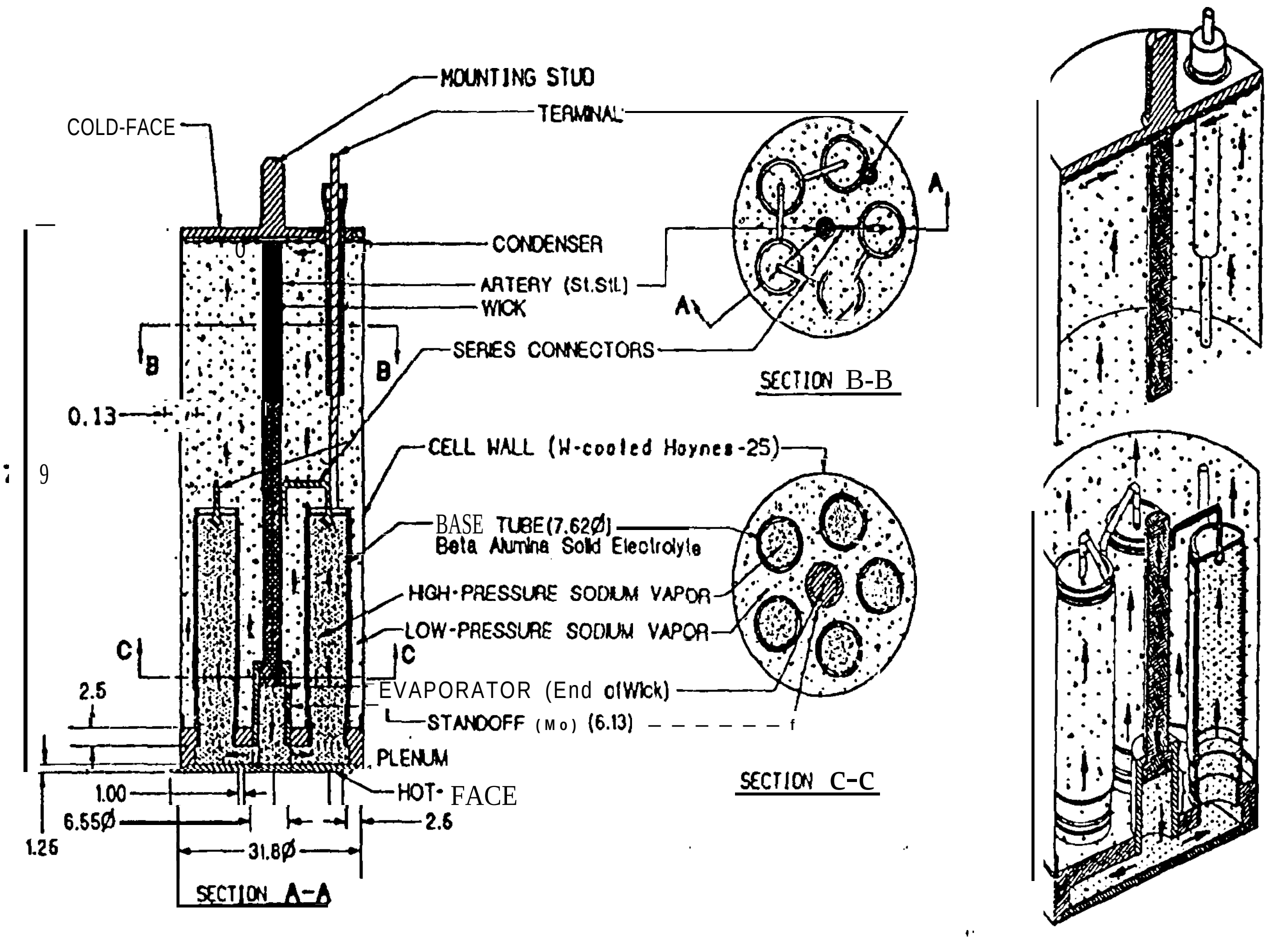

FIGURE 1. Multitube AMTEC Cell (all dimensions arc in cm.)

Stirling Conversion Technology

The Stirling technology is being developed for usc as a potential space power system. The Stirling engine. is also being developed for ground based applications. The Stirling engine is a high efficiency free displacer and power piston device with a linear alternator to convert thermal power to electric power. The Stirling engine can bc made very small and is in fact used as a very, very small compressor for cryogenic cooling in a hand held infrared camera. The engine requires high-pressure helium gas, a regenerator and a radiator to reject the waste heat to space. The pistons are supported on hydrodynamic bearings or flexure bearings to keep the pistons from touching the wall. The linear alternator produces ac power at a frequency dependent on the cycles pcr second of the displacer and the power pistons. Figure 2 shows a conceptual design of a Stirling engine for a potential RPS.

