IECEC 95-264

ADVANCED RADIOISOTOPE POWER SOURCE OPTIONS FOR PLUTO EXPRESS

Mark L. Underwood
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, California 91109-8099
Tel # (818) 354-9049 Fax# (818) 393-4272

ABSTRACT

In the drive to reduce mass and cost, Pluto Express is investigating using an advanced power conversion technology in a small Radioisotope Power Source (RPS) to deliver the required mission power of 74 W(electric) at end of mission. Until this year the baseline power source under consideration has been a Radioisotope Thermoelectric Generator (RTG). This RTG would be a scaled down GPHS RTG with an inventory of 6 General Purpose Heat Sources (GPHS) and a mass of 17.8 kg. High efficiency, advanced technology conversion options are being examined to lower the power source mass and to reduce the amount of radioisotope needed. Three technologies are being considered as the advanced converter technology: the Alkali Metal Thermal-to-Electric Converter (AMTEC), Thermophotovoltaic (TPV) converters, and Stirling Engines. Conceptual designs for each of these options have been prepared. Each converter would require only 2 GPHS to provide the mission power and would have a mass of 6.1, 7.2, and 12.4 kg for AMTEC, TPV, and Stirling Engines respectively. This paper reviews the status of each technology and the projected performance of an advanced RPS based on each technology. Based on the projected performance and spacecraft integration issues, Pluto Express would prefer to use the AMTEC based RPS. However, in addition to technical performance, selection of a power technology will be based on many other factors. The technology community must continue the development of the converters in order to bring them to a state of readiness by 1997 or 1998 such that they can be contenders in the later selection of the Pluto Express power source.

INTRODUCTION

One goal of Pluto Express is to revolutionize our knowledge of Pluto and its moon Charon. In order to help reach this goal, Pluto Express is aggressively pursuing advanced technologies that can reduce the mass and cost of the mission. Radioisotope heated power systems that have traditionally provided electrical power for outer planetary spacecraft are typically viewed as massive, inefficient, and expensive. Several advanced thermal-to-electric converter technologies are on the horizon that could change this view. These converters operate with up to five times the efficiency of the thermoelectrics used in traditional radioisotope thermoelectric converters (RTGs). Due to the increased efficiency, advanced radioisotope power sources (RPSs) require much less Pu-238 radioisotope fuel and have a much lower mass. These factors reduce the cost of the RPS and the overall mission. Also, by conserving the Pu-238 fuel and demonstrating an advanced conversion technology, Pluto Express would enable future deep space missions at even lower cost. This paper describes the advanced RPS concepts that are being considered for Pluto Express. The advanced converter options that are being considered are the Alkali Metal Thermal-to-Electric Converter (AMTEC), Thermophotovoltaic (TPV) converters, and Stirling Engines.

First, a brief overview of Pluto Express and the sciencecraft approach to low cost mission design is provided. The technology status of the three converter options and the design concepts that could be integrated into Pluto Express is then discussed. A brief discussion of the factors in selecting a single power source technology that will be pursued to flight concludes the discussion.

PLUTO EXPRESS OVERVIEW

Pluto is the only planet in our Solar System that has not been visited by a spacecraft. Pluto is the largest of a class of primordial bodies at the edge of our Solar System which have comet-like properties and remain relatively unmodified by warming from the sun. The composition of Pluto is thought to be similar to that of Triton, the largest moon of Neptune, which was reconnoitered by Voyager 2. These two bodies may also be similar to Chiron at 10 to 20 AU and the recently discovered Kuiper belt objects out at 40 AU and beyond. All of these objects could hold important clues to the origin of comets and the evolution of the solar system. Pluto has a large moon, Charon, which has properties very different from Pluto. This bizarre double body system is believed to be the result of a catastrophic planetary collision (McKinnon, 1989).

At the present time, Pluto has just passed perihelion at 30 AU and is now moving further away from the sun on its way out to 50 AU. Stellar occultation observations have shown that Pluto currently has a temporary atmosphere now that it has been warmed by the sun during this very brief "summer" in its 248 year orbit. Over the next two decades it is anticipated that these gasses will freeze onto the planet's surface. It is highly desirable to observe this atmosphere with UV and radio occultation experiments before it disappears, and to observe surface features and chemical makeup that may be obscured if and when the atmosphere collapses (Stern, 1993).

In order to achieve low cost exploration of Pluto, a new implementation approach is being used for the Pluto program whereby the Science team and Mission Operations team will be integrated with the spacecraft development team very early in the design phase. This is to enable the spacecraft to be optimized around the science measurements to be taken while allowing the flight system to be easily operated during the mission, Conversely, Science and Mission Operations team members will have greater visibility into spacecraft engineering issues and be more willing to moderate and tailor their requirements in order to achieve a lower cost total system design. The science package is to be an integral part of the spacecraft and may share common elements rather than be stand-alone modules. The resulting flight system is called a "sciencecraft" rather than a spacecraft. Figure I shows a current drawing of a Pluto Express sciencecraft option. Shown near the top of the sciencecraft is a proposed advanced RPS. Three options for this RPS are described below; the AMTEC option is shown. At this stage in the sciencecraft design, solar energy options are also being evaluated as alternatives to using an RPS.

POWER DEMAND

Power demand on the Pluto Express Sciencecraft is very low. The 74 W(electric) power demand at end of mission is composed of the current best estimate (CBE) power demand for the various loads plus a 20% contingency for power growth. Table I is a summary of the CBE power demand for the various

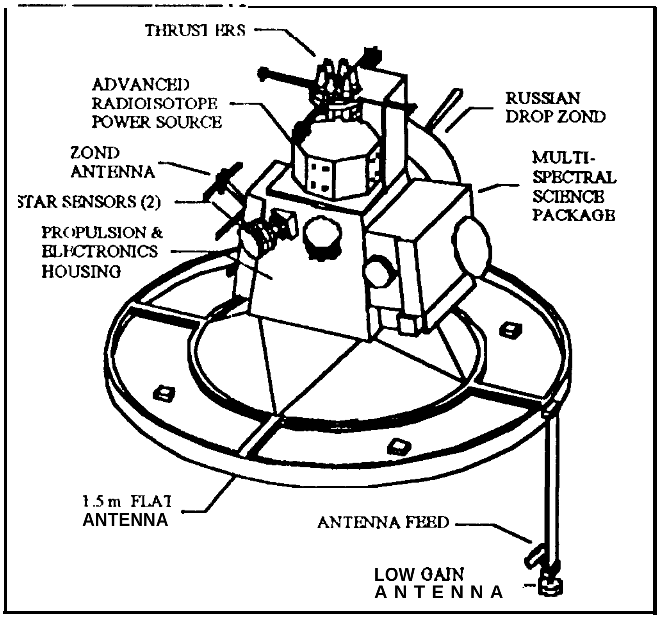

Figure 1: Pluto Express Sciencecraft Concept, one of several configurations designed by Shawn Goodman and Annette Nasif of JPL.

power loads. The technologies represented by these power demands are the lowest power technologies available that potentially satisfy the Pluto Express development schedule. Given the CBEs in the table, 74 W will not be enough power to supply all load at all times. To achieve this low power level, the sciencecraft will require cycling power between

