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Thermoelectric Alloys and Devices for Radioisotope Space Power Systems: State of the Art and Current Developments

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ABSTRACT

Lead telluride and silicon germanium type alloys have served over the past several decades as the preferred thermoelectric conversion materials for U. S. radioisotope thermoelectric generator (RTG) power systems for planetary deep space exploration missions. The Pioneer missions to Jupiter and Jupiter/Saturn and the Viking Mars Lander missions employed TAGS-2N (lead and germanium telluride derivatives) power conversion devices. Since 1976, silicon germanium (SiGe) alloys, incorporated into the unicouple device, have evolved as the thermoelectric materials of choice for U. S. RTG powered space missions. These include the U. S. Air Force Lincoln Experimental Satellites 8 & 9 for communications, in 1976, followed in 1977 by the National Aeronautics and Space Administration Voyager 1 and 2 planetary missions. In 1989, advanced SiGe RTGs were used to power the Galileo exploration of Jupiter and, in 1990, will be used to power the Ulysses investigation of the Sun. In addition, SiGe technology has been chosen to provide RTG power for the 1995 Comet Rendezvous and Asteroid Flyby mission and the 1996 Cassini Saturn orbiter mission. Summaries of the flight performance data for these systems are presented.

Current U. S. Department of Energy thermoelectric development activities include (1) the development of conversion devices based on hi-density, close packed couple arrays and (2) the development of improved performance silicon germanium type thermoelectric materials. The silicon germanium type "multicouple", being developed in conjunction with the Modular RTG Program, is discussed in a companion paper. A lead telluride type close-packed module, discussed herein, offers the promise of withstanding high velocity impacts and, thus, is a candidate for a Mars Penetrator application.

Recent projects sponsored by the U. S. Department of Energy, including the Improved Thermoelectric Materials and Modular Radioisotope Thermoelectric Generator programs, have shown that improvements in silicon germanium thermoelectric energy conversion capabilities of at least 50 percent can be achieved by tailoring the characteristics of the silicon germanium alloy materials and devices. This paper compares the properties and characteristics of the SiGe alloys now being developed with those used in the operational space power system.

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INTRODUCTION

The launch of the Galileo spacecraft, on October 18, 1989, continued a series of highly successful Radioisotope Thermoelectric Generator (RTG) powered spacecraft. The Galileo spacecraft was launched to explore Jupiter and its moons in great detail. Its level of power and capabilities were dramatically greater than the first "proof-of-principle" spacecraft in the series; namely, the tiny SNAP-3B flown on Transit 4A in June 1961. To date, the U. S. has successfully launched twenty (20) spacecraft powered by a total of thirty six (36) RTGs. The RTGs have been quite varied in characteristics. There have been eight basic designs using three types of thermoelectric materials, and the RTGs had four different forms of plutonium 238 fuel for their heat sources.

Each of these RTG powered space systems used the experience gained on prior missions to improve the performance characteristics of the power system from the standpoints of generator efficiency, power outputs and specific powers. As an example, the initial power output of the generator on Transit 4A was about 2.7 watts electrical compared to the 600 watts supplied by the two units on the Galileo spacecraft.

This paper will present a brief overview of the types of generators and missions, the trends in generator performance with time, and some of the recent projects being conducted to further enhance performance. Much more detailed design and performance data on these RTGs have been reported previously by Bennett, Lombardo and Rock [1], C. E. Kelly [2], Skrabek and McGrew [3], Brittain and Skrabek [4], and Skrabek [5].

GENERATOR CHARACTERISTICS

Table 1, compiled by Skrabek [5], provides a chronological listing of the successful U. S. RTG launches to date. From the design characteristics of these generators listed in Table 2, he has concluded that there are eight generator designs which can be separated into three general classifications.

The SNAP series (3B, 9A, 19B, 19 and 27) shared many features. They all utilized telluride type thermoelectric materials with heat transfer from the fuel source to the thermoelectric converter being accomplished by conductive coupling. These RTGs operated at moderate hot junction temperatures of about 780K to 890K and, except for the first SNAP 3B, a cover gas was used to help retard sublimation.

The Transit-RTG used PbTe thermoelectrics but had a different approach for controlling sublimation; namely, reduction of the hot junction temperature to 673K. Also, the thermoelectric elements were radiatively coupled to the heat source.

Since 1976, emphasis has been directed toward the use of silicon germanium alloys in RTGs for deep space missions. The first application of this system, in 1976, was the United States Air Force Lincoln Experimental Satellite 8 & 9 (USAF LES 8/9) communication satellites which were followed, in 1977, by the NASA Voyager 1 and 2 planetary missions. The units employed on these missions were called multi-hundred watt (MHW) RTGs. In 1989, General Purpose Heat Source Radioisotope Thermoelectric Generators (GPHS-RTGs) were used to power the Galileo exploration of Jupiter and will be used in 1990 to power the Ulysses investigation of the Sun. In addition, SiGe technology has been chosen to provide power for the 1995 launch of CRAF (Comet Rendezvous Asteroid Flyby) and the 1996 launch of the Cassini Saturn orbiter.

RTGs with SiGe thermoelectric materials operate at a higher hot junction temperature of about 1273K. Radiative coupling is used between the heat source and unicouples for these designs and sublimation is retarded by a chemical vapor deposition (CVD) silicon nitride coating on the thermoelectric elements. The figures-of-merit of SiGe alloys are lower than that for PbTe alloys, but the higher operating temperatures provide for a larger Carnot efficiency and result in overall improvement in the specific power of the system.

The heat sources for the RTGs have evolved over the years from metallic Pu 238 to the hot pressed plutonia pellets encased in iridium metal used in MHW and GPHS RTGs. These are protected by graphite enclosures from reentry heating and are designed for intact reentry in the event of accidents.

RTG MISSION AND GENERATOR PERFORMANCE

Skrabek [5] has recently summarized the performance data for all these RTGs and the results are summarized in Figure 1 through 8. Specific details for several of the more important missions are summarized below. These include Pioneer, Viking, LES 8/9, and Voyager.

SNAP 19 Pioneer RTGs - Jupiter and Saturn Spacecraft

The Pioneer 10 and 11 spacecraft (Figure 9) blazed a trail through the asteroid belt, were the first to explore Jupiter and Saturn by flyby and went on to the outer solar system. They have now reached beyond the borders of the solar system and will ultimately journey to the distant stars [6]. The four RTGs on both spacecraft continue to perform well above design levels and are now beginning, respectively, their 18th and 19th years of space flight. Pioneer 10 is the longest successfully operating system to date and is even now producing as much power as was required for the Jupiter encounter more than 12 years ago. As shown in Figure 6, the Pioneer RTGs are still producing about 56% of their original power after over 150,000 hours, based upon spacecraft telemetry data, an average power decay rate of less than 0.3% per 1000 hours.

Because of the continued good condition of both spacecraft as they travel in interstellar space, useful scientific data are now expected well into the 1990s, as long as spacecraft signal strength to Earth is adequate for reception by NASA's Deep Space Network.

SNAP 19 RTGs/Viking-Mars Landers

NASA's Viking missions were initiated in August and September 1975, when two spacecraft were launched for extended exploration of the planet Mars to search for life and to evaluate other scientific features. Following planet rendezvous in the summer of 1976, each orbiting spacecraft successfully released its Lander for descent and soft landing at preselected sites on the Martian surface. Aboard each Lander were two (2) SNAP 19 RTGs, shown in Figure 10. The RTGs provided thermal protection for the scientific instrumentation and communication equipment in addition to the prime electrical power. The SNAP 19 RTGs far exceeded their two (2) years of planetary cruise/orbit and ninety (90) day landed mission design requirements as shown in Figure 5. When Orbiter/Lander transmission was terminated, it was projected that the RTGs could adequately operate Lander equipment for at least another decade [5].

Of the twenty-five (25) experiments aboard the Orbiter/Lander, including meterology, seismology and biology, the surface imagery and organic sampling capabilities were particularly noteworthy [7]. Man's first view of the Martian horizon, taken within minutes of the Viking 1 landing on July 20, 1976, is shown in Figure 11.

MHW RTG for LES 8/9 and Voyager Missions

The MHW RTG is an isotope fueled static power supply using SiGe alloy thermoelectric materials. It was designed to provide an electrical power output of 150 watts with a thermal inventory of 2400 watts at beginning of mission. Major components of the RTGs are the heat source, SiGe alloy unicouples, a multifoil insulation system and a beryllium outer housing as shown in Figure 12. The heat source radiated heat to 312 couples (Figure 13) operating at a hot junction temperature of 1273K. Except for heat source configuration and number of couples, similar design considerations have been also used for the GPHS RTGs on the Galileo converters.

The MHW RTGs on the LES 8/9 and Voyager 1 and 2 missions are performing very close to their predicted levels (Figures 7 and 8). All the generator outputs have been above the predicted values, and it is expected that they will send data back from well outside the limits of the solar system until the beginning of the next century.

This capability for predicting accurately the performance trends for the space power systems reflects the experimental and theoretical emphasis that was directed at determining the relative magnitudes, rates and temperature dependency of the critical degradation mechanisms. These include factors such as radioisotope fuel decay, alteration of bulk thermoelectric properties due to dopant precipitation, changes in the characteristics of the semiconductor electrode interfaces, geometry and compositional changes due to material sublimation, and degradation of the multifoil insulation. Predictive models for each of these effects were generated based on coupon and ground based module tests and prior flight mission performance characteristics.

General Characteristics of RTGs

The reliability demonstrated for SNAP 19, MHW RTGs and GPHS RTGs can now be measured in decades rather than months, and the designs have matured to the point where precise power levels and operating lifetimes can be achieved, permitting extremely long space missions. In fact, the scientific test equipment and telemetry systems rather than the isotope power supplies may provide the mission limiting contraints for future RTG powered spacecraft.

RECENT EXAMPLES OF U. S. DEPARTMENT OF ENERGY PROJECTS

The United States Department of Energy has a series of on-going activities to make further improvements in the mission-related characteristics of RTGs and in energy conversion capabilities. Two examples of these projects are summarized below; namely, (a) shock resistant close packed array thermoelectric modules, and (b) improved performance SiGe thermoelectric alloys.

Shock Resistant CPA Thermoelectric Modules

- Close Packed Array Module Technology

The design of small RTGs which have relatively high voltage power output, and are capable of high level shock loads associated with possible hard landings on planet Mars, requires special consideration for thermoelectric module design and support within the RTG housing. An attractive approach to achieve high impact integrity, designated Close Packed Array (CPA), has been extensively used for over two (2) decades with bismuth telluride thermoelectric materials. This technical approach has more recently been applied to the higher operating temperature lead telluride family of thermoelectrics. A typical bismuth telluride CPA module is shown in Figure 14.

