THERMION: VERIFICATION OF A THERMIONIC HEAT PIPE IN MICROGRAVITY

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1.0 INTRODUCTION

The Idaho National Engineering Laboratory (INEL) is conducting intensive research in the design and development of a small excore heat-pipe-thermionic space nuclear reactor power system (SEHPTR). The SEHPTR spacecraft will be able to supply 40 kW of power in any given orbit. Figure 1-1 shows a conceptual diagram of the SEHPTR spacecraft. The key components in this reactor are the thermionic heat pipes. The heat pipes have two major functions: first, to convert heat energy into electrical energy, and second, to radiate the excess heat to space.

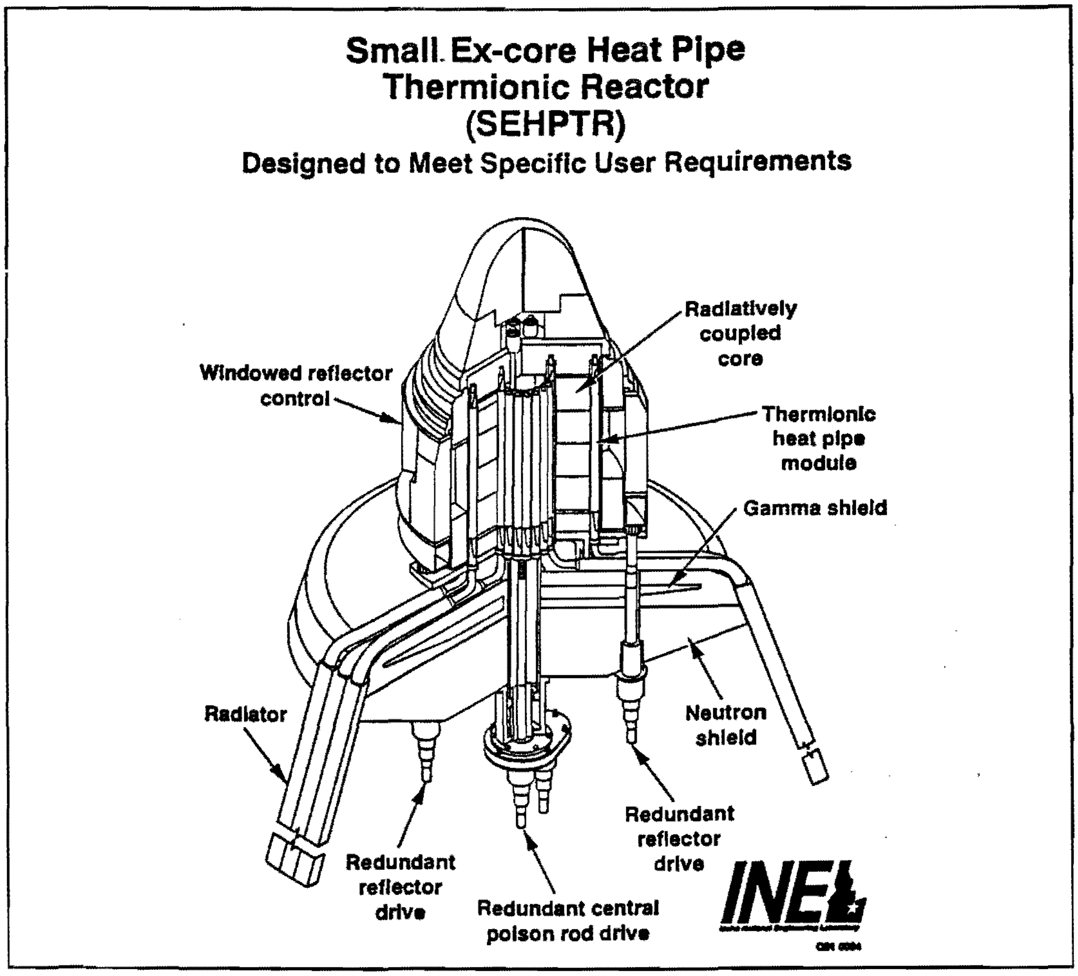

Figure 1-1 Space nuclear reactor power system (SEHPTR).