Table 1: Current Best Estimate (CBE) Power Demand for Pluto Express Components

Assembly	CBE Power	Assembly	CBE Power
Telecommunications		Power	
Transponder	11.0 W	Electronics	4.2 W
SSPA	17.0 W	DC-DC Conv	— <12 W
Attitude Control		**Propulsion**	
Star Sensor	3.5 W	Cat. Bed Htrs	12.0 w
IRU	6.1 W	1 lb Thrusters	27 W (- -
Sun Sensor	0.18 W	Cold Gas Thr	20W (2.5 ms)
VDE	0.5 w	Sensors	1.2 W
Integrated Electronics Mod.		Latch Valves	15W (2.5 ms)
Flt Computer		Thermal Control	
Prgmable I/O	3.4 W 03	Heaters	7.0 W
Mass Mem.	2.15		
		Drop Zond	
Science		Receiver	2.0 W
Instruments	6.0 W	Probe Check	2.0 w

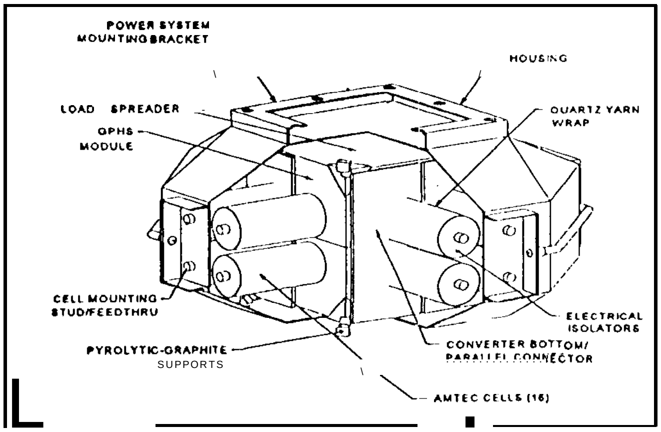

Figure 3: AMTEC RPS Concept Ivanenok and Sievers (1995)

by failures of auxiliary components such as heaters. Lifetime demonstration remains a key challenge for AMTEC development.

An AMTEC based RPS concept has been developed by Ivanenok and Sievers (1995) of AMPS (see Figure 3). This design uses 2 GPHS modules and 16 AMTEC cells in a 6.1 kg package. The RPS would be 23.2 cm across and 12.7 an high. The housing area is large enough to radiate the waste heat at near 300 °C. Power projections are that this RPS would produce 87 W(electric) 10 years after launch using the F5 GPHSs.

Pluto Express finds this design attractive for several reasons. The AMTEC RPS is the lowest mass concept of those under consideration and AMTEC has no radiation induced degradation modes. The latter characteristic results in more power available for Pluto encounter and for potential Pluto Express extended missions to Kuiper belt objects and beyond. The small physical size of the converter cases integration into the sciencecraft and minimizes thruster plume impingement problems. In addition, the waste heat is at a temperature that is useful for thermal control. The sciencecraft concept shown in Figure 1 takes advantage of the waste heat by creating thermal zones that keep the hydrazine thrusters, the hydrazine tank, and the electronics within temperature operating limits. Besides being an elegant solution to potential thermal problems at 30 AU, thermal zoning eliminates RHUs and should reduce tbc overall cost of the mission. The reasons that make AMTEC attractive for Pluto Express, in particular the sciencecraft integration impacts, also make AMTEC attractive for other outer planet missions. If AMTEC meets these projections, then it could enable multiple, low cost outer planet missions.

However, AMTEC has several technical issues that need to be overcome. The current program to demonstrate ccl I efficiency most be completed successfully. To this needs to be added lifetime and systems performance demonstrations. Also, the micro-gravity operation of the AMTEC cells must be validated. A micro-gravity experiment of AMTEC has been proposed to the NASA IN-STEP program by the current author in collaboration with R. Sievers of AMPS.

TPV

Thermophotovoltaics ('TPV) is a photovoltaic (PV) conversion of infrared radiation to make electricity, The system is composed of four basic elements: the heat source, an emitter or filter to modify the emitter spectrum, the PV cell, and a heat rejection system. For an RPS, Pluto Express assumes the heat source is the GPHS. Given the temperature limits of the GPHS, welt known PV cells such as Si or GaAs have too large bandgaps to convert GPHS radiation with high efficiency. Highly developed, low band gap alternative PV cells include GaSb and InGaAs. These have been developed for other applications such tandem PV cells, and either one could be ready for use in a TPV based RPS by the time of the Pluto Express launch. in order to achieve high efficiency, the emitted thermal spectrum from the GPHS must be modified with a selective emitter or a band pass filter. Either of these assures that as much as possible of tbc energy reaching the PV lies at or just below the bandgap. Photons that are too energetic are above the bandgap and create excess heat if absorbed. Lower energy photons (below bandgap) cannot be absorbed, and all the energy is wasted as heat. The RPS system described below uses the band pass filter method in which most of the high and low energy photons are reflected back to the source. The final element of the TPV system is the radiator. The PV cells must operate below about 80 °C in order to achieve reasonable efficiency. Thus the radiator in a space system will be large to achieve the low cell temperature.

TPV development is conducted by a number of firms with a variety of applications in mind. Pluto Express worked with Boeing Defense and Space Group to help develop a TPV system. The Boeing program has subsequently been moved to a small business called EdTek of Seattle Washington. L. Horne of EdTek is working with DOE funding to develop a band pass filter. JPL is also working with JXCrystals to develop advanced RPS concepts. Other collaborations are also being pursued. The work by Boeing under the Pluto Advanced Technology Insertion initiative in 1993 resulted in fabrication and testing of a one third scale TPV system. This was the first demonstration of an entire TPV system (exclusive of the radiator) designed for the temperature range achievable by the GPHS. The system was composed of a heater, a thermo-optical cavity, and two arrays of TPV cells and filters. Up to 13% of the thermal input to the arrays was converted to electricity. The "photon recycling" performance of the optical cavity was not as good as expected resulting in low system performance. EdTek is currently working on improving the filter performance. The Boeing/EdTek components have been various loads. For example, during encounter the transmitter in the telecommunications subsystem will be turned off to allow enough power for the science instruments and the inertial reference units.

In order to make the sciencecraft easier to operate, it is desirable to have enough power margin to permit turning on additional units without extensive constraint checking. This would require about 104 W(electric) of power to be available. If an advanced RPS could deliver this power level and still meet the low mass goals, then it could give the sciencecraft more operational flexibility.

All the advanced RPS options meet the 74 W power demand using 2 GPHS modules, With a large mass penalty, each option could be expanded to include a third GPHS to supply the additional power. The details of the converter options are described below. All the designs discussed assume GPHS modules recovered from the *Cassini* spare RTG known as F5. These GPHSs were manufactured in 1982 and thus have a reduced heat value relative to new units. The expected thermal value of one F5 GPHS at Pluto Express launch in 2003 is 215 W. The use of these older modules saves the project several million dollars for new GPHSs that would have a higher heat value (nominally 250 W at launch), The EOM power estimates provided below assume a 10 year mission.