Figure 15 shows a CPA module containing lead telluride type thermoelectric elements being prepared for application of hot and cold shoes. An "egg crate" is first assembled into a holding fixture and the individual elements inserted in the matrix. Figure 16 shows the completed module with power leads installed.

Table 3 shows the initial performance of a completed module. Module performance agreed well with the predicted values.

- Minicouple PbTe Module Technology

An optional technical approach for the thermoelectric module to obtain relatively high voltage at low power output consists of individual minicouples arrayed in a circular configuration to form a cylindrically-shaped module assembly. Figure 17 pictures a completed module ready for testing.

a. Bell Jar Tests

Table 4 presents initial data for three modules which were tested in a bell jar. All modules were very close to the performance prediction. Note that the design point for the disc-type module is 850/210°F hot/cold junction temperatures and 5.25V load voltage.

b. Generator Testing

Referring to Figure 18, the two electrically heated generator assemblies were initially operated at 850/210°F hot/cold junction temperature and 5.25V load voltage. Later, operating temperatures were reduced. One unit has since been operating at 800/200°F and the other unit at 750/150°F hot junction and cold junction temperatures, respectively. Load voltage for both units is set at 5V.

Silicon Germanium Alloy Thermoelectric Materials

As indicated above, silicon germanium alloys have been established as the material of choice for high temperature thermoelectric power generation. Although Si and Ge have high melting points, large band gaps and good chemical stability, their lattice thermal conductivities are too high and the pure elements are of no use in thermoelectric applications. However, when these isomorphous elements are alloyed to form a solid solution, there is a marked reduction in the lattice thermal conductivity due to the scattering of the short wavelength phonons with atoms of different mass (hence, the term mass fluctuation scattering)[8, 9]. Further reductions are realized by the addition of n- or p-type dopants[10, 11] due to the interaction of phonons with the charge carriers at intermediate wavelengths and the use of fine grained materials to effect scattering of the long wavelength phonons at the grain boundaries[12-15]. By introducing additional disorder into the SiGe lattice, Pisharody and Garvey[16] reduced the lattice thermal conductivity even further by the addition of GaP. This, however, was complicated by porosity and grain size effects.

Fabrication of the SiGe alloys used in the space power missions up to now has been prepared by the melting/casting/grinding/hot pressing technique. More recent investigations are involved with the development of improved SiGe alloys with GaP additions. As early as 1976, gallium phosphide was suggested as a promising additive for improving the performance of SiGe alloys. GaP was postulated to reduce the lattice thermal conductivity by increasing the "complexity" or mass fluctuation scattering of the lattice in a manner similar to the mechanism which results from the addition of Ge to Si [16]. A significant decrease (40-50%) in the thermal conductivity was experimentally observed by Pisharody and Garvey [16] when GaP was added to hot pressed 63/37 SiGe alloys. Unfortunately, the electrical resistivity also increased and the net gain in the figure-of-merit was small. The reported reduction in thermal conductivity may be due to other effects like the reduction in particle size (from 180 to 44 um) and the high degree of porosity (3-8%). Two approaches currently under investigation to improve the figure-of-merit are: (1) a two step process involving hot pressing of a mixture of materials - a SiGe alloy with a high solubility for GaP and a highly doped silicon based material, and (2) hot pressing of a SiGe/GaP powder prepared by mechanical alloying. The first approach was developed by the General Electric Company and the second approach is being developed by Ames Laboratory at Iowa State University. Several gallium phosphide alloys of identical composition have been prepared and characterized for their high temperature thermoelectric properties.

The fabrication process employed by GE is an extension of the melting/chill casting/grinding/hot pressing technique used successfully in earlier RTG projects. Initially, castings of a SiGe alloy with a high solubility for GaP and a highly doped Si alloy are prepared. Reduction to a small particle diameter and hot pressing of the resulting powders followed.

An alternate fabrication method used at Ames Laboratory involves room temperature solid state alloying and hot pressing. Silicon, germanium and gallium phosphide are placed in a container, along with several steel balls, and vigorously shaken to produce a homogeneous alloy. The resultant powder of extremely small diameter is then hot pressed.

The Seebeck coefficient, electrical resistivity and thermal conductivity were measured up to 1000°C and used to compute the figure-of-merit in order to assess the thermoelectric performance of these new materials. The figure-of-merit of the GaP containing alloys prepared by these two techniques are similar and are about 25% higher than the current state-of-the-art n-type SiGe alloy used in the Voyager and Galileo RTGs. The increase in the figure-of-merit is attributed to a higher carrier concentration and smaller particle size which act to increase the electrical power factor and decrease the thermal conductivity. Further investigation is necessary to verify that both fabrication techniques allow for reproducibility of the improved thermoelectric properties.

CONCLUSIONS

A variety of isotope powered RTGs has been fabricated and used successfully in deep space missions. The technology is mature and very reliable: performance can be predicted with a high degree of accuracy. It is expected that future missions will tend to emphasize the tailoring of the RTG characteristics to specific requirements of the mission such as shock and vibration, and to improving generator efficiencies, power outputs and specific powers by module design and/or materials changes.

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Table 1. Summary of Radioisotope Thermoelectric Generators Successfully Launched by the United States (1961-1989) [Reference 5]

POWER SOURCE	NUMBER OF POWER SOURCES	INITIAL AVE. POWER PER POWER SOURCE (W)	SPACECRAFT	MISSION TYPE	LAUNCH DATE*	INITIAL ORBIT	ORBITAL LIFETIME (YEARS)
SNAP-3B7	1	2.7	Transit 4A	Navigational	6/29/61 (ETR)	~890x1000 km 67.5°, 104min.	500
SNAP-3B8	1	2.7	Transit 4B	Navigational	11/15/61 (ETR)	~960x1130 km 32.4°, 106 min.	1200
SNAP-9A	1	>25.2	Transit 5BN-1	Navigational	9/28/63 (WTR)	~1090x1150 km 89.9°, 107 min.	1900
SNAP-9A	1	26.8	Transit 5BN-2	Navigational	12/5/63 (WTR)	~1080x1110 km 90.0°, 107 min.	1800
SNAP-19B	2	28.2	Nimbus III	Meteorological	4/14/69 (WTR)	1070x1131 km 99.9°, 107 min.	3600
SNAP-27	1	73.6	Apollo 12	Lunar	11/14/69 (KSC)	Lunar Trajectory	On Lunar Surface
SNAP-27	1	72.5	Apollo 14	Lunar	1/31/71 (KSC)	Lunar Trajectory	"
SNAP-27	1	74.7	Apollo 15	Lunar	7/26/71 (KSC)	Lunar Trajectory	"
SNAP-19	4	40.7	Pioneer 10	Planetary	3/2/72 (ETR)	Solar System Escape Traj.	Beyond Solar System
SNAP-27	1	70.9	Apollo 16	Lunar	4/16/72 (ETR)	Lunar Trajectory	On Lunar Surface
Transit-RTG	1	35.6	Triad	Navigational	9/2/72 (WTR)	716x863 km 90.1°, 101 min.	137
SNAP-27	1	75.4	Apollo 17	Lunar	12/7/72 (KSC)	Lunar Trajectory	On Lunar Surface
SNAP-19	4	39.9	Pioneer 11	Planetary	4/5/73 (ETR)	Solar System Escape Traj.	Out of Solar System
SNAP-19	2	42.3	Viking 1	Mars Lander	8/20/75 (ETR)	Trans-Mars Trajectory	On Martian Surface
SNAP-19	2	43.1	Viking 2	Mars Lander	9/9/75 (ETR)	Trans-Mars Trajectory	On Martian Surface
MHW-RTG	2	153.7	Les-8	Communications	3/14/76 (ETR)	35.787 km 25.0°, 1436 min.	1,000,000
MHW-RTG	2	154.2	Les-9	Communications	3/14/76 (ETR)	35.787 km 25.0°, 1436 min.	1,000,000
MHW-RTG	3	159.2	Voyager 2	Planetary	8/20/77 (ETR)	Solar System Escape Traj.	Out of Solar System
MHW-RTG	3	156.7	Voyager 1	Planetary	9/5/77 (ETR)	Solar System Escape Traj.	Out of solar system
GPHS-RTG	2	287.4	Galileo	Planetary	10/18/89 (KSC)	Veega-Jupiter	Venutian Trajectory (Eventual Jovian Orbit)

*Key to launching stations: ETR, Eastern Test Range; WTR, Western Test Range; KSC, Kennedy Space Center.

Table 2. General Characteristics of RTGs in Space [Reference 5]

SPACECRAFT	POWER SOURCE	T/E MATERIALS	GENERATOR INTERNAL ENVIRONMENTS	THERMAL COUPLING	T/E MOUNTING	T_{HOT} (K)	NOMINAL EFFICIENCY %	SPECIFIC POWER (W(E)/KG)
Transit 4A	SNAP 3B	PbTe 2N/2P	Soft Vacuum	Conduction	Spring+Piston	783	5.0	1.48
4B	"	"	Kr/H_2	"	"	"	"	"
Transit 5BN1	SNAP-9A	"	Ar/He	"	"	790	5.1	2.2
5BN2	"	"	"	"	"	"	"	"
Apollo 12	SNAP-27	PbTe 3N/3P	Ar	Conduction	"	855-890	5.0	2.34
14	"	"	"	"	"	"	"	"
15	"	"	"	"	"	"	"	"
16	"	"	"	"	"	"	"	"
17	"	"	"	"	"	"	"	"
Triad	Transit	PbTe 2N/3P	Vacuum	Radiation	Panel	673	4.2	2.6
Nimbus III	SNAP-19B	PbTe 2N/3P	Ar/He	Conduction	Spring+Piston	780	6.0	2.1
Pioneer 10	SNAP-19	PbTe 2N/ TAGS-85	"	"	"	785	6.3	3.0
Pioneer 11	"	"	"	"	"	"	"	"
Viking Lander 1	"	"	"	"	"	819	"	"
Viking Lander 2	"	"	"	"	"	"	"	"
LES-8	MHW-RTG	SiGe	Vacuum	Radiation	Cantilever	1273	6.7	3.94
9	"	"	"	"	"	"	"	"
Voyager 1	"	"	"	"	"	"	"	"
2	"	"	"	"	"	"	"	"
Galileo	GPHS-RTG	"	"	"	"	"	6.8	5.14

Table 3. 126-Couple CPA Module Performance
(Element Size = .061" Sq. x .466" Lg.)

	Prediction	Module S/N 5
Power Output (Watts(e))	4.51	4.47
Power Input (Watts(t))	59.7 (1)	60.0 (2)
Hot Junction (^{o}F)	925	925 (3)
Cold Junction (^{o}F)	160	160
Open Circuit Voltage (VDC)	19.27	19.30
Load Voltage (VDC)	9.63	9.72
Internal Resistance (Ohms)	20.56 (4)	20.83

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(1) Includes: $Q_{T/E}$(49.4W) + $Q_{SEPARATORS}$(8.2W) + $Q_{INERT\ COUPLES}$(2.1W)

(2) Measured Power Input Less Test Fixture Tare Losses.