Thermionic power conversion is the process of converting heat energy into electrical energy with no moving parts. Heat is applied to the cathode surface, as shown in Figure 1-2. This heat will boil off electrons that will jump across the gap to the cooler surface of the anode, which will cause a potential difference between the two plates and induce a current through the load.

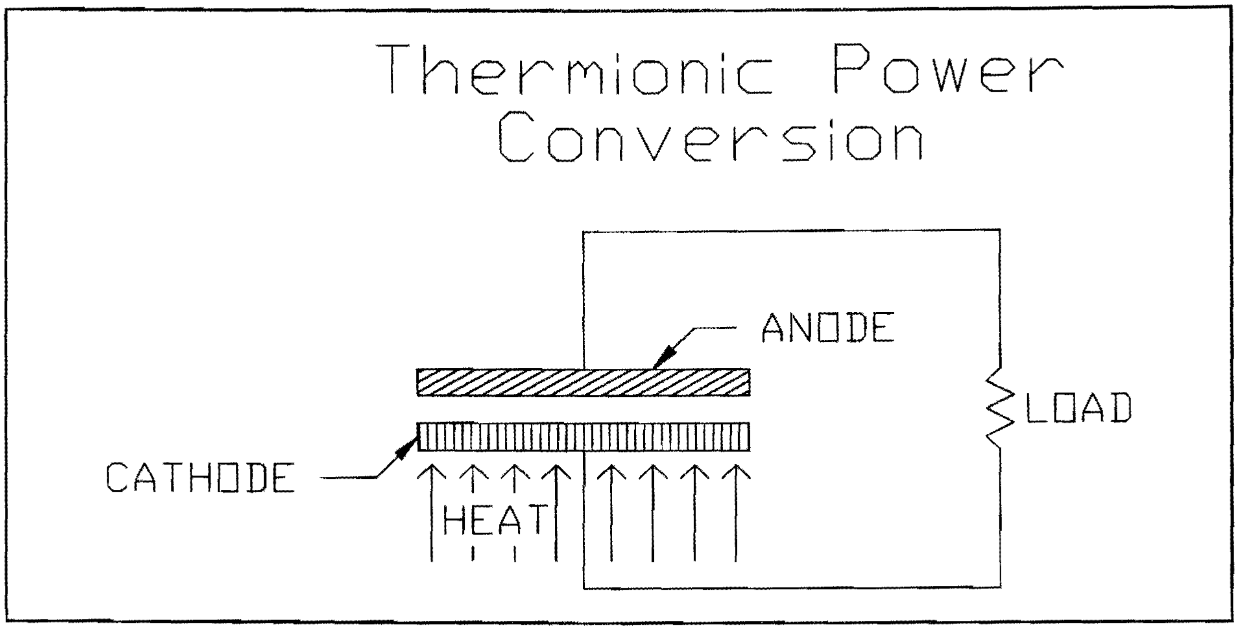

Figure 1-2 Thermionic power conversion converts heat energy into electrical energy.

Thermionic power conversion is incorporated as part of the heat pipe. The heat pipe, which is being developed by Thermacore Inc., is actually two heat pipes. It uses a radial heat pipe, called the emitter, and an axial heat pipe collector, as shown in Figure 1-3. The emitter heat pipe will pass the heat from the nuclear core to the cathode surface. The collector heat pipe keeps the anode surface cooler by transferring the heat from the anode surface and radiating it to space.

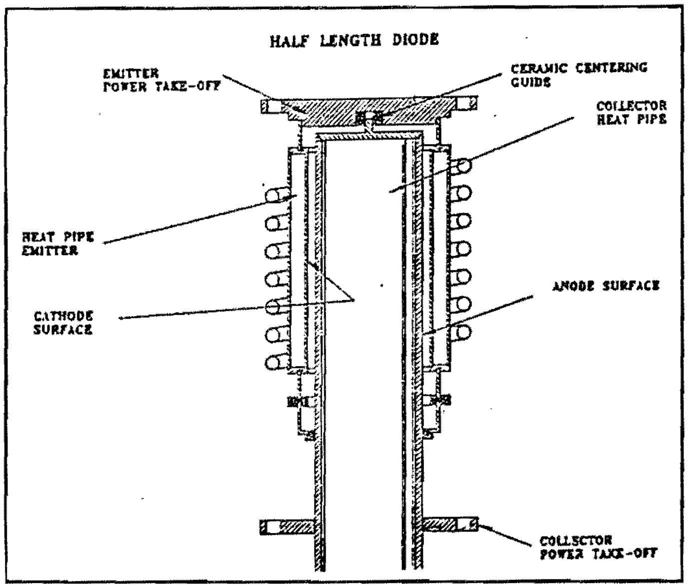

Figure 1-3 Heat pipe design by Thermacore.