The Stirling conversion technology is a closed cycle heat engine with external heating and a cooling. With a very effective regenerator the engine can approach Carnot cycle efficiency. The engine/altemator only has three moving parts. Materials limit the engine hot side operating temperature. A typical Stirling using stainless steel or super alloy materials is limited to a hot side temperature of about 975K and a cold side temperature set by the radiator size and mass for space power source. The linear alternator is highly developed at room temperature and has to be cooled in space to about 350K.

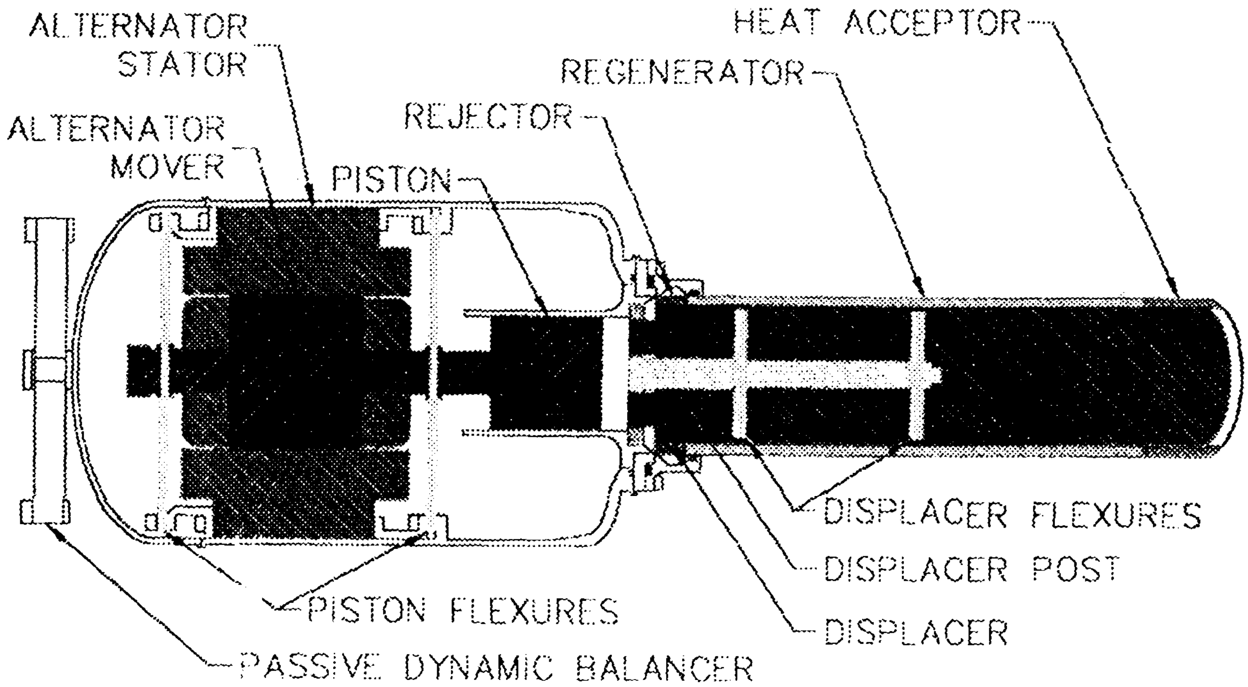

FIGURE 2. Sterling Engine Concept

Thermal PhotoVoltaic Technology

The thermal photovoltaic (TPV) technology requires a hot heat source that radiates to photovoltaic (PV) cells. The photovoltaic cells can only efficiently convert selective wavelengths from a hot heat source to electricity. The Radioisotope TPV generator consists of a hot heat source that radiates to a photovoltaic army of closely space gallium antimonide cells. The cell arrays arc covered with a spectrally selective infrared filter that transmits those wavelengths that can bc efficiently converted to electricity by the PV cells, and reflects all other wavelengths back to thc heat source. Thus, the reflected cncrgy is conscrvcd and rc-emittcd as a full spectrum, which greatly incrcascd thc efficiency of the generator. The PV cclls arc covcrcd with a thin gold film deposited on a transparent substrate containing over two hundred million sub-micron holes pcr cm^2 opposite each PV ccll. The size, spacing, and geometry of the hole pattern dctermincs the performance oft hc rcsonant filter.