(3) Inferred Temperature Based on Power Input and Open Circuit Voltage.

(4) Includes $R_{T/E}$(20.40 ohms) + R_{STRAPS}(.06 ohms) + R_{LEADS}(.10 ohms).

Table 4. Module Initial Performance Summary Bell Jar Tests

	Prediction @ 100 Hrs.	Normalized Test Data Module S/N 6 @ 115 Hrs.	Module S/N 7 @ 114 Hrs.	Module S/N 12 @ 504 Hrs.
Power Output (W(e))	3.66	3.69	3.70	3.72
Hot Junction (^{o}F)	850	850	850	850
Cold Junction (^{o}F)	210	210	210	210
Load Voltage (V)	5.25	5.25	5.25	5.25
Open Circuit Voltage (V)	9.04	8.83	8.83	8.91
Internal Resistance(Ohms)	5.43	5.09	5.08	5.16

Module Configuration Summary

- Disc-type module.
- Element size: 0.104 in. sq. x 0.625 in. lg.
- 68 couples connected electrically in series.
- PbTe N-leg; TAGS P-leg.
- Schottky diode open circuit protection.
- PC board cold side electrical straps.

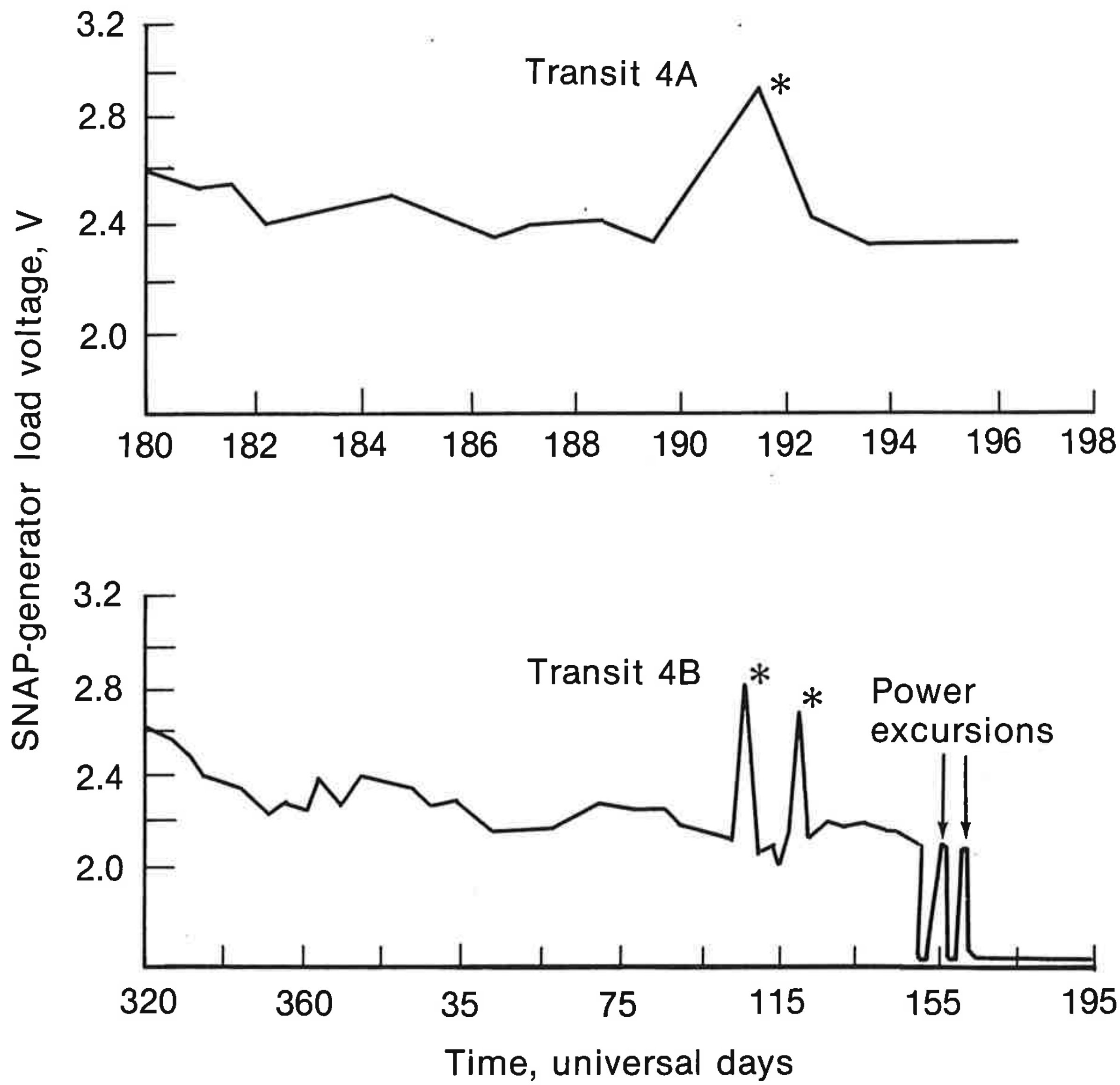


Figure 1. SNAP-3B Operating Data Telemetered from Transit 4A (top) and Transit 4B (bottom) [Reference 5]

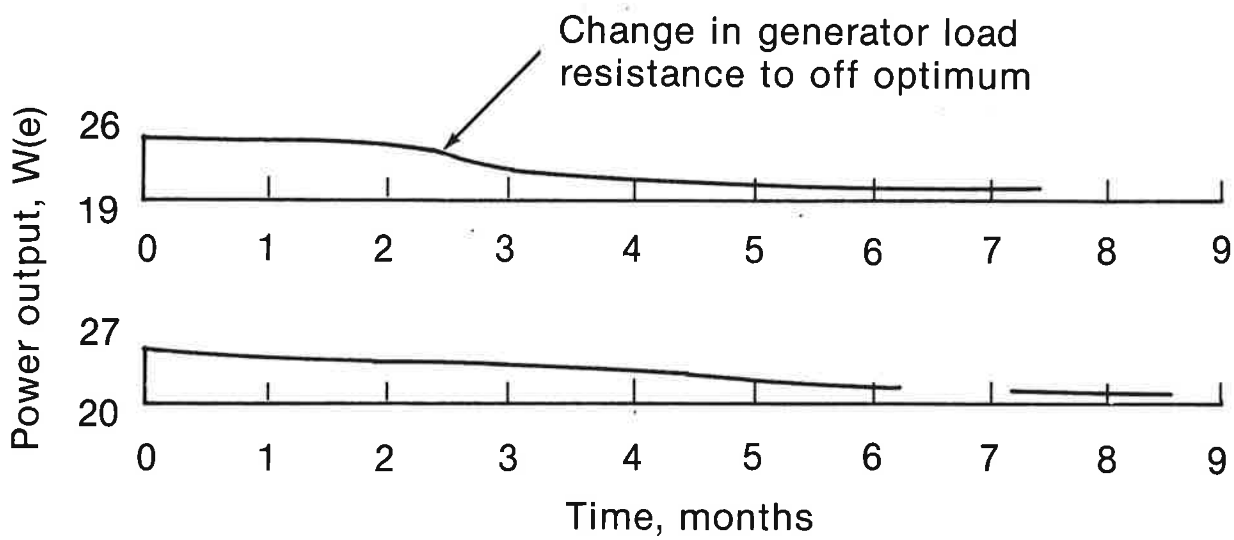


Figure 2. SNAP-9A Power Performance (Smoothed Data) as Telemetered by Transit 5BN-1 (top) and 5BN-2 (bottom) [Reference 5]

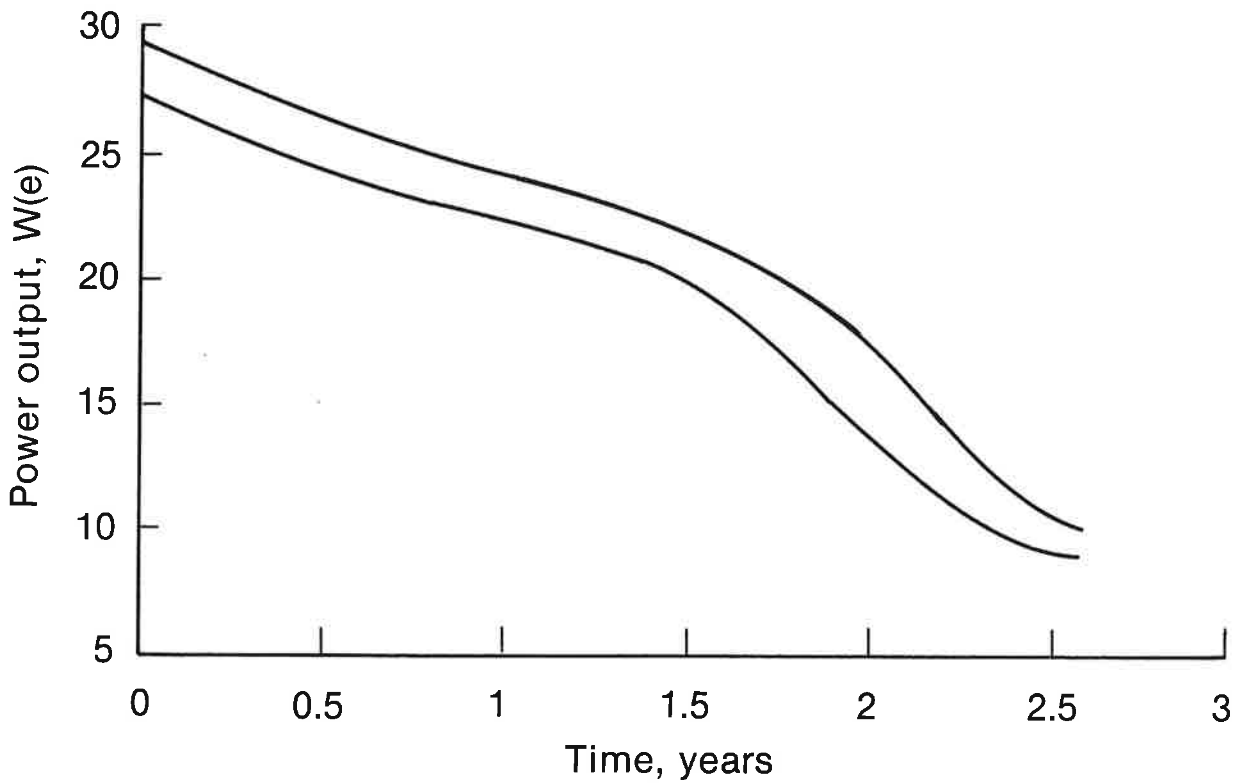


Figure 3. Nimbus III/SNAP-19 Power Output (Smoothed Data) [Reference 5]

