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SNAP 19 PIONEER F & G

FINAL REPORT

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I. INTRODUCTION

The generator developed for the Pioneer mission evolved from the SNAP 19 RTG's launched aboard the NIMBUS III spacecraft. In order to satisfy the power requirements and environment of earth-escape trajectory, significant modifications were made to the thermoelectric converter, heat source, and structural configuration. Specifically, a TAGS-2N thermoelectric couple was designed to provide higher efficiency and improved long term power performance, and the electrical circuitry was modified to yield very low magnetic field from current flow in the RTG. A new heat source was employed to satisfy operational requirements and its integration with the generator required alteration to the method of providing support to the fuel capsule.

II. MISSION AND SPACECRAFT INTERFACES

The objectives of the Pioneer mission are to explore interplanetary space beyond the orbit of Mars and to achieve a close proximity flyby of Jupiter. To this end, the Pioneer 10 and Pioneer 11 spacecrafts employing AEC-supplied nuclear thermoelectric power sources were launched on March 2, 1972 and April 5, 1973, respectively. The instrumentation on board each spacecraft includes radiation meters, meteoroid detectors, magnetometers, charged particle detection and an imaging photopolarimeter. Of significant interest is the meteoroid density in the asteroid belt.

As of this date, June 1973, both spacecrafts are operating normally with Pioneer 10 already having traversed the asteroid belt and only about 90 million miles from Jupiter encounter which will occur in early December 1973. If the information received from Pioneer 10 is deemed sufficient, the trajectory of Pioneer 11 may be altered to allow a different encounter with Jupiter and the potential for Saturn flyby in October 1979. On its present course, Pioneer 11 will achieve Jupiter flyby in December 1974.

The Pioneer spacecraft employs four SNAP 19/2N-TAGS generators as the sole power source mounted in tandem pairs on extendable booms 120° apart. For this first all nuclear power application in outer space, each RTG is required to produce 30 watts at high probability (0.995) at Jovian encounter which is specified to occur up to 36 months after delivery to NASA. This performance is to be achieved in accord with the constraints of 38 to 42.5 watts at delivery and a maximum weight of 30.5 pounds. The flight time through the asteroid belt and up to encounter with Jupiter is between 20 and 30 months. Thus, the 36 month specification includes six months operation (most with RTG output shorted) prior to launch and the maximum travel time.

The design features of the RTG for satisfying specific mission and spacecraft requirements are categorized herein as external envelope, mechanical attachment and electrical interfaces. The external envelope is concerned with overall generator dimensions and weight; the mechanical attachment deals with the provisions for mounting to the spacecraft and supplying damper cable attachment; and the electrical interface is concerned with details of the output connector receptacle, temperature sensors and current-caused magnetic field characteristics of the RTG. The specific mission requirements for power and reliability are treated in Section IV.

A. EXTERNAL ENVELOPE

1. Fin Span Dimensions

The RTG mechanical interface drawing shown in Fig. II-1 depicts the external envelope characteristics for accommodation within the spacecraft structure. Of particular significance is the 20 inch fin tip-to-tip dimension with the triangular cutouts in each fin to enable mating with the spacecraft-RTG mounting frame (delta-frame). Although only two fins of each inboard generator require such alteration, all fins of every generator are configured the same to provide symmetry within each RTG and interchangeability among the five generators fabricated each for the Pioneer F and G missions.

2. Height of RTG

The overall height (or length) of each RTG was established early in the Pioneer program as 11.15 inches maximum. Although this parameter was not of crucial importance to the RTG (or spacecraft) design it was necessary to select a limit to enable progression of the spacecraft design concurrent with the RTG design development.

3. Weight

A total weight limit of 30.5 pounds maximum evolved from design modifications which added about one pound to the original generator configuration of nearly 29 pounds. The changes concerned an increase in fin size from a 15.7-inch span to 20.0-inch span and the addition of zirconium getters in each end of the RTG. Each feature added about one-half pound so that the final delivered generator weights were nearly 30 pounds, well within the specified limit.