1.1 DESIGN PROJECT

This year's design project was in collaboration with the Idaho National Engineering Laboratory to design a space flight-demonstration of a scaled-down thermionic heat pipe. The mission of this satellite would be to demonstrate the performance of an integrated thermionic heat pipe device concept in microgravity. The letter of contract can be found in Appendix A of the final report. During the course of the design, we developed two design concepts - THERMION-I and THERMION-II.

1.1.1 THERMION-I

THERMION-I is a small satellite that will have a one-year mission. A solar collecting mirror will be used to focus the Sun's energy into a cavity that will transfer the heat into a 6-cm heat pipe. The 6-cm heat pipe is a scaled down version of the 40-cm heat pipe that will be used in SEHPTR. The satellite will be flown as a secondary payload on the Delta II.

1.1.2 THERMION-II

THERMION-II is a more brute-force approach to conducting the experiment. Instead of being deployed from the Delta II, it will be permanently mounted to the second stage. THERMION-II will use batteries rather than the Sun to heat up the heat pipe. Because of the limited number of batteries we can launch on the Delta II due to their weight, the experiment will last only a little more than a day.

1.2 DESIGN CONSIDERATIONS

Confirmation that the thermionic heat pipe will operate in a micro-gravity environment is the primary performance driver for this THERMION mission. To confirm this, temperature measurements of the heat pipe are necessary. Measurement of the power generated will also be needed to prove that the device works properly.

1.3 DESIGN EVOLUTION OF THERMION-I

THERMION-I had five major design criteria:

- Test a 6-cm thermionic heat pipe module (THPM)
- Use Solar Energy to heat the THPM
- Small satellite
- 1-year mission
- Secondary payload in a Delta II as launch vehicle

A summary for each subsystem on THERMION-I follows:

1.3.1 Heat Pipe Testing System

The heat pipe temperature will be monitored through 12 thermocouples: 6 distributed over the emitter heat pipe surface and 6 distributed over the collector heat pipe surface.

The thermionic power conversion of the heat pipe will be approximately 11%. A 6-cm heat pipe requires 1050 watts of heat energy. It will convert 11% of the 1050 watts into electrical energy (116 watts). The electrical power breaks down into a 0.7 voltage and a current of 165 amps. The power pick-off points on the heat pipe are at 1000 K. This makes measuring the voltage and current with conventional techniques very difficult. We have chosen to measure the power lost through heat ($I^2 R$ losses) and calculate what the power is. This technique is discussed in more detail in Section 2 of the final report.

1.3.2 Solar Collection System

A parabolic mirror that is 58.6 x 41.6 in (148.8 x 105.7 cm) will be used to collect 2050 watts of the Sun's energy. The mirror will focus the energy into a cavity that resembles Planck's black body box (see Figure 1-4). Once the energy is trapped into the cavity, it will conduct into the heat pipe.

1.3.3 Attitude Control and Determination System

The mirror has a pointing requirement of ±0.75°. To accomplish this accuracy, the following sensors and actuators are used:

- Sensors
  - Wide Angle Sun Sensor
  - High Accuracy Sun Sensor
  - Horizon Crossing Sensor
  - Photo Diodes

- Actuators
  - Torque Rods (Magnetometer)
  - Momentum Wheel

1.3.4 Satellite Structure and Configuration System

The structure consists of a bus, mirror, mirror support, payload, payload arm, and internal components. Figure 1-4 shows the satellite in its deployed configuration.

1.3.5 Data Management System

Data acquisition is the main task of data management. The data will be collected and transmitted in a store and forward manner. The data will be dumped to a ground station every eight hours.

1.3.6 Communications System

Since the satellite's attitude control will be tracking the Sun, a near omni-directional antenna is needed. Two transmitting antennas will use S-band to downlink data to a mobile ground station. Two receiving antennas will be used to uplink any information that might be needed.