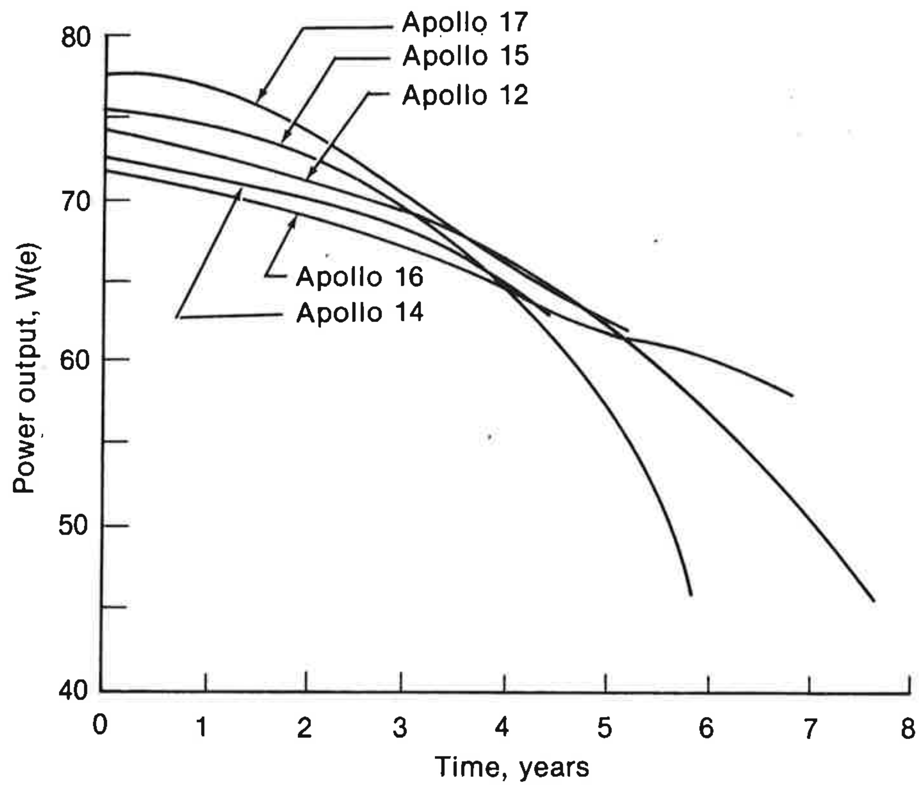


Figure 4. Power History of the SNAP-27 RTGs (Smoothed Data) [Reference 5]

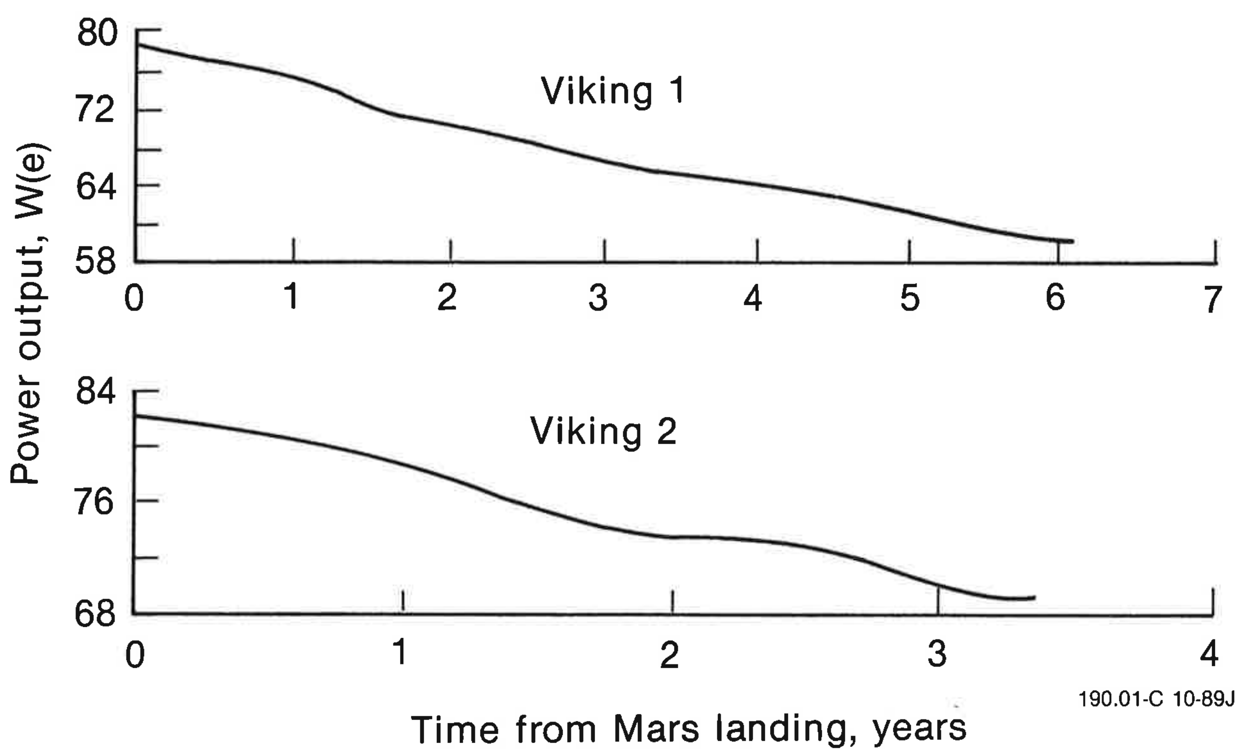


Figure 5. Power History of the Viking SNAP-19 RTGs
(Summed and Smoothed Data) [Reference 5]

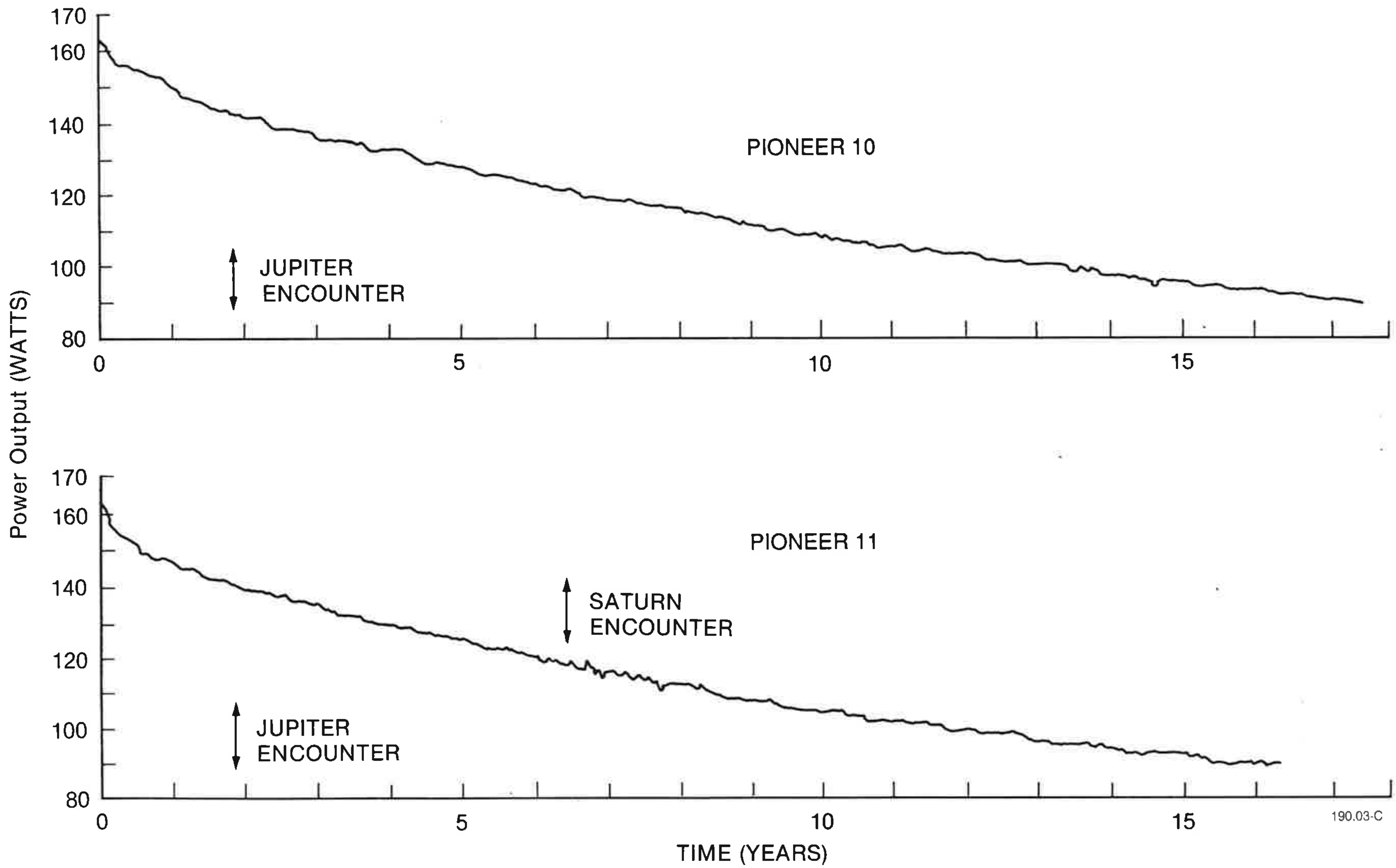
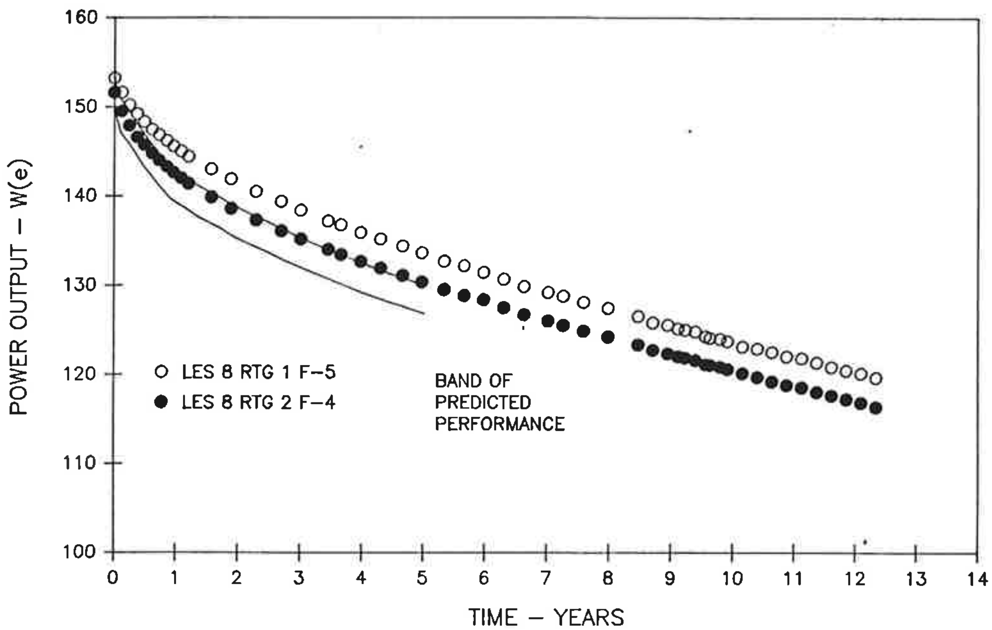