B. MECHANICAL ATTACHMENT

1. Mounting Provisions

An interface specification established early in the SNAP 19 Pioneer program was the mounting bolt hole configuration of the RTG. The six 0.281-inch bolt holes equally spaced on a 7.656-inch diameter were established for the early bolted end cover design which was very close to the SNAP 19/NIMBUS end-cover arrangement on a 7.531-inch diameter. When the welded end cover was selected for the Pioneer application, the interface was considered frozen,

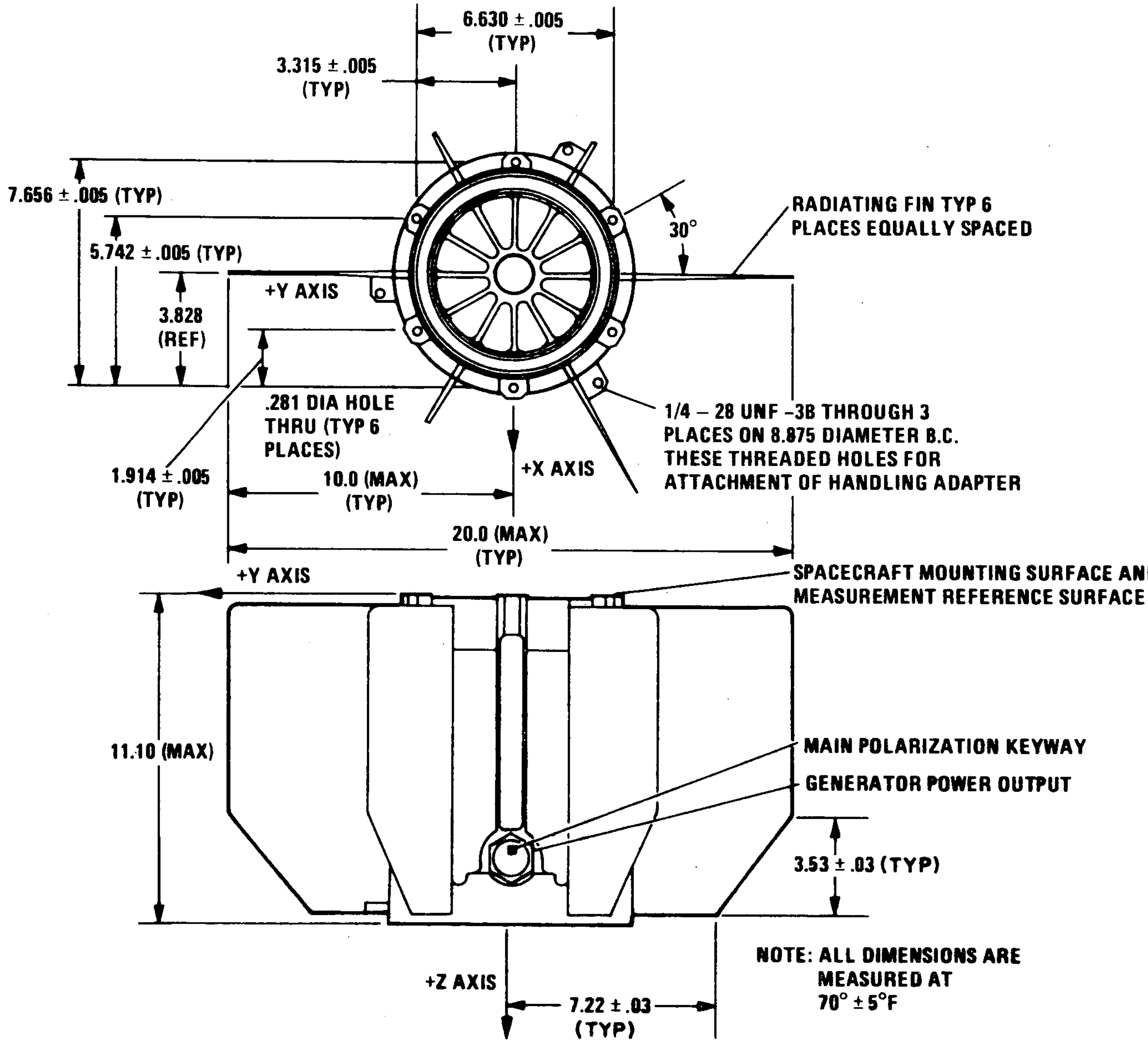


FIG. II-1. SNAP 19 RTG UNIT FOR PIONEER F/G, SERIAL NO. 42 AND UP and modification of the RTG housing and lower end cover was implemented to maintain the 7.656-inch diameter mounting circle.

2. Damper Cable Attachment

Provision for using a damper cable to relieve loads during deployment of the generators was made by allowing attachment of the cable to the upper end cover. Four threaded inserts pressed into a center boss of the cover form the attachment points. Thus, one generator of each pair transmits the damping