RTG

Though an RTG is not an advanced RPS option, the RTG description is included here for comparison. An RTG for Pluto Express would be a down-sized GPHS RTG similar to those flown on *Galileo* and Ulysses and baselined for *Cassini*. It would use unicouple thermoelectric converters to produce electricity from the heat generated by 6 GPHS modules. These unicouples would be of identical design to those from the earlier missions; however, the converter housing and GPHS supports would need re-designing for the smaller size and to reduce the mass The scaled down RTG mass would be 17.8 kg and it would produce about 75 W(electric) at EOM if the F5 GPHSs are used. Figure 2 is a diagram of a scaled down RTG concept developed by Schock (1994a).

Unicouples have demonstrated many millions of device hours without a known failure. However, the promise of higher efficiency, lower mass, and lower cost is driving the attempt to move to one of the advanced converter options. The advantages of the advanced converters, once realized in a mature RPS, may enable future low cost planetary exploration.

AMTEC

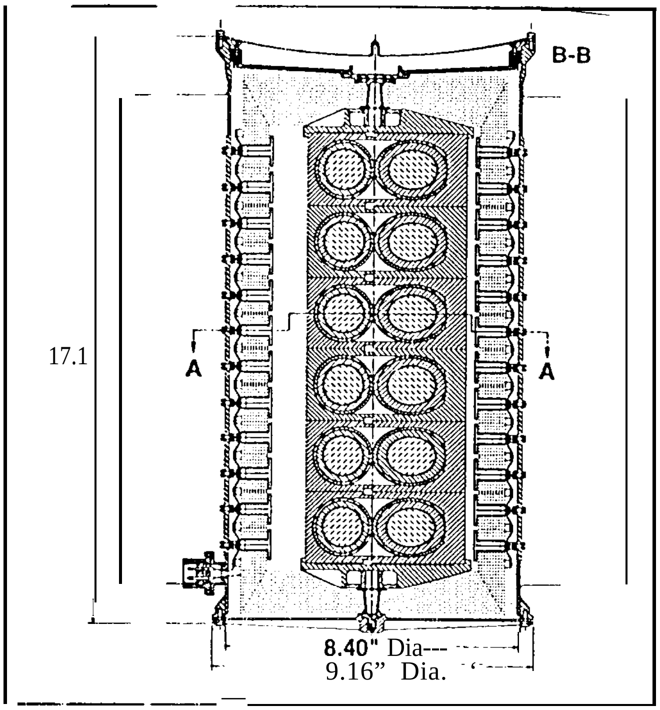

Figure 2: Small RTG Concept (Schock, 1994a)

The Alkali Metal Thermal-to-Electric Converter (AMTEC) is a thermally regenerated sodium concentration cell, At the heart of an AMTEC cell is the ceramic known as beta" alumina solid electrolyte (BASE). In a high temperature region (about 800 to 900 °C), the BASE is a separator between high pressure (up to 1 atm) sodium and a low pressure region, The pressure (or activity) gradient creates a potential (or voltage) that drives the AMTEC cycle. Because BASE is a sodium conductor, the potential difference drives positive sodium ions into the BASE while electrons travel through an external electrical circuit producing work. At the low pressure side of the BASE, an electron neutralizes a sodium ion resulting in a sodium metal atom. This sodium evaporates from the surface, travels to a remote condenser that is held at 100-300 C. Condensed sodium circulates back to the high temperature region and is pressurized by a high performance capillary wick. A complete description of the AMTEC cycle can be found in Cole (1983).

AMTEC development is being led by Advanced Modular Power Systems (AMPS) of Ann Arbor Michigan with funding primarily from the Air Force Phillips laboratory (AFPL) and SBIRs. AMPS has recently demonstrated 18% efficiency (thermal-to-electric) in a prototypic cell operating in an RPS-like environment. AMPS has an ongoing program with plans to demonstrate a 30% efficient cell by May of 1996, Though the program funding the development of these cells envisions a solar-thermal application, the same cells could be used in a GPHS heated design. Prototypic cells have been operated for periods of over one year though not at prototypic temperatures or with high conversion efficiency. These long life tests have typically failed due to air corrosion of the sodium containment. Life tests in vacuum have similarly been plagued integrated into a systems concept by Fairchild Space (now Orbital Sciences Corporation, OSC) that is described below.

The TPV RPS concept developed by Schock of OSC is shown in Figure 4 (Schock, 1994b). Like the AMTEC design this design uses 2 GPHS modules. The estimated mass is 7.2 kg for a design to produce 110 W (electric) BOM. Adding a 10% radiation induced degradation for Schock's performance estimates results in an estimated EOM power of 75 W. The major visible feature of the TPV RPS is the large radiator. The fins in Figure 4 are 76 cm long and 51 cm high at the ends.

TPV's inherent simplicity make it attractive for advanced RPS applications. The low band gap PV cells are highly developed and will not require significant additional development to be optimized for this application. The system is low mass and does not have the complication of a working fluid. It is not expected that a TPV system will need a micro-gravity validation of system performance in order to be qualified for space missions.

The technical issues for TPV are related to the TPV system and the sciencecraft integration. As for the TPV system, the radiation degradation of the TPV cells is not known. Early indications are that the cells may degrade 10 to 15% in close proximity to a GPHS for 10 years. However, these are only preliminary tests on a few GaSb cells, More tests need to be done. Similarly, the lifetime of the TPV design is not known; life tests and modeling are needed. Sciencecraft integration issues include the size of the radiator and the low temperature of the waste heat. The large radiator will make placement of the TPV system difficult on a small vehicle. Thruster plume impingement problems are the most critical issue. Also, if the waste heat is rejected near 0 °C, then this heat is not useful for sciencecraft thermal control. Additional RHUs or other thermal control measures will be required,

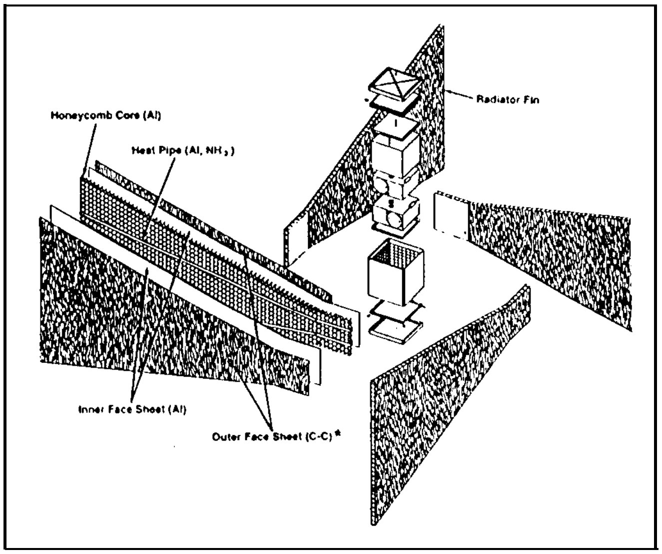

Figure 4: TPV RPS Concept, exploded view (Schock, 1994b)

STIRLING ENGINE

A third advanced thermal-to-electric converter for an advanced RPS is the Stirling Engine. For space applications, the free piston Stirling engine would be selected due to its inherent simplicity with only two moving parts. These parts, the displacer and power pistons are mounted on flexure bearings, or they ride on hydrodynamic gas bearings. In either case, there is no contact between the piston and the cylinder wall during normal operation. The power piston drives a linear alternator which produces A.C. power.