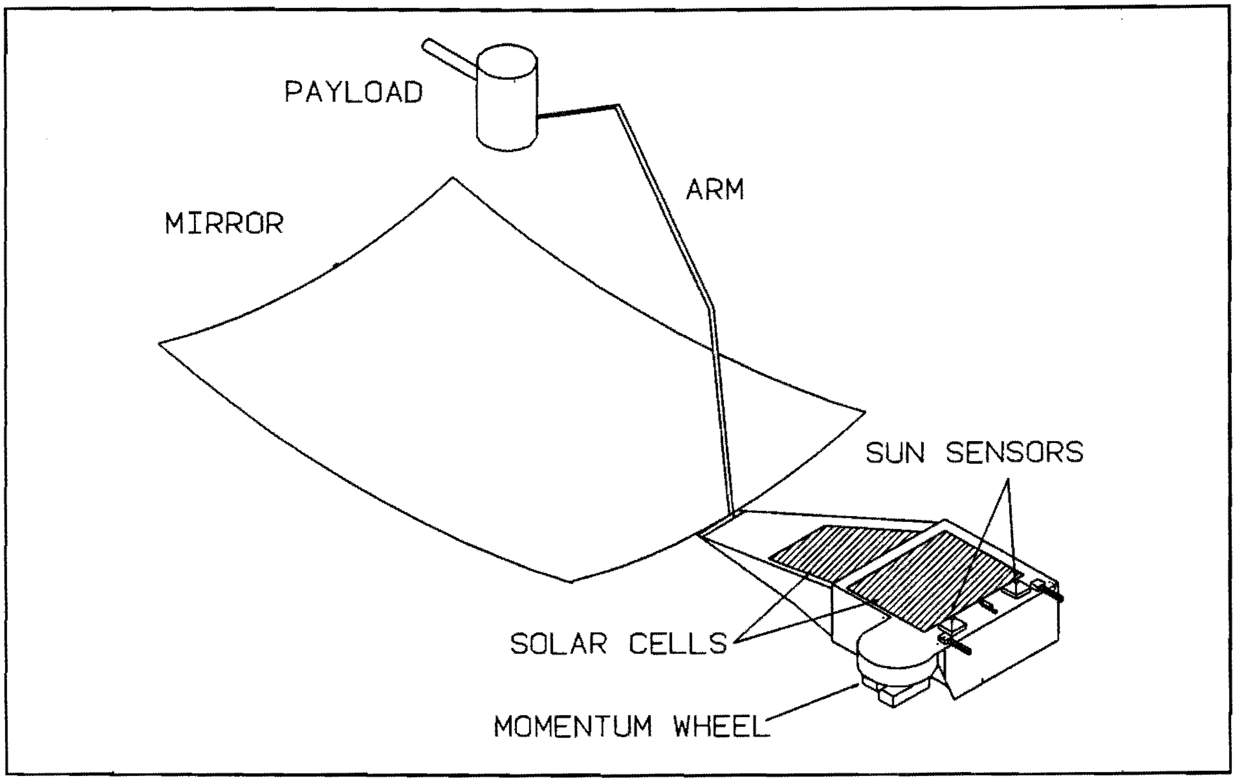

Figure 1-4 THERMION-I satellite in its deployed configuration.

1.3.7 Power System

The power generated by the thermionic heat pipe cannot be turned into useful power for operation of the satellite. Therefore, silicon solar cells were placed on top of the satellite to generate the required operating power. Nickle-cadmium batteries will be used when the satellite is in the shadow of the Earth. These batteries will then be charged on the Sun side of the orbit.

1.3.8 Launch Vehicle Interface and Deployment System

There will be several Global Positioning Satellite (GPS) missions in the next few years with available space on the Delta II secondary stage to launch a small satellite. THERMION-I was designed to fit in the secondary payload volume of the Delta II. The satellite is mounted to the Delta II via a Marman clamp. Once the Delta II secondary stage has reached a circular orbit of 375 nmi, explosive bolts will fire and eject THERMION-I from the vehicle into its circular orbit.