Figure 6. Power History of the Pioneer SNAP-19 RTGs (Summed Data) [Reference 5]



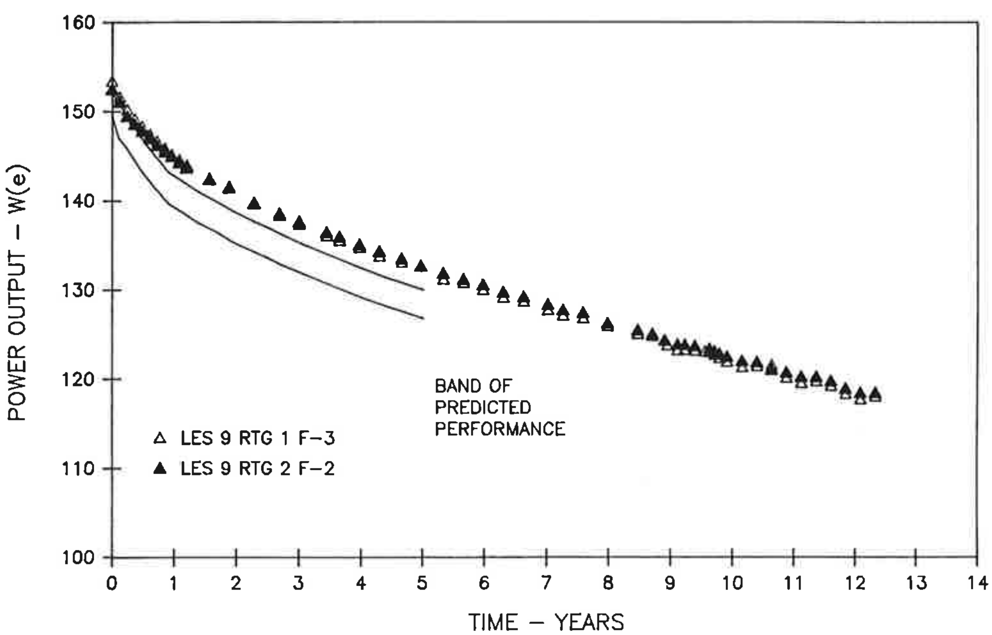


Figure 7. Power History of LES-8 and LES-9 MHW RTGs
Compared to Predicted Performance

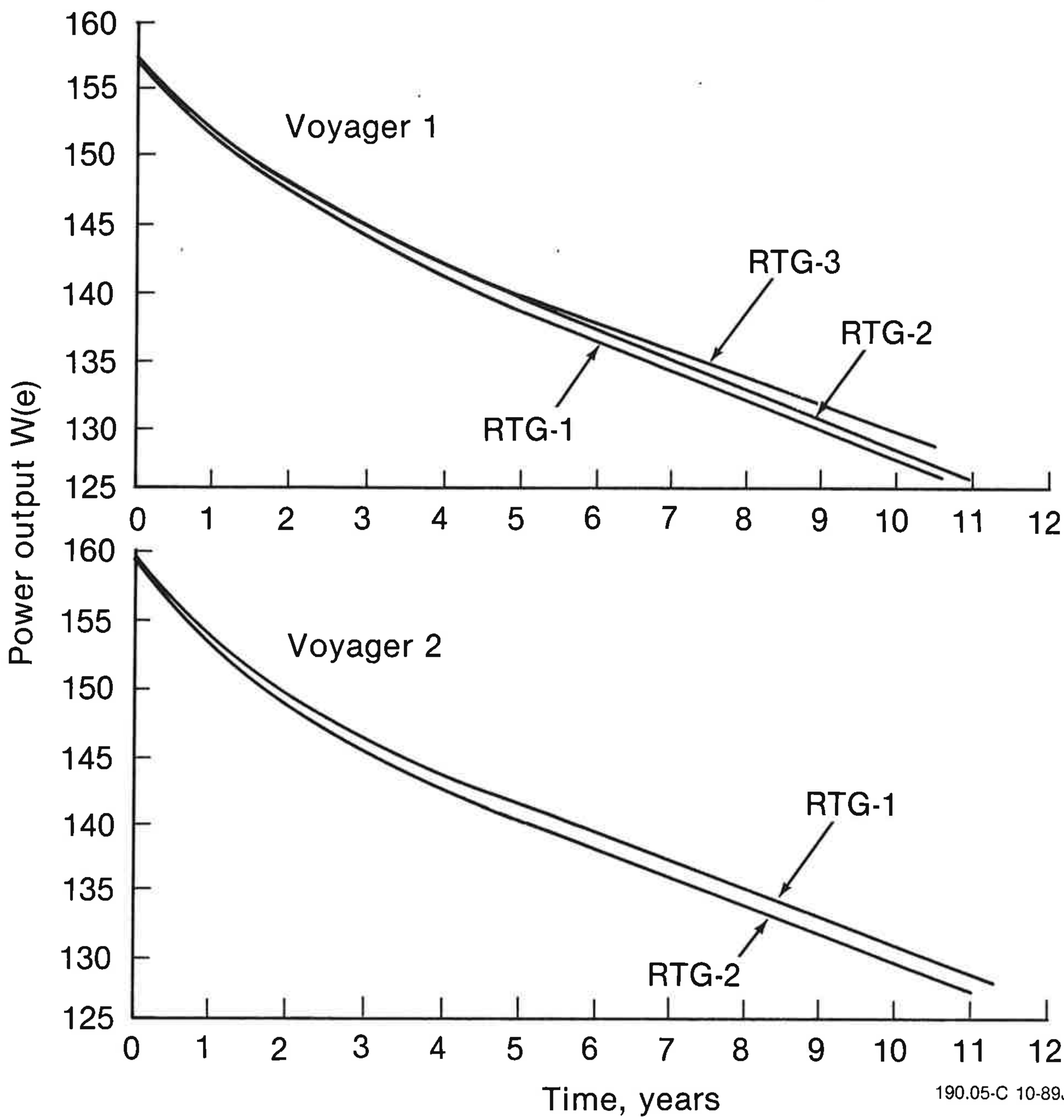


Figure 8. Power History of Voyager MHW RTGs [Reference 5]