Free piston Stirling engines have been under development for a number of years by many firms. Small, flexure bearing engines, however, are the specialty of Stirling Technology Corporation (STC) of Richland, Washington. STC has on going endurance tests of a prototype 11 W(electric) engine that has operated about 15,000 hours (Schock, 1995). Long life has also been demonstrated with other similar Stirling engine designs,

STC recently scaled an 11 W (electric) engine design up to a 35 W(electric) size. OSC integrated this design into an advanced RPS concept for Pluto Express (Schock, 1995). Figure 5 shows a diagram of this concept, Four 35 W engines are used to achieve redundancy with low mass. A four engine design requiring three engines in operation to satisfy the full power demand is lower in mass than a two engine design requiring only one. The concept shown in Figure 5 has an estimated mass of 12.4 kg and a maximum diameter of 62.9 cm. The power output is projected to be 80 W(electric) at BOM and 74 W at EOM. The EOM power outpot can be increased to about 96 W by increasing the size of the radiator and adding about 1 kg to the RPS. Schock (1995b) assumed new GPHS modules with 250 W(thermal) each at BOM. The power estimates here are. scaled to the lower thermal power available from the older F5 modules.

Development of the Stirling Engine is probably the most advanced of the three converter concepts under consideration. Long life, high efficiency Stirling engine operation has been demonstrated although not for the specific engine needed for Pluto Express. The engine performance numbers listed above assume a radiator temperature near 175 ‘C which is warm enough to produce waste heat that can be used for spacecraft thermal zoning as planned for the AMTEC RPS.

The technical issues for Stirling are the mass, redundancy, life, and probably the most critical – vibration. This Stirling Engine concept is the heaviest of the three advanced RPS options. It is more than twice the mass of the AMTEC concept. The redundancy strategy is to plan to deliver full power from three engines but operate four under normal conditions. This strategy is probably adequate, but significant modeling will be required to evaluate the strategy and to understand any transitions and synergistic effects. Though Stirling has the longest demonstrated life of any of the advanced options, the

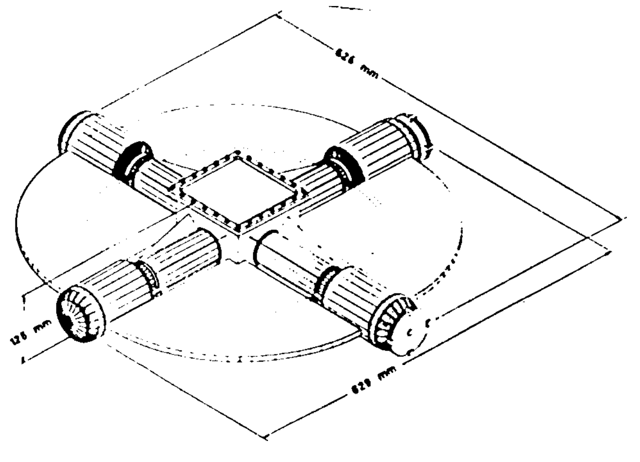

Figure 5: Stirling Engine RPS Concept (Schock, 1994b)

demonstrated lifetime is still short of the mission duration. Finally the amount of vibration in the normal mode as well as the single engine failure mode is a critical concern. Any vibration can degrade the science being conducted on board the sciencecraft. The amount of degradation that can be tolerated needs to be determined. Another concern is whether or not the engine designed for Pluto Express could be used for other outer planets mission. This will depend on the spacecraft power demand and vibration tolerance. Some redesign would almost certainly be required.

FUTURE DIRECTIONS

Even with two sciencecraft, Pluto Express will only fly one type of RPS, if any. The development over the next two to three years will be critical to determining which technology could be ready for the mission. Table 2 summarizes the critical parameters for the current design concepts for each converter. Each converter has advantages and issues. Clearly, if all the options meet the design concept performance, then AMTEC has several advantages for Pluto Express and future outer planet missions. These include low mass, static operation, a small high-temperature radiator, and minimum power degradation over the mission duration.

The final power source selection will depend on many other factors besides technical performance. If Pluto Express does use a radioisotope heated system, then the converter selection will be based on factors such as: technical status, performance risk, cost, and the importance of the technology to other missions and markets. As advanced RPS converter development continues, each converter's capability relative to these factors is becoming increasingly clear.

Table 2: Summary of RPS Design Concept Performance

	RTG	AMTEC	TPV	Stirling
# GPHS*	6	2	2	2
Mass, kg	17.8	6.1	7.2	12.4
EOM Power W	74	87	75	74
Radiator **Temp**	2s0 °C	300 °C	o °C	175 °C
Radiator Area	0.66 m^2	0.10 m^2	1.9 m^2	0.33 m^2
Reference	Schock (1994a)	Ivanenok & Sievers (1995)	Schock (1994b)	Schock (1995)

* Assume GPHS modules from the *Cassini* spare RTG (F5)

ACKNOWLEDGMENTS

The author wishes to thank Humphrey Price for help with the science and sciencecraft descriptions, Candida Nunez and the rest of the Pluto Team for a top notch sciencecraft design, and Doug Abraham, Carol Lewis, and Bill Nesmith for assistance in reviewing this document. Thanks also go to David Rogers, Pat Beauchamp, Larry Soderblom, and Greg Vane for developing the sciencecraft concept,

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Cole, T. (1983) "Thermoelectric Energy Conversion with **Solid** Electrolytes," *Science*, **221**, pp. 915-920.

Ivanenok, J. F., and Sievers, R. K., (1995), (AMTEC Radioisotope Power System for the Pluto Express Mission," 1995 IECEC paper #395.

McKinnon, W.B. (1989), "The Origin of the Pluto Charon Binary," Astrophysical Journal, 344, p. 1,41.

Schock, A , Or, T., and Kumar, K., (1994a) "Design Modifications for Increasing the BOM and EOM Power Output and Reducing the Size and Mass of RTG for the Pluto Mission," in 1994 IECEC Proceedings,

Schock, A., Mukunda, M., Or, C., Komar, K., and Summers, G., (1994b) "Radioisotope ThermoPhotovoltaic (RTPV) Generator and Its Applicability to an Illustrative Space Mission," Doc# FSC-ESD-217-93-519A, Fairchild Space and Defense Corporation, Germantown MD.

Schock, A., Or, T., and Kumar, K., (1995) "Radioisotope Stirling System," 1995 IECEC Paper #159.

Stern, A. (1993), "Pluto Reconisance Flyby Mission," EOS, Vol. 74, pp. 73, 76-78.