1.3.9 Thermal Management System

Temperature extremes of the THERMION-I satellite were determined by considering the hottest and coldest orbits. A 90 minute orbit was assumed with 60 minutes of this orbit in the Sun. The hottest orbit is during the 60 minutes that the satellite is in the Sun and appropriate instruments are turned on. In this case, all of the onboard components will stay within their operating temperature ranges. The coldest orbit is where the satellite stays in the shadow of the Earth for over 30 minutes. All of the components except the Sun sensors and the solar cells stayed in their temperature limits. This is not of much concern because those components will not be on in the shadow of the Earth. Three watts of power have been incorporated into the power system for heater use, and emissive coatings can be used to bring the instruments into their operating temperature ranges, if deemed necessary.

1.3.10 Test and Evaluation System

The test and evaluation system has been investigating ways of ensuring mission success. Test procedures have been developed to validate instrument operation.

1.3.11 Conclusions

The THERMION-I satellite has a total mass of 85.19 lb (38.64 kg), and will cost less than $1.2 million for the construction of the satellite. The integration costs for mounting to the Delta II will cost approximately $1 million.

2.0 THERMION-II

2.1 INTRODUCTION

Half way through the design of the satellite THERMION-I, it was realized that the thermionic heat pipe module (THPM) need only be tested in a space environment. A free-flying satellite is just one of several solutions. Flight on NASA's KC-135 parabolic test platform, or on a sounding rocket such as the STARFIRE or JOUST series were considered. They provide 30 seconds, 5 minutes, and 15 minutes of microgravity, respectively. We finally settled on flying, as THERMION-I does, on the Delta II launch vehicle. The Delta II can provide months of microgravity and is capable of carrying up to 340 kg as a secondary payload. Unlike THERMION-I, THERMION-II will merely be an appendage to the Delta II; it will not separate. Instead of using a solar collector, THERMION-II will use 253 kg of alkaline cells to power an electric tungsten grid heater on the THPM. Flying on the Delta II gives the best combination of low cost and performance. The experiment can run continuously for 21 hours using the alkaline cells or 63 hours using lithium cells. THERMION-II will complete an identical test of the THPM as THERMION-I, but for a much shorter time. THERMION-II's THPM is 65% larger than the THPM presently proposed on THERMION-I and much closer to the full-scale THPM proposed for the Small Excore Heat-Pipe-Thermionic Space Nuclear Power System (SEHPTR).

The U.S. Air Force and Idaho National Engineering Laboratory (INEL) would like to conduct a test of THPM because it is a critical component of SEHPTR. SEHPTR is a space nuclear reactor nominally capable of generating 40 kW of power. Due to its extremely toxic nature and high cost, it is desirable to conduct realistic tests of critical new components. THERMION-II will simulate the reactor heat load on the THPM using an electric heater.

See Appendix K of final report, for more detail on the THPM and SEHPTR.

2.1.1 Description

THERMION-II is composed of five elements: four battery pallets of 480 alkaline cells each and one payload module. They are fixed to the secondary payload volume of the Delta II launch vehicle as shown in Figure 2-1. Two pallets plus the payload module are on one side, while the remaining two battery pallets are 180° around on the other side of the Delta II second stage.