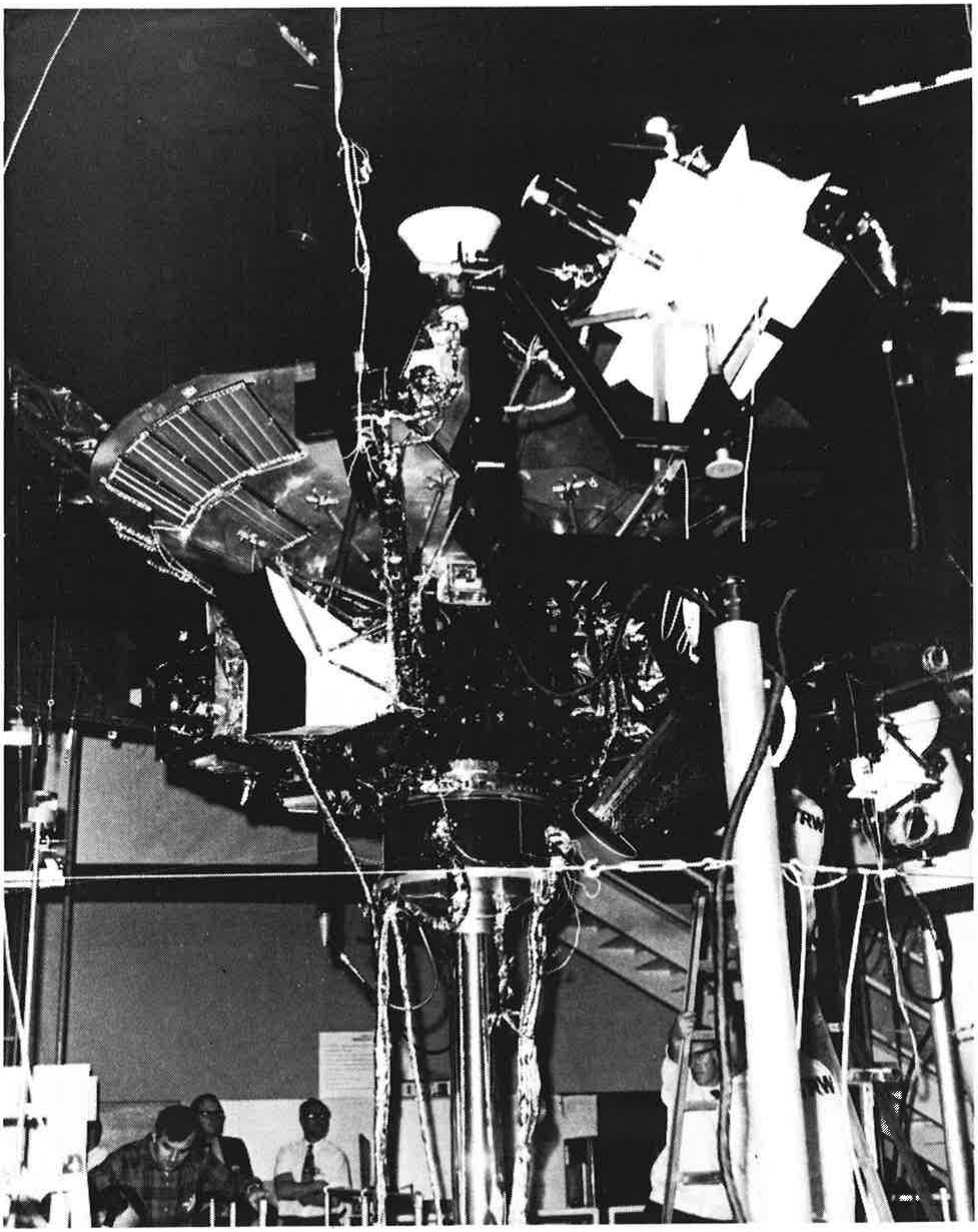


Figure 9. SNAP-19 RTG Integration Test on Pioneer Spacecraft

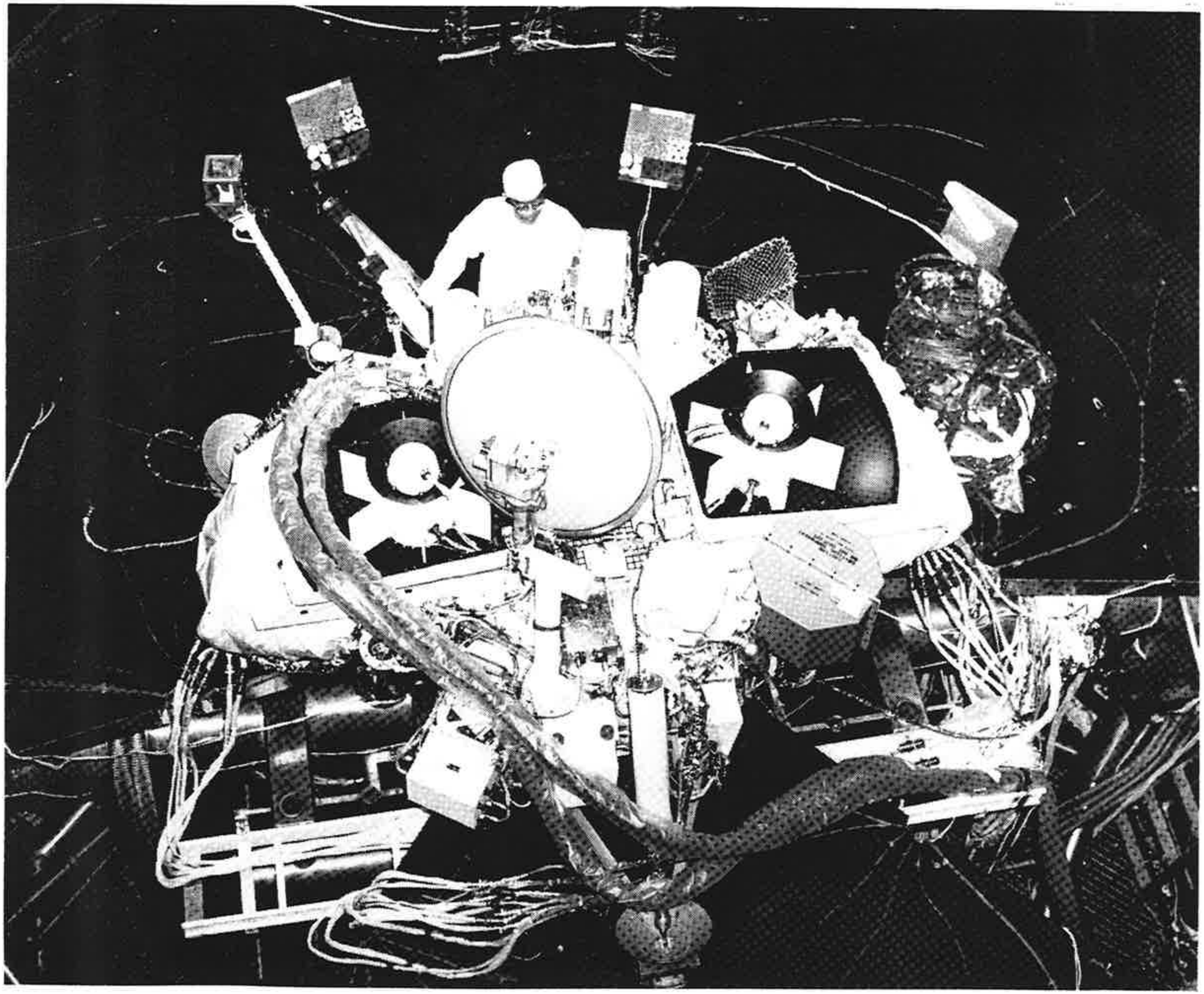


Figure 10. SNAP-19 RTG Integration Test on Viking Lander

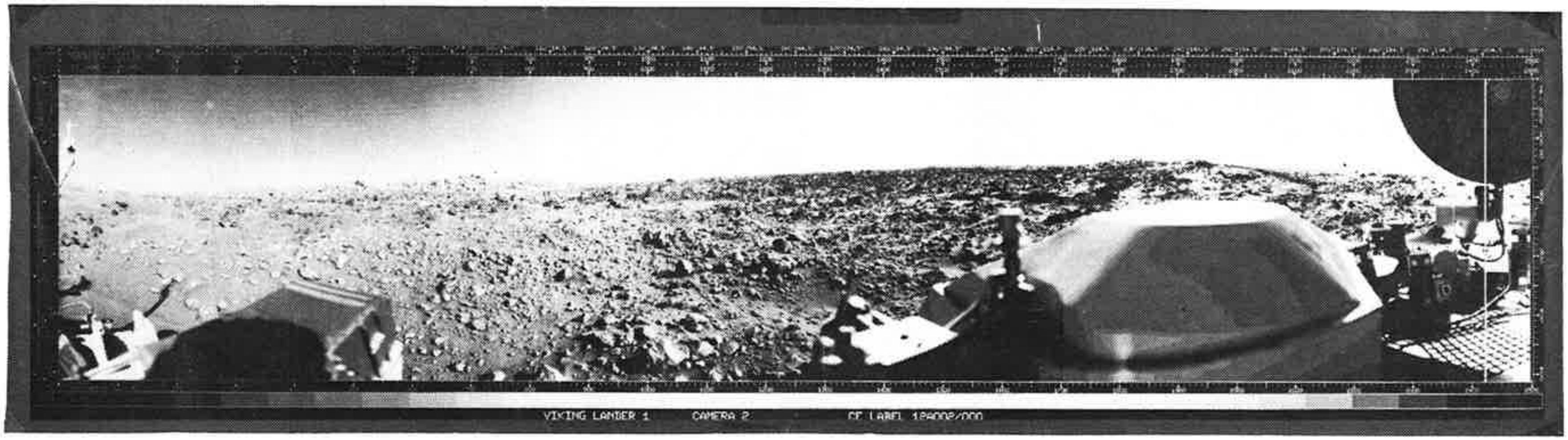


Figure 11. Photograph of Martian Surface and Horizon from Viking Lander
(Courtesy Martin Marietta Co.)