[illegible]
Revised 5/31/9
recommendations
IECEC 9-264
made
concerning
RTGs

ADVANCED RADIOISOTOPE POWER SOURCE OPTIONS FOR PLUTO EXPRESS

Mark L. Underwood
Jet Propulsion Laboratory,
California Institute of Technology
4S00 Oak Grove Dr.
Pasadena, California 91109-8099
Tel # (818) 354-9731 Fax# (818) 3934$272

Camera Ready Manuscript prepared for:

30th Intersociety Energy Conversion Engineering Conference (IECEC)
hdy31 to August 4, 1995
Orlando, Florida

IECEC 95-264

ADVANCED RADIOISOTOPE POWER SOURCE OPTIONS FOR PLUTO EXPRESS

Mark L. Underwood
Jet Propulsion Laboratory,
California Institute of Technology
4800 OakGrove Dr.
Pasadena, California 91109-8099
Tel # (818) 354-9731 Fax# (818) 393-4272

ABSTRACT

In the drive to reduce mass and coat, Pluto Express is investigating using an advanced power conversion technology in a small Radioisotope Power Source (RPS) to deliver the required mission power of 74 W(electric) at end of mission. Until this year the baseline power source under consideration has been a Radioisotope Thermoelectric Generator (RTG). This RTG would be a scaled down GPHS RTG with an inventory of 6 General Purpose Heat Sources (GPHS) and a mass of 17.8 kg. High efficiency, advanced technology conversion options are being examined to lower the power source mass and to reduce the amount of radioisotope needed. Three technologies are being considered as the advanced converter technology: the Alkali Metal Thermal-to-Electric Converts (AMTEC), Thermophotovoltaic (TPV) converters, and Stirling Engines. Conceptual designs for each of these optiona have been prepared. Each converter would require only 2 GPHSS to provide the mission power and would have a mass of 6.1, 7.2, and 12,4 kg for AMTEC, TPV, and Stirling Engines respectively. This paper reviews the status of esch technology and the projected performance of an advanced RPS based on each technology. Based on the projected performance and spacecraft integration issues, Pluto Express would prefer to use the AMTEC based RPS. However, in addition to technical performance, selection of a power technology will be baaed on many other factors. The technology community must continue the development of the converters in order to bring them to a state of technology readiness by 1997 or 1998 such that they can be contenders for systems development which could lead to selection of the Pluto Express power source. Pluto Express is currently planned for launch in 2003

INTRODUCTION

One goal of Pluto Express is to revolutionize our knowledge of Pluto and ita moon CharOn. To help reach this goal, Pluto Express is aggressively pursuing advanced technologies that can reduce the mass and coat of the mission. Radioisotope heated power systems that have traditionally provided electrical power for outer planetary spacecraft are one area for potential savings. several advanced thermal-to-electric converter technologies are on the horizon that operate with up to five times the efficiency of the thermoelectrics used in tractional radioisotope thermoelectric converters (RTGs). Due to the increased efficiency, advanced radioisotope power sources (RPSs) require less IN-238 radioisotope fuel and have a lower mass. These factors reduce the cost of the RPS and the overall mission. Also, by conserving the Pu-238 fuel and demonstrating an advanced conversion technology, Pluto Express would enable future deep apace missions at lower cost. This paper describes the advanced RPs concepts that are being considered for Pluto Express. The advanced converter options are the Alkali Metal Thermal-to-Electric Converter (AMTEC), Thermophotovoltaic (TPV) converters, and Stirling Engines. None of these converters is yet ready to power a spacecraft, but technology development followed by systems development must continue so that at least one technology could possibly be ready for the Pluto Express launch now planned for 2003.

First, a brief overview of Pluto Express and the sciencecraft approach to low cost mission design is provided. The technology status of the three converter options and the design concepts that could be integrated into Pluto Express are then discussed. A brief discussion of the factors in selecting a power source technology that will be possibly pursued to flight concludes the discussion.

PLUTO EXPRESS OVERVIEW

Pluto is the only planet in our Solar System that has not been visited by a spacecraft. Pluto is the largest of a class of primordial bodies at the edge of our Solar System which have comet-like properties and remain relatively unmodified by warming from the sun. The composition of Pluto is thought to be similar to that of Triton, the largest moon of Neptune, which was reconnoitered by Voyager 2. These two bodies may also be similar to Chiron at 10 to 20 AU and the recently discovered Kuiper belt objects out at 40 AU and beyond. All of these objects could hold important clues to the origin of comets and the evolution of the solar system. Pluto has a large moon, CharOn, which has properties very different from Pluto. This bizarre double body system is believed to be the result of a catastrophic planetary collision (McKinnon, 1989).

At the present time, Pluto has just passed perihelion at 30 AU and is now moving further away from the sun on its way out to 50 AU. Stellar occultation observations have shown that Pluto currently has a temporary atmosphere now that it has been warmed by the sun during this very brief "summer" in its 248 year orbit. Over the next two decades it is anticipated that these gasses will freeze onto the planet's surface. It is highly desirable to observe this atmosphere with UV and radio occultation experiments before it disappears. and to observe surface features and chemical makeup that may be obscured if and when the atmosphere collapses (Stern, 1993).

In order to achieve low cost exploration of Pluto, a new implementation approach is being used for the Pluto program whereby the Science team and Mission Operations team will be integrated with the spacecraft development team very early in the design phase. This is to enable the spacecraft to be optimized around the science measurement to be taken while allowing the flight system to be easily operated during the mission. Conversely, Science and Mission Operations team members will have greater visibility into spacecraft engineering issues and be more willing to moderate and tailor their requirements in order to achieve a lower cost total system design. The science package is to bean integral part of the spacecraft and may share common elements rather than be stand-alone modules. The resulting flight system is called a "sciencecraft" rather than a spacecraft. Figure 1 shows a current drawing of a Pluto Express sciencecraft option. Shown near the top of the sciencecraft is a proposed advanced RPS. Three options for this RPS are described below, the AMTEC option is shown. At this stage in the sciencecraft design, solar energy options are also being evaluated as alternatives to using an RPs.

POWER DEMAND

Power demand on the Pluto Express Sciencecraft is very low. The 74 W(electric) power demand at end of mission is composed of the current best estimate (CBE) power demand for the various loads plus a 20?? contingency for power growth. Table 1 is a summary of the CBE power demand for the various power loads. The technologies represented by these power demands are the lowest power technologies available that potentially satisfy the Pluto Express development schedule. Given the CBES in the table, 74 W will not be enough power to supply all load at all times. To

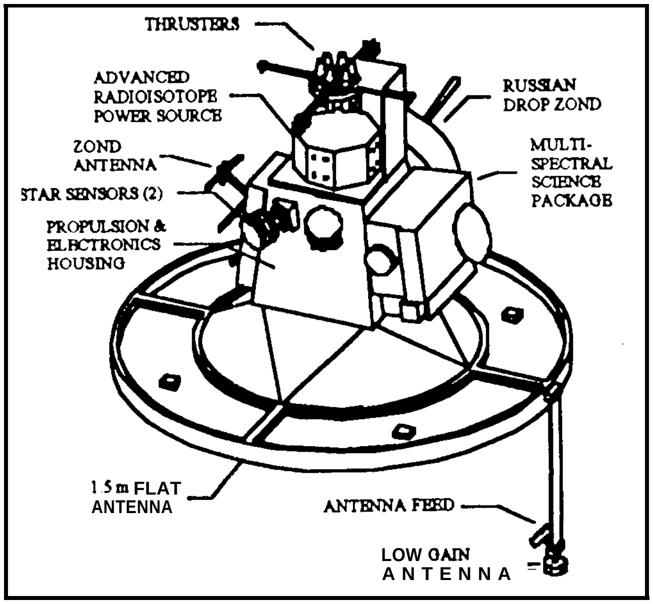

Figure 1: Pluto Express Sciencecraft Concept, one of severa **configurations designed** by Shawn Goodman and **Annette** Nasifof JPL.