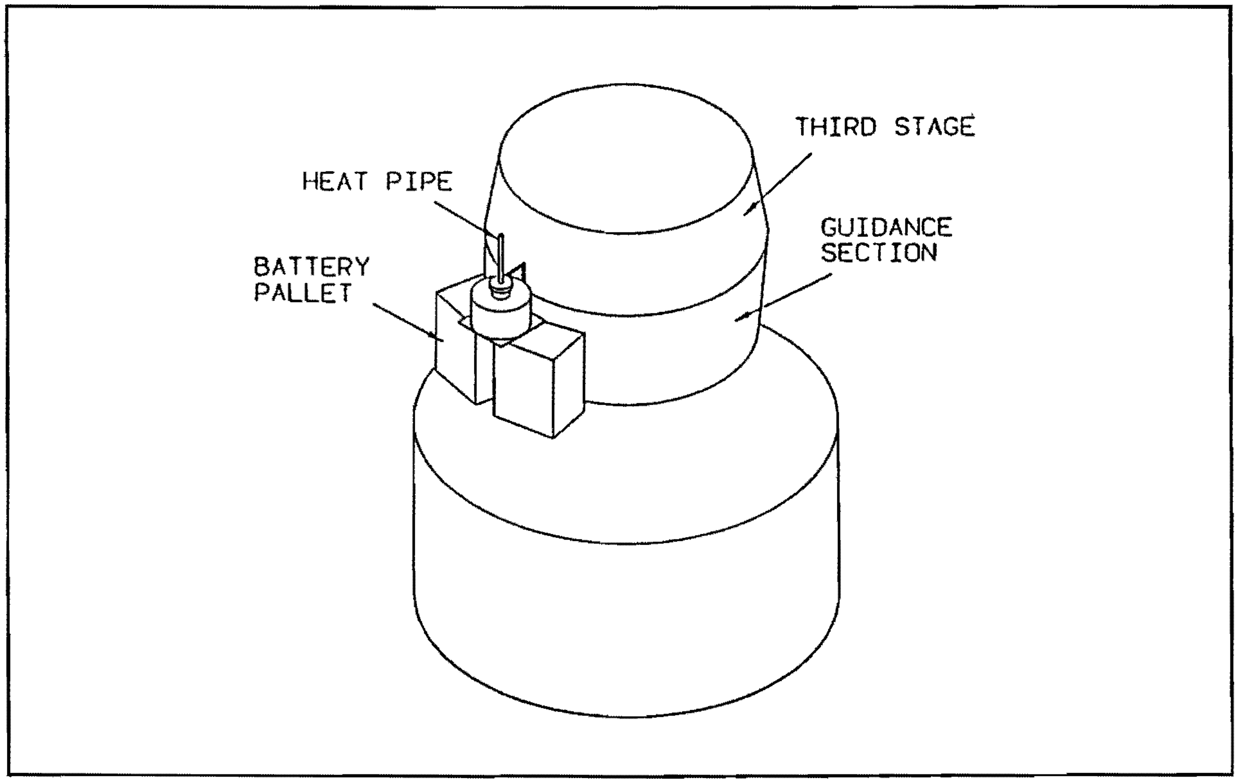

Figure 2-1 THERMION-II in Delta II secondary volume.

2.1.2 Payload Description

The THPM is actually two heat pipes in one. The outer one is shorter. It is called the emitter. The inner and longer heat pipe is called the radiator. It radiates the heat from the nuclear reactor core. The emitter converts 11% of the heat transferred through it into electric power. The other 89% of the heat energy is carried away by the radiator heat pipe. Nominally, the heat input surface of the emitter is at 1925 K The radiator's surface is at 1000 K. So the THPM has two functions:

1) Generate electricity and
2) Transport heat away from the reactor core.

Figure 2-2 shows the SEHPTR reactor design.