The PV cells arc arrayed in a series-parallel arrangement to generate the voltage desired for the radioisotope TPV generator. Thc PV cells nccd to bc cooled to about 270K to achieve their high efficicncics. Therefore, large, low-mass radiators are required to radiate heat from the PV cells to space. The radiator mass is the largest mass component of the Radioisotope TPV Power Source. An exploded view of the TPV generator is shown in Figure 3.

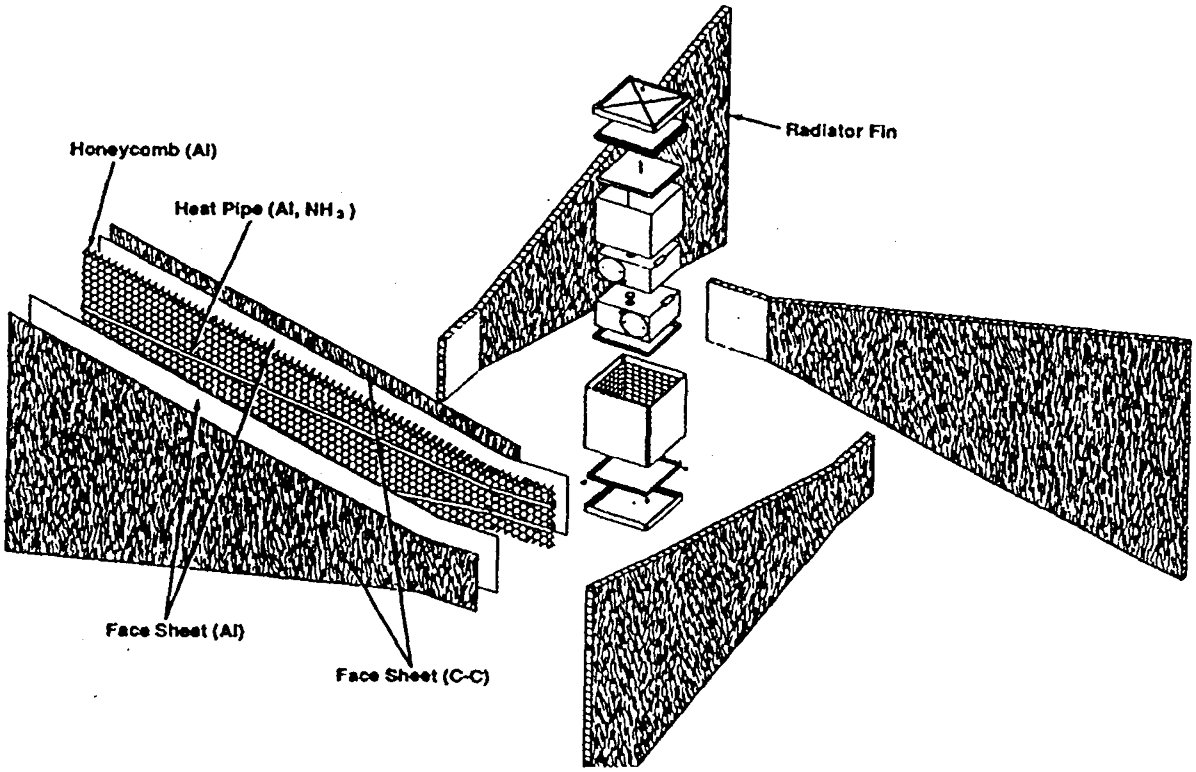

FIGURE 3. Exploded View of a TPV Generator

Mission Requirements

The ARPS requirements for the Europa Orbiter and Pluto/Kuipcr Express missions, (Mondt, Underwood and Ncsmith, 1997), areas follows:

1. Must meet all space nuclear safety requirements.
2. Minimum mass to meet low cost launch vchiclc constraints.
3. Minimum volume to meet launch vehicle shroud, acrocapturc volume constraints.
4 Minimum radiator area to maximize instrument field of view simplifies launch packaging/vibration, improve deployment reliability and minimize thruster plume impingement.
5. Capability to meet the Delta II or 111 launch cnvironment (e.g. vibration, acoustic, etc.).
6. Provide a minimum of 150 watts of electric power at the cnd of a six-year Europa Orbiter mission and 130 watts at the end of a potential ten-year Pluto/Kuipcr Express mission