Tabk 1: Current Best Estimate (CBE) Power Demand for Pluto Express Components

Assembly	CBE Power	Assembly	CBE Power
Telecommunications		**Power**	
Transponder	11.0 W	Electronics	4.2 W
SSPA	17.0 w	DC-DC Conv	<12 W
Attitude Control		**Propulsion**	
star sensor	3.5 w	Cat. Bed Htrs	12.0 W
IRU	6.1 W	1lb Thrusters	27W (10 ms)
Sun Sensor	0.18 W	Cold Gas Thr	20W (2.5 ms)
VDE	0.5 W	Sensors	1.2 W
		Latch Valves	15W (2.5 ms)
Integrated Electronics Mod.			
Flt Computer	3.4 w	**Thermal Control**	
Prgmable I/O	0.3	Heaters	7.0 W
Mass-Mere.	- - - . 1 5		
		Drop Zond	
Science		Receiver	2.0 W
Instruments	6.0 W	Probe Check	2.0 W

achieve this low power level, the. sciencecraft will require cycling power between various loads. For example, during encounter the transmitter in the telecommunications subsystem will be turned off to allow enough power for the science instruments and the inertial reference units.

In order to make the sciencecraft easier to operate, it is desirable to have enough power margin to permit turning on additional units without extensive constraint checking. This would require about 104 W(electric) of power to be available. If an advanced RPS could deliver this power level and still meet the low mass goals, then it could give the sciencecraft more operational flexibility.

All the advanced RPS options meet the 74 W power demand using 2 GPHS modules. With a large mass penalty, each option could be expanded to include a third GPHS to supply the additional power. The details of the converter options are described below. All the designs discussed assume GPHS modules recovered from the *Cassini* spare RTG known as F5. These GPHSS were manufactured in 1982 and thus have a reduced heat value relative to new units. The expected thermal value of one F5 GPHS at Pluto Express launch in 2003 is 215 W. The use of these older modules saves the project several million dollars for new GPHSs that would have a higher heat value (nominally 250 W at launch). The EOM power estimates provided below assume a 10 year mission.

RTG

Though an RTG is not an advanced RPS option, the RTG description is included here for comparison. An RTG for Pluto Express would be a down-sized GPHS RTG similar to those flown on *Galileo* and Ulysses and baselined for *Cassini*. It would use unicouple thermoelectric converters to produce electricity from the heat generated by 6 GPHS modules. These uncouples would be of identical design to those from the earlier missions; however, the converter housing and GPHS supporta would need re-designing for the smaller size and to reduce the mass. The scaled down RTG mass would be 17.8 kg and it would produce about 75 W(electric) at EOM if the F5 GPHSS are used. Figure 2 is a diagram of a scaled down RTG concept developed by Schock (1994a).

Uncouples have demonstrated many millions of device hours without a known failure. However, the potential for higher efficiency, lower mass, and lower cost is driving the attempt to move to one of the advanced converter options. The advantages of the advanced converters, once realized in a mature RI%, may enable future low cost planetary exploration.

AMTEC

The Alkali Metal Thermal-to-Electric Converter (AMTEC) is a thermally regenerated sodium concentration cell. At the heart of an AMTEC cell is the ceramic known as beta" alumina solid electrolyte (BASE). In a high temperature region (about 800 to 900 °C), the BASE is a separator between high pressure (up to 1 atm) sodium and a low pressure region. The pressure (or activity) gradient creates a potential (or voltage) that drives the AMTEC cycle. Because BASE is a sodium conductor, the potential difference drives positive sodium ions into the BASE while electrons travel through an external electric-al circuit producing work. At the low pressure side of the BASE, an electron neutralizes a sodium ion resulting m a sodium metal atom. This sodium evaporates from the surface, travels to a remote condenser that is held at 100-300 C. Condensed sodium circulates back to the high temperature region and is pressurized by a high performance capillary wick. A complete description of the AMTEC cycle can be found in Cole (1983).

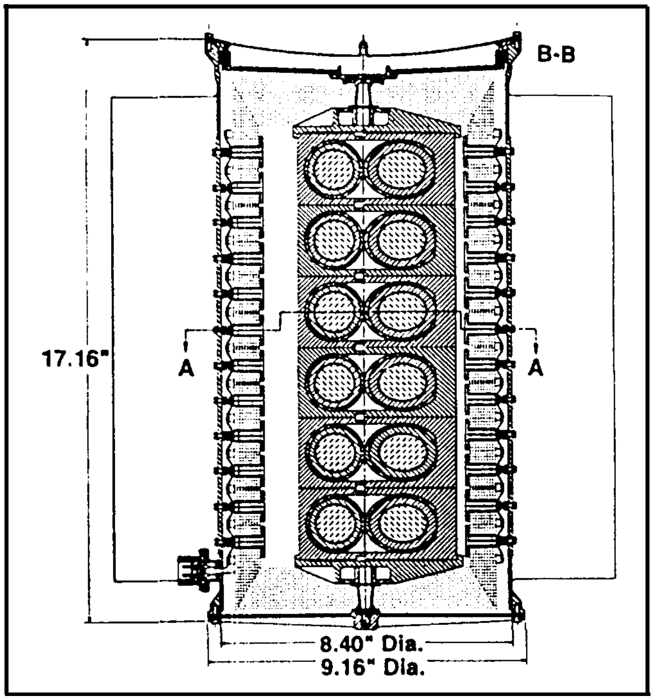

Figure 2: Small RTG Concept (Schock, 1994a)

AMTEC development is being led by Advanced Modular Power Systems (AMPS) of Ann Arbor Michigan with funding primarily from the Air Force Phillips Laboratory (AFPL) and SBIRs (Sievers, 1995). AMPS has recently demonstrated 18'%0 efficiency (thermal-to-electric) in a prototypic cell operating in an RPS-like environment. AMPS has an ongoing program with plans to demonstrate a 30% efficient cell by May of 1996. Though the program funding the development of these cells envisions a solar-thermal application, the same cells could be used m a GPHS heated design. Prototypic cells have been operated for periods of over one year though not at prototypic temperatures or with high conversion efficiency. These long life tests have typically failed due to air corrosion

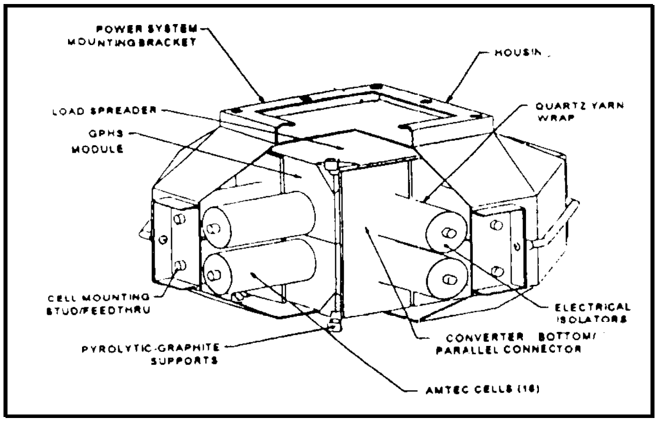

Figure 3: AMTEC RPS Concept Ivanenok and Sievers (1995)

of the sodium contaimnent. Life tests in vacuum have similarly been plagued by failures of auxiliary components such as heaters. Lifetime demonstration remains a key challenge for AMTEC development.