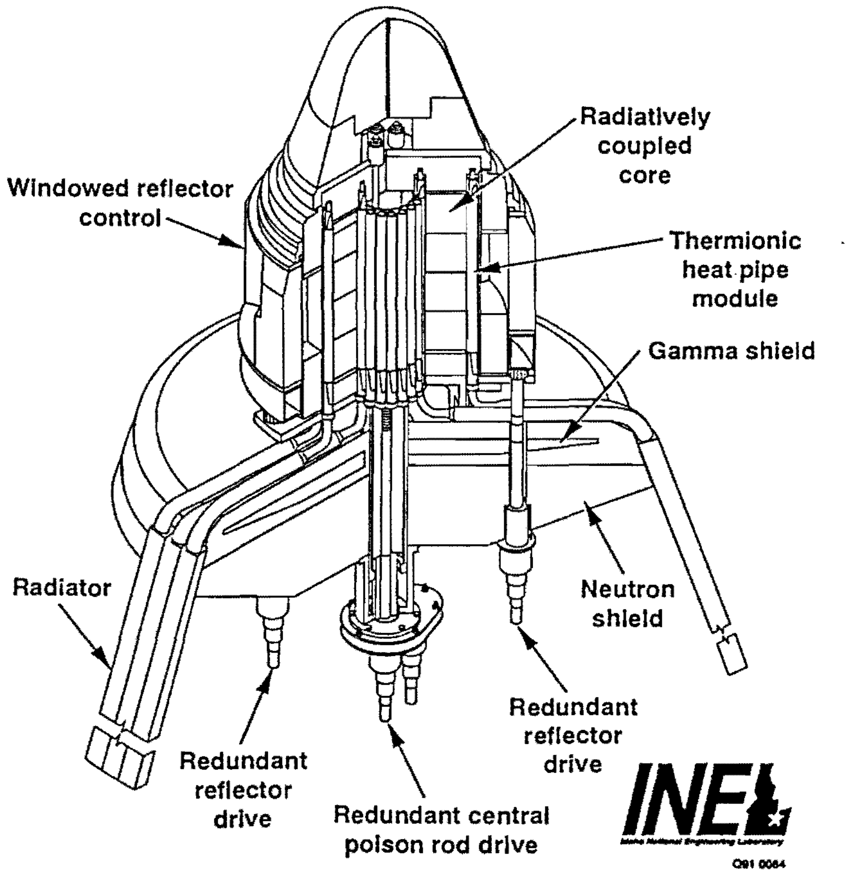

Figure 2-2 The THPM inside the SEHPTR reactor.

11.1.3 Nominal Payload for THERMION-II

THERMION-II can test any scale THPM, but as the heat pipe gets larger, the required input power gets larger. The time of the experiment is reduced because of the finite amount of energy available from the batteries. As a baseline, THERMION-II will test a one-quarter length heat pipe. This is equivalent to a heat pipe with a 10-cm emitter length and an approximate radiator length of 70-cm. The final dimensions on the test THPM are not set because the scale of heat pipe has not been decided on, and so the final performance of the THPM has not yet been determined. However, Utah State University has been working closely with Thermacore, Inc., the likely manufacturer of the THPM, and the finalization of parameters is imminent.

2.2 SYSTEM-LEVEL REQUIREMENTS OF THERMION-II

The requirements of THERMION-II are to simulate the thermal environment of SEHPTR's nuclear reactor core on a scaled version of the THPM on orbit, measure the performance, and telemeter data to the ground. Other requirements are to:

- Provide a structure to fly in the Delta II secondary payload volume that supports the required batteries and the THPM,
- Design a low cost alternative to THERMION-I, and
- Provide a safe and reliable design.

2.3 DESIGN PHILOSOPHY

The design philosophy of THERMION-II is as follows:

- Take a simple straight-forward approach to the THPM space test. Avoids unproven systems and items of questionable safety.
- Offer a low cost option. If it is simple to design and understand, it will be easy and inexpensive to implement.

2.4 MISSION DESCRIPTION

The THPM test requires a microgravity environment for some length of time. The THPM should be exposed to an environment that closely matches that of its intended use, inside a reactor core. To achieve this, the THPM payload will be mounted to the Delta II secondary payload volume along with batteries, power control system computer, and interface to the Delta II telemetry system. Once the orbit has been achieved, the primary payload will separate from the Delta II and the Delta II will zero the rotation rates of the second stage and activate the experiment. From this time on, the Delta II will only provide telemetry capability. No active attitude control system will remain, and some power will be diverted from the batteries to power the Delta II telemetry system. Detailed integration into the Delta II has not been seriously addressed, and it is anticipated the use of its telemetry system will be involved.

Using a one-quarter length THPM, the experiment may be operated continuously for 21 hours or longer if variable heating rates are applied to the THPM. For example, the high amount of control of an electric-based heater allows for very slow and very fast heating of the THPM.

2.5 CONCLUSIONS

THERMION-II is not a satellite and, consequently, is free of the cost, complexity, and development time that a satellite is heir to. THERMION-II capitalizes on existing systems on board the Delta II (attitude control and telemetry) and does not depend on external power sources. Because it has no moving parts, there is no question of mechanical reliability. THERMION-II can also be developed and flown in much less time than any satellite.

THERMION-II is versatile since it has excellent control over heating rates of the electric heater. This is a closed loop system. Any transients can be simulated and excess power input may also be simulated. While THERMION-I may run for a year, it has the drawback that it cycles the THPM every orbit due to the loss of the Sun when it is in shadow.

THERMION-II should be pursued if a 21 hour test or a series of 21 hour tests (several THERMION-II's) will satisfy the reliability and functional concerns of the thermionic heat pipe module in a space environment. Finally, THERMION-II can be optimized using lithium cells instead of alkaline cells. This will triple the experiment time. However, lithium cells have had an explosive history. If the cells are not internally fused, they may overheat and explode when shorted, and though modern lithium cells are much safer, their legacy remains. The cost of qualifying them for flight may exceed their benefit.

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