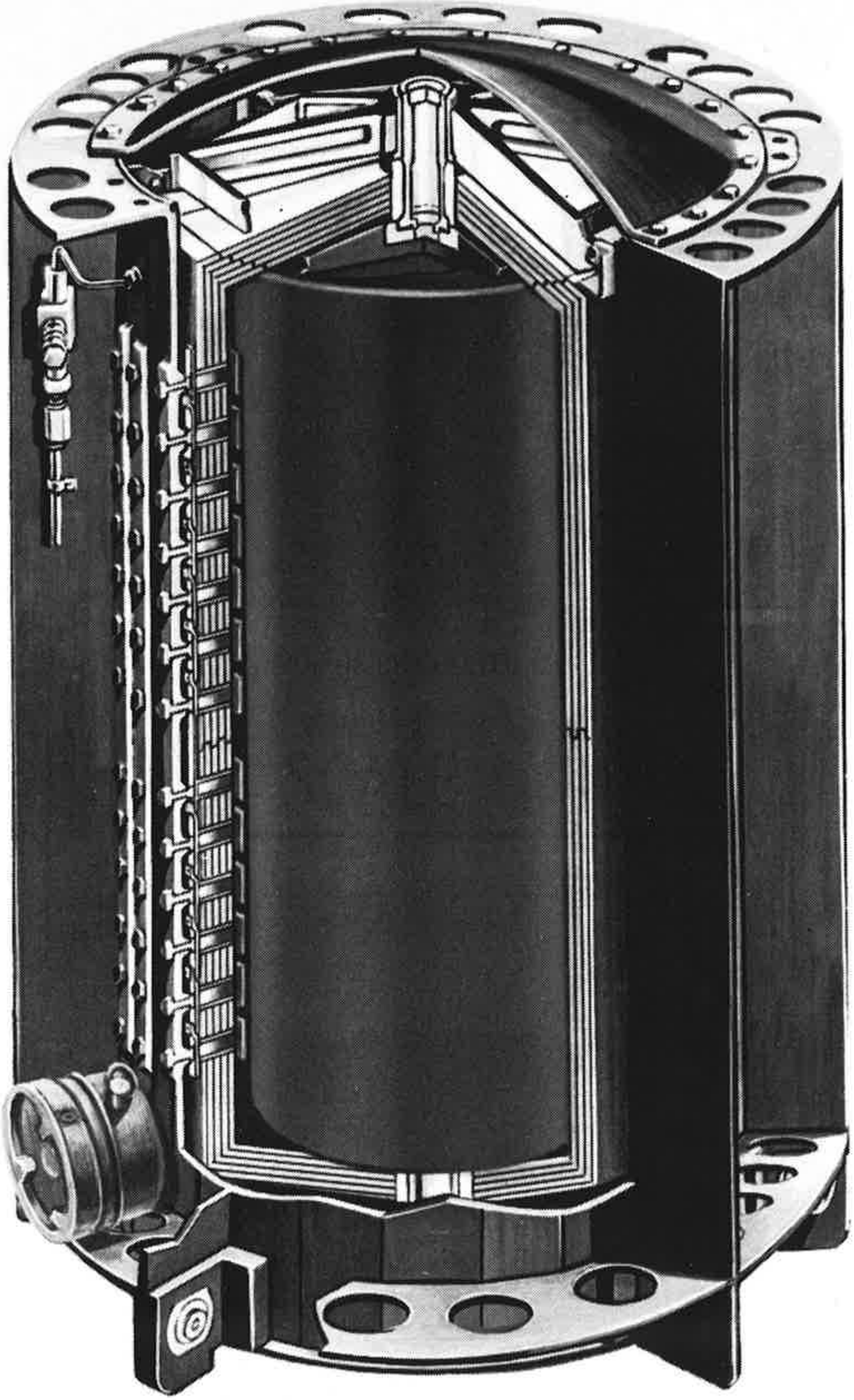


Figure 12. MHW-RTG

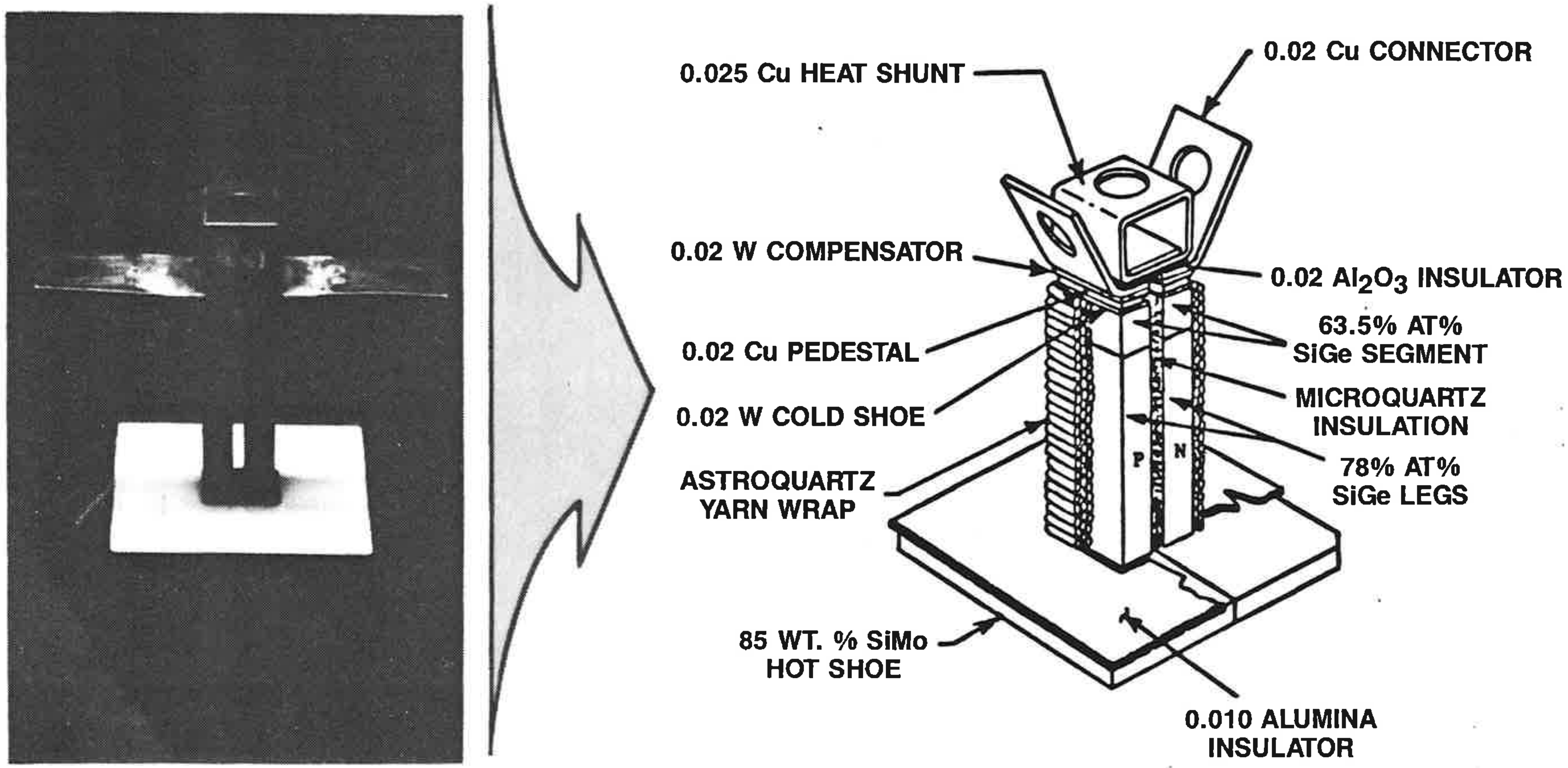


Figure 13. MHW-RTG Unicouple

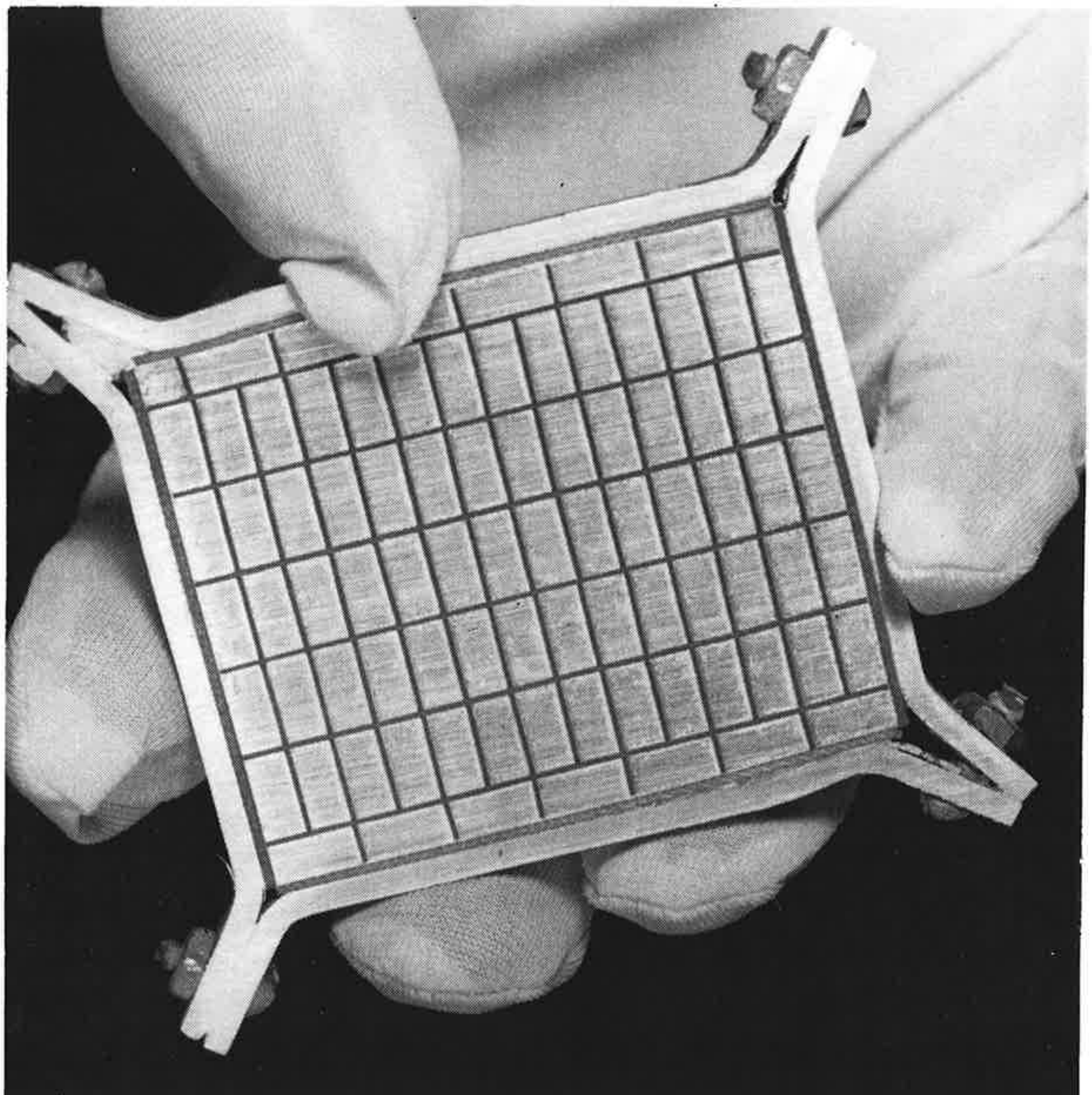
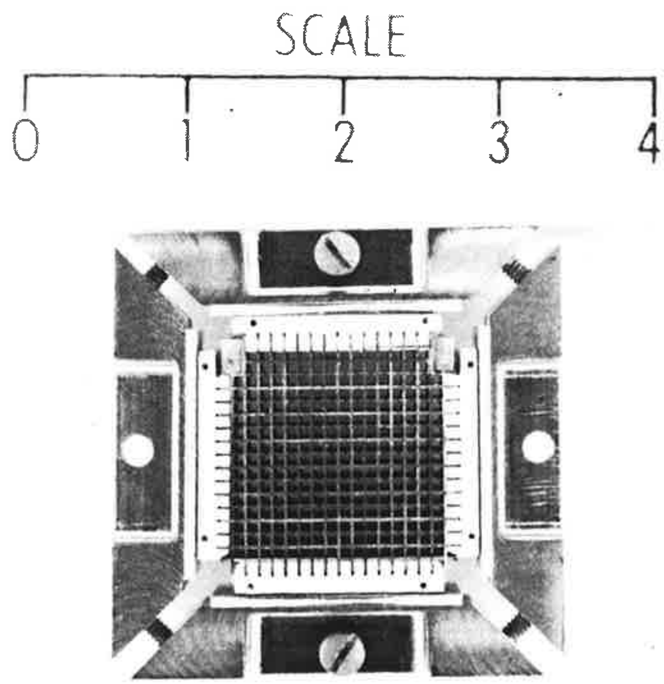
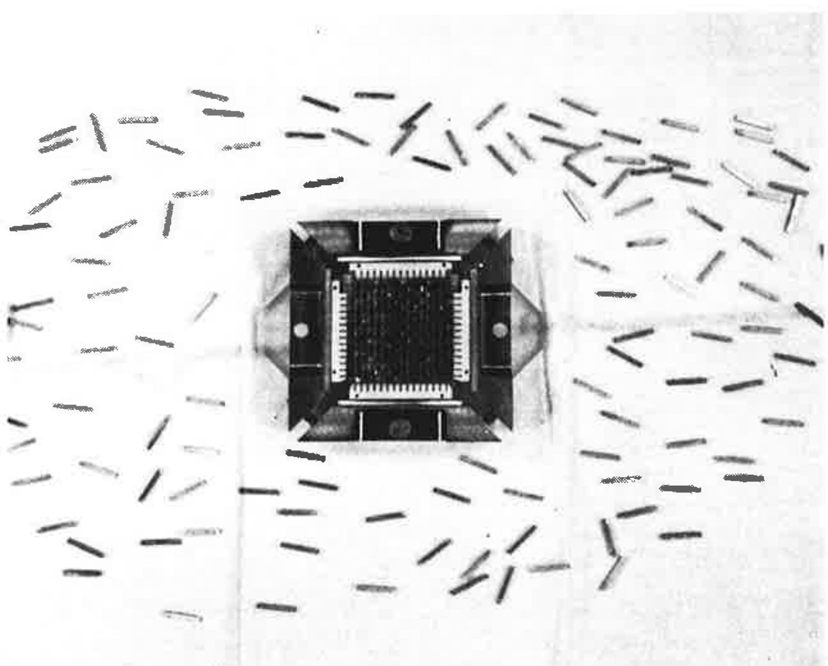