An AMTEC based RPS concept is being developed by Ivanenok and Sievers (1995) of AMPS (see Figure 3). This concept uses 2 GPHS modules and 16 AMTEC cells in a 6.1 kg package. The RPS would be 23.2 cm across and 12.7 cm high. The housing area is large enough to radiate the waste heat at near 300 °C. Power projections are that this RPS would produce 87 W(electric) 10 years after launch using the F5 GPHSS.

Pluto Express finds this design attractive for several reasons. The AMTEC RPS is the lowest mass concept of those under consideration and AMTEC has no radiation induced degradation modes. The latter characteristic results in more power available for Pluto encounter and for potential Pluto Express extended missions to Kuiper belt objects and beyond. The small physical size of the converter eases integration into the sciencecraft and minimizes thruster plume impingement problems. In addition, the waste heat is at a temperature that is useful for thermal control. The sciencecraft concept shown in Figure 1 takes advantage of the waste heat by creating thermal zones that keep the hydrazine thrusters, the hydrazine tank, and the electronics within temperature operating limits. Besides being an elegant solution to potential thermal problems at 30 AU, thermal zoning eliminates RHUs and should reduce the overall cost of the mission. The reasons that make AMTEC attractive for Pluto Express, in particular the sciencecraft integration impacts, also make AMTEC attractive for other outer planet missions. If AMTEC meets these projections, then it could enable multiple, low cost outer planet missions.

However, AMTEC has several technical issues that need to be overcome. The current program to demonstrate cell efficiency must be completed successfully. To this needs to be added lifetime and systems performance demonstrations. Also, the micro-gravity operation of the AMTEC cells must be validated A micro-gravity experiment of AMTEC has been proposed to the NASA IN-STEP program by the current author in collaboration with R. Sievers of AMPS.

TPV

Thermophotovoltaics (TPV) is a photovoltaic (PV) conversion of infrared radiation to make electricity. The system is composed of four basic elements: the heat source, an emitter or filter to modify the emitter spectrum, the PV cell, and a heat rejection system. For an RPS, Pluto Express assumes the heat source is the GPHS. Given the temperature limits of the GPHS, well known PV cells such as Si or GaAs have too large bandgaps to convert GPHS radiation with high efficiency. Highly developed. low band gap alternative PV cells include GaSb and InGaAs. These have been under development for other applications such as tandem PV cells, andeither onernay bereadу foruse ina TPVbased RPS by the time of the Pluto Express launch. In order to achieve high efficiency, the emitted thermal spectrum from the GPHS must be modified with a selective emitter or a band pass filter. Either of these assures that as much as possible of the energy reaching the PV lies at or just below the bandgap. Photons that are too energetic are above the bandgap and create excess heat if absorbed Lower energy photons (below bandgap) cannot be absorbed, and all the energy is wasted as heat. The RPS system described below uses the band pass filter method in which most of the high and low energy photons are reflected back to the source. The final element of the TPV system is the radiator. The PV cells must operate below about 80 °C in order to achieve reasonable efficiency. Thus the radiator m a space system will be large to achieve the low cell temperature.

TPV development is conducted by a number of firms with a variety of applications in mind Pluto Express worked with Boeing Defense and Space Group to help develop a TPV system. The Boeing program has subsequently been moved to a small business called EdTek of Seattle Washington. E Horns of EdTek is working with DOE funding to develop a band pass filter. J'PI. is also working with JXCrystals to develop advanced RPS concepts. Other collaborations are also being pursued The work by Boeing under the Pluto Advanced Technology Insertion Initiative in 1993 resulted in fabrication and testing of a one third scale TPV proof-of-concept experiment. This was the frost experiment of an entire TPV system (exclusive of the radiator) designed for the temperature range achievable by the GPHS. The experiment was composed of a GPHS-simulating heater, a thermo-optical cavity, and two arrays of PV cells and filters. Up to 13% of the incident thermal input to the best individual filter/cell combination was converted to electricity. The "photon recycling" performance of the optical cavity was not as good as expected resulting in low system performance. EdTek is currently working on improving the filter performance. The Boeing/EdTek components have been integrated into a systems concept by Fairchild Space (now orbital Sciences Corporation, OSC) that is described below.

The TPV RPS concept developed by Schock (1994b) of OSC is shown in Figure 4. Like the AMTEC concept, the TPV concept uses 2 GPHS modules. The estimated mass is 7.2 kg to produce 110 W (electric) BOM Adding a 10?4 radiation induced degradation for Schock's performance estimates results in an estimated EOM power of 75 W. The major visible feature of the TPV RPS is the large radiator. The fins in Figure 4 are 76 cm long and 51 cm high at the ends.

TPV's similarity to space photovoltaic systems make it attractive for advanced RPS applications. The low band gap PV cells have been tested for solar power applications which will provide significant inheritance for TPV. The system has potential for low mass and does not have the complication of a working fluid. It is not expected that a TPV system will need a micro-gravity validation of system performance in order to be qualified for space missions.

The technical issues for TPV relate to the TPV system and the sciencecraft integration. As for the TPV system, the radiation degradation of the TPV cells is not known. Early indications are that the cells may degrade 10 to 150/0 in close proximity to a GPHS for 10 years. However, these are only preliminary tests on a few GaSb cells. More tests need to be done. Similarly, the lifetime of the TPV design is not known; life tests and modeling are needed. The band pass filter, required for high efficiency TPV operation, also needs significant development. A method must be developed to reproducibly fabricate high transmissivity, narrow band filters. Sciencecraft integration issues include the size of the radiator and the low temperature of the waste heat. The large radiator will make placement of the TPV system difficult on a small vehicle in order to avoid thruster plume impingement problems. Also, if the waste heat is rejected near O °C, then this heat is not useful for sciencecraft thermal control. Additional RHUs or other thermal control measures will be required.

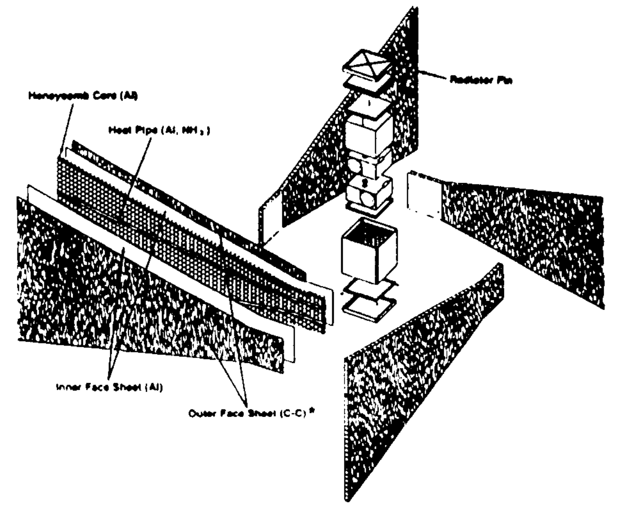

Figure 4: TPV RPS Concept, exploded view (Schock, 1994b)

STIRLING ENGINE

A third advanced thermal-to-electric converter for an advanced RPS is the Stirling Engine. For space applications, the free piston Stirling engine would be selected due to its inherent simplicity with only two moving parts. These parts, the displacer and power pistons are mounted on flexure bearings, or they ride on hydrodynamic gas bearings. In either case, there is no contact between the piston and the cylinder wall during normal operation. The power piston drives a linear alternator which produces A.C. power,

Free piston Stirling engines have been under development for a number of years by many firms. Small, flexure bearing engines, however, are the specialty of Stirling Technology Corporation (STC) of Richland, Washington. STC has on going endurance tests of a prototype 11 W(electric) engine that has operated about 15,000 hours (Schock, 1995) at 18.5% conversion efficiency. Long life has also been demonstrated with other similar Stirling engine designs.