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7. Power source technology readiness must validate that failure rates and power degradation as a function of time arc compatible with mission lifetime.
8. Recurring costs (cost to the flight project) should bc less than 10% of the flight project ($ 10M to $15 M). The total Europa or Pluto mission costs arc from $ 100M and $150 M.
9. The maximum time from mission approval to S/C launch for Europa and Pluto will be three years.
10. Flight unit fabrication, acceptance test, delivery and launch approval must bc accomplished in less than three years after mission approval.
11, The distance from the power source to the sun will vary between 0.7 and 40 AU and 2 to 0.0006 suns.
12, The mass of the ARPS radioisotope fuel must bc as low as possible.

ARPS Near Term Requirements Based on the Near Term Missions Requirements

The requirements for the advanced radioisotope power source (ARPS) based on the above near term missions requirements arc listed below. These are the requirements that were used to prepare a selection criteria for evaluating and selecting the near term conversion technology.

1. Minimum End of Mission (EOM) Power Level: 100 watts, scalable to 150 watts
2. Power Output on the Launch Pad: 15 to 20 watts
3. Mass: 8 kg at 100 watts and 12 kg at 150 watts
4. Lifetime: 6 to 10 years from launch with the potential of 15 *years*
5. Minimum Radiator Area
6. Minimum Stowage Volume for Launch
7. Failure Mechanisms and Design Margins Understood
8. Power Level Degradation predicable as a Function of Time
9. Delta Class Launch Vehicle Environment
10. Radiation Dose: =25 Mrad Si for the Europa Obiter mission
11. Vibration Compatible with Science Instruments and Star Trackers
12. Recurring Costs (Total ARPS flight project cost $10 to $ 15M per mission)
13. Maximum time from mission approval to launch: 3 years
14. Space Solar Environment (between 0.7 to 40 au or 2 to 0.0006 suns)
15. High Converter Efficiency
16. Converter to Have No Negative impact on GPHS safety

Selection Criteria

The selection criteria for the conversion technology was prepared base on the above near term requirements. The selection criteria were described in the terms of the following five design characteristics each with equal weight.

1. Safety
2. Performance
3. Development
4. Spacecraft Interfaces and Operations
5. Scalability

The design characteristics were compared based on an integrated power system for each conversion technology. The **Safety** characteristic was evaluated based on the conversion technology effect on the nuclear safety of the existing GPHS modules. The **Performance** characteristics were evaluated at the system level in terms of the highest system efficiency, lowest system mass and the potential for 15-year system lifetime. The **Development** characteristic included an assessment of present conversion technology readiness, an estimate of the nonrecurring and the recurring cost and the projected the risk of the conversion technology being flight ready for a 2002 launch. The **Spacecraft Interfaces and Operations** characteristic was evaluated at the power system level on the following. 1) The ease of integrating the ARPS into a spacecraft (simple S/C interfaces and low mass, high efficient power electronics), 2) the case of integrating the power source into the launch stack and 3) the autonomy of the power source during all operational phases of the mission. The **Scalability** characteristic was also evaluated at the system level based on selecting a conversion technology that if developed for the near term missions was easily adapted to a high performance radioisotope power sources at 50 watts and/or 10 watts.

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Technical Evaluation Team Results

A technical conversion technology team, composed of technical experts in the technology of each of the three conversion technologies was appointed, The team reviewed the technology status of each conversion technology and projected the performance results when integrated into an advanced radioisotope power system. The team's evaluation of the three conversion technologies with respect to the above selection criteria is as follows:

Alkali Metal Thermal to Electric (AMTEC)

Safety: The AMTEC conversion technology could be integrated with the GPHS modules with no impact on safety.

Performance: The AMTEC conversion technology was rated overall best in this characteristics because it has the highest system efficiency and lowest system mass. The potential system lifetime was rated second best because of lack of lifetime data at operating temperatures.

Development: The AMTEC conversion technology was rated overall second best in this characteristic. The technology maturity and schedule risk of the AMTEC conversion technology was rated second best because there is no ground system test of a space flight configuration, The estimated nonrecurring and recurring costs for the AMTEC converter was rated equal to the Stirling converter.

Spacecraft Interface and Operations: The AMTEC conversion technology was rated overall best in this characteristic. In S/C integration and operations the AMTEC was best because it has the smallest volume, the smallest radiator area and highest temperature radiator (no special S/C orientation at 0.7 au), no moving parts (no vibration), and the most autonomy during all phases of the mission, In S/C interfaces AMTEC was best because the dc power output results in the lowest mass power electronics.

Scalability: The AMTEC conversion technology was rated best in this characteristic because the developed AMTEC cell for the 100watt ARPS is directly applicable to a 150 or a 50-watt class ARPS and the AMTEC cell technology can be applied to a 10-watt class ARPS.

Stirling Conversion Technology

Safety:

The Stirling conversion technology could be integrated with the GPHS modules with no impact on safety.

Performance:

The Stirling conversion technology was rated overall last in this characteristic. The Stirling technology was rated last because it is a lower conversion efficiency technology and a higher mass power source for space than AMTEC or TPV. The potential system lifetime was rated best because of a ground system Stirling 11 watt engine with a similar configuration as a space design has operated for over 30,000 hours. However, the 11 watt ground test engine does not have a regenerator, which is required for the high efficiency space engine, and the engine is operating at lower power and lower temperatures than required for a space engine.

Development:

The Stirling conversion technology was rated overall best in this characteristic. The technology maturity and schedule risk of the Stirling conversion technology was rated best because there is a ground system test of a Stirling with a configuration that is similar to a space flight configuration. The estimated nonrecurring and recurring costs for the Stirling converter was rated equal to the AMTEC converter.

Spacecraft Interface and Operations:

The Stirling conversion technology was rated overall second best in this characteristic. In S/C interfaces the Stirling was second best because it has the largest volume and the second largest radiator area. In S/C operations the ST technology was rated second best because of its low temperature radiator (requires special S/C orientation at 0.7 au), moving parts (creates a vibration environment onboard the S/C) and ac power output (requires the highest mass power electronics. The ST technology also has the least autonomy during all phases of the mission.

Scalability:

The Stirling conversion technology was rated last in this characteristic because the technology developed for the 100-watt class requires four 33.4 watt engines which arc not directly applicable for the 150, 50 or 10-watt class ARPS. The technology is applicable at the three power levels but a ncw engine has to be developed for each.

Thermal photovoltaic (TPV) Technology

Safety:

The TPV conversion technology was rated last in this characteristic because it requires a higher temperature GPHS module than presently qualified

Performance:

The TPV conversion technology was rated overall second best in this characteristic. The potential system lifetime was rated last because of a limited lifetime data on the filter lifetime. The TPV technology was rated second because its potential conversion efficiency is better than the Stirling but not as high as the AMTEC conversion efficiency. Because of the large radiator the TPV results is a higher mass power source for space than AMTEC.

Development:

The TPV conversion technology was rated overall last in this characteristic. The technology maturity and schedule risk of the TPV conversion technology was rated last because the filter technology is very immature and there is no ground system test of a space flight configuration, The estimated nonrecurring and recurring costs for the TPV converter was not rated because of the unknowns at such an early technology development stage.

Spacecraft Interface and Operations:

The TPV conversion technology was rated last in this characteristic, In S/C integration operations the TPV was last because it has the largest radiator area (difficult to integrate with the S/C) and lowest temperature radiator (special S/C orientation and pointing required for the power source radiator at 0.7 au).

Scalability:

The TPV conversion technology was rated second best in this characteristic because the technology developed for the 100-watt class can be applied to the 150,50 and 10-watt class ARPS.

CONCLUSIONS

The technical conversion evaluation team concluded that:

1. The **Thermal PhotoVoltaic (TPV) Conversion Technology is** not technology ready for the near term ARPS.

2. The **Stirling (ST) Conversion Technology** has the least schedule and technical risk but a much poorer performance than AMTEC or TPV. The Stirling technology has a large impact on the S/C interface in terms of the ac to dc power electronics and the electrical control of the linear alternators, The Stirling technology also has a large negative impact on S/C operations in terms of vibration and S/C orientation at 0.7 au.

3. The **Alkali Metal Thermal-to-Electric (AMTEC) Conversion Technology** has schedule and technical risk but the best performance, the best attributes for S/C interfaces and operations and the best scalability characteristics.

Based on the above findings a DOE/NASA/JPL Converter Selection Board selected AMTEC as the conversion technology to be developed for the near term ARPS with approximately 10'%. of the first years' technology effort spent on the **ST** conversion technology as a backup.

Acknowledgments

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