Figure 14. Close Packed Array (CPA) Thermoelectric Module

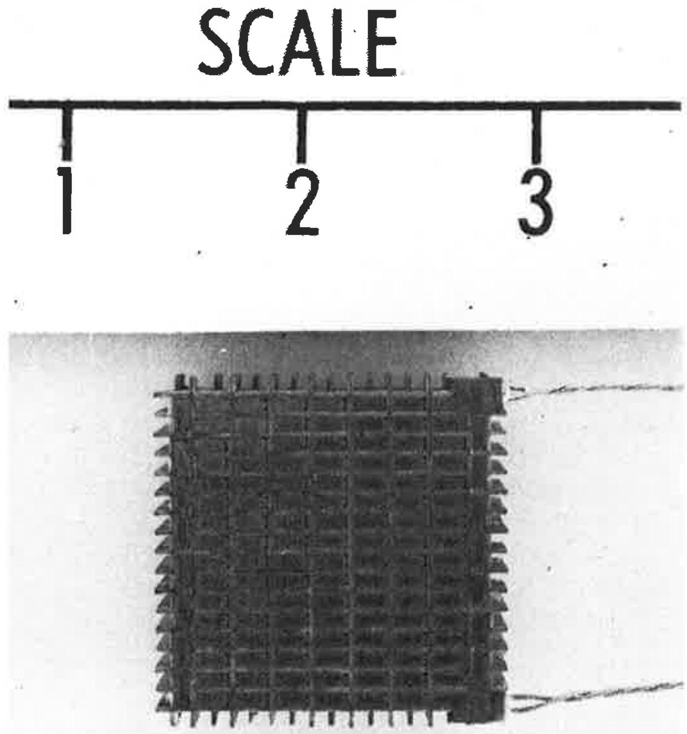


EGG CRATE IN ASSEMBLY HOLDING FIXTURE

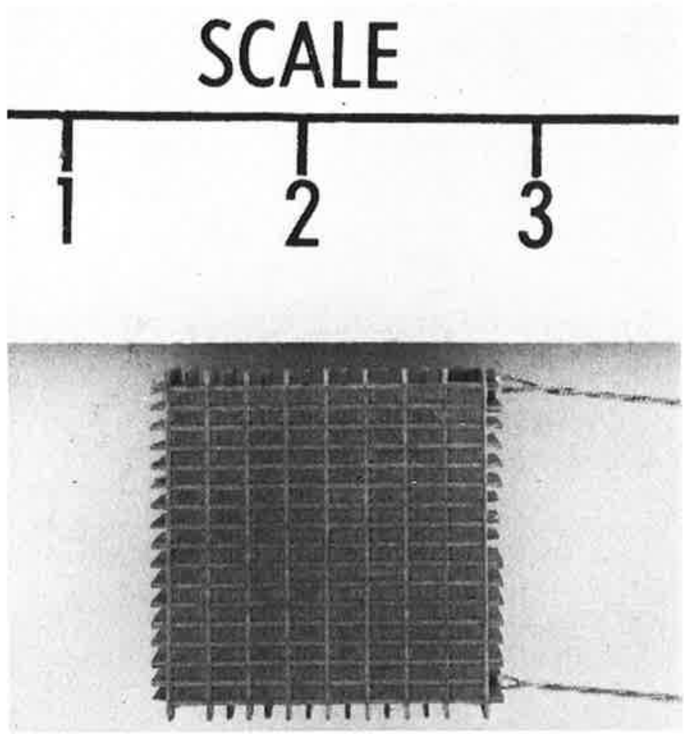


PARTIALLY "STUFFED" MODULE

Figure 15. CPA Development Thermoelectric Module Tooling



COLD SIDE OF COMPLETED MODULE



HOT SIDE OF COMPLETED MODULE

Figure 16. CPA Development Thermoelectric Module

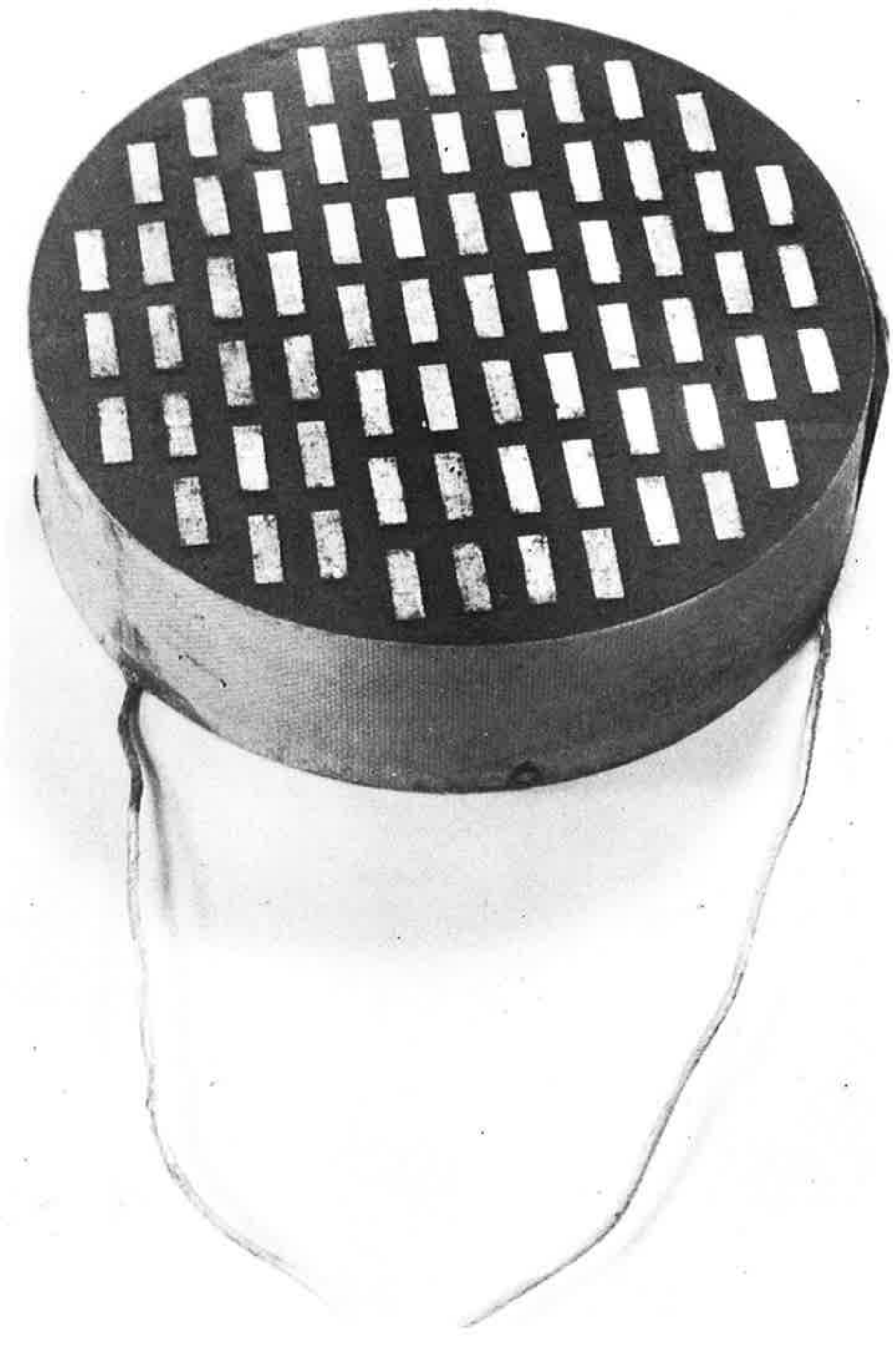


Figure 17. Completed Thermoelectric Module Hot Side View

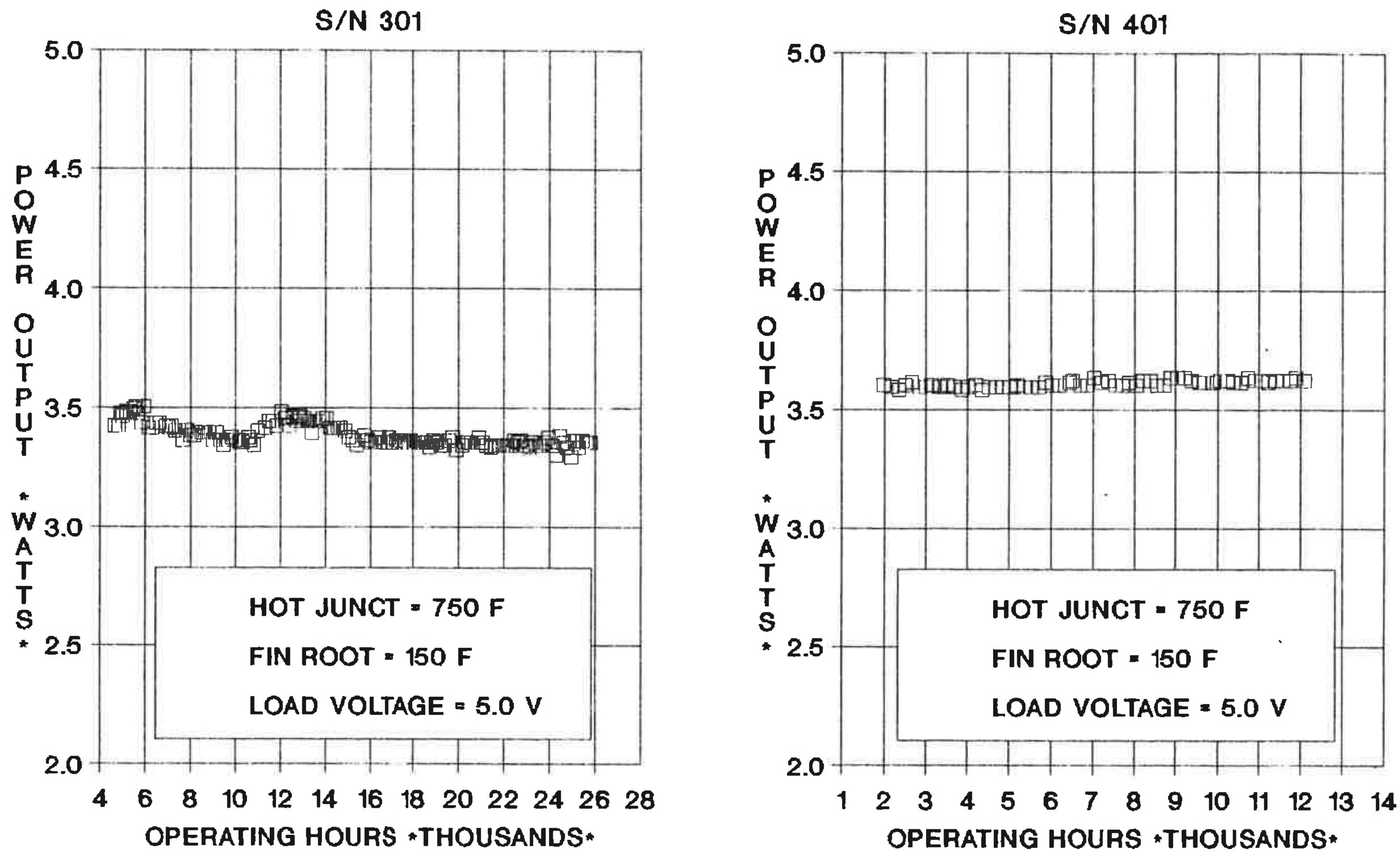


Figure 18. Thermoelectric Generator Life Test Data