STC recently scaled an 11 W (electric) engine &sign up to a 35 W(electric) size. OSC integrated this design into an advanced RPS concept for Pluto Express (Schock, 1995). Figure 5 shows a diagram of this concept. Four 35 W engines are used to achieve redundancy with low mass. A four engine design requiring three engines in operation to satisfy the full power demand is lower in mass than a two engine design requiring only one. The concept shown in Figure 5 has an estimated mass of 12.4 kg and a maximum diameter of 62.9 cm. The power output is projected to be SO W(electric) at BOM and 74 W at EOM The EOM power output can be increased to about 96 W by increasing the size of the radiator and adding about 1 kg to the RPS. Schock (1995b) assumed new GPHS modules with 250 W(thermal) each at BOM The power estimates here are scaled to the lower thermal power available from the older F5 modules.

Development of the Stirling Engine is probably the most advanced of the three converter concepts under consideration. Long life, high efficiency Stirling engine operation has been demonstrated although not for the specific engine needed for Pluto Express. The engine performance numbers listed above assume a radiator temperature near 175 'C which is warm enough to produce waste heat that can be used for spacecraft thermal zoning as planned for the AMTEC RPS.

The technical issues for Stirling are the mass, redundancy, life, and probably the most critical - vibration. This Stirling

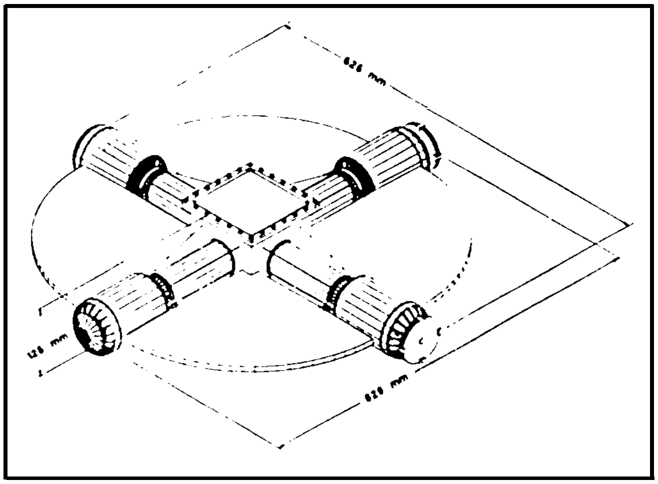

Figure 5: Stirling Engine RPS Concept **(Schock, 1994b)**

Engine concept is the heaviest of the three advanced RPS options, It is more than twice the mass of the AMTEC concept. The redundancy strategy is to plan to deliver full power from three engines but operate four under normal conditions. This strategy is probably adequate, but significant modeling will be required to evaluate the strategy and to understand any transitions and synergistic effects. Though Stirling has the longest demonstrated life of any of the advanced options, the demonstrated lifetime is still short of the mission duration. Finally the amount of vibration in the normal mode as well as the single engine failure mode is a critical concern. Any vibration can degrade the science being conducted on board the sciencecraft. The amount of degradation that can be tolerated needs to be determined. Another concern is whether or not the engine designed for Pluto Express could be used for other outer planets mission. This will depend on the spacecraft power .demand and vibration tolerance. Some redesign would almost certainly be required.

FUTURE DIRECTIONS

Even with two sciencecraft, Pluto Express will only fly one type of RPS, if any. The development over the next two to three years will be critical to determining which technology could be ready for the mission. Table 2 summarizes the critical parameters for the current design concepts for each converter. Each converter has advantages and issuea. Clearly, if all the options meet the design concept performance, then AMTEC has several advantages for Pluto Express and future outer planet missions. These include low mass, static operation, a small high-temperature radiator, and minimum power degradation over the mission duration.

The final power source selection will depend on many other factors besides technical performance. If Pluto Express does use a radioisotope heated system, then the converter selection will be based on factors such as: technical status, performance risk, cost, and the importance of the technology to other missions and markets. As advanced RPS converter development continues, each converter's capability relative to these factors is becoming increasingly clear.

Table 2: Summary of RPS Design Concept Performance

	RTG	AMTEC	TPV	Stirling
# GPHS*	6	2	2	2
Mass, kg	17.8	6.1	7.2	12.4
EOM Power, W	74	87	75	74
Radiator Temp	250 ‘c	300 °C	0 °C	175 °C
Radiator Area	0.66 m²	0.10 m²	1.9 m²	0.33 m²
Reference	Schock (1994a)	Ivanenok & Sievers (1995)	Schock (1994b)	Schock (1995)

* Assume GPHS modules from the *Cassini* spare RTG (F5)

ACKNOWLEDGMENTS

The author wishes to thank Humphrey Price for help with the science and sciencecraft descriptions, Candida Nunez and the rest of the Pluto Team for a top notch sciencecraft design, and Doug Abraham, Carol Lewis, and especially Bill Nesmith for assistance in reviewing this document. Thanks also go to David Rogers, Pat Beauchamp, Larry Soderblom, and Greg Vane for developing the sciencecraft concept.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Cole, T. (1983) ‘Thermoelectric Energy Conversion with Solid Electrolytes; Science, 221, pp. 915-920.

Ivanenok, J.F., and Sievers, R.K., (1995), “AMTEC Radioisotope Power System for the Pluto Express Mission,” 1995 IECEC paper #395.

McKinnon, W.B. (1989), ‘The Origin of the Pluto Charon Binary,” Astrophysical Journal, 344, p. L41.

Schock, A., Or, T., and Kumar, K, (1994a) “Design Modifications for Increasing the BOM and EOM Power Output and Reducing the Size and Mass of RTG for the Pluto Mission,” in 1994 IECEC Proceedings,

Schock, A., Mukunda, M., Or, C., Kumar, K, and Summers, G., (1994b) “Radioisotope Thermophotovoltaic (RTPV) Generator and Its Applicability to an Illustrative Space Mission,” Doc# FSC-ESD-2 17-93-519A, Fairchild Space and Defense Corporation, Germantown MD.

Schock, A., Or, T., and Kumar, K., (1995) “Radioisotope Stirling System,” 1995 IECEC Paper #159.

Sievers, RK., (1995), Personnal Communication.

Stem, A. (1993), “Pluto Reconnaissance Flyby Mission,” EOS, Vol. 74, pp. 73,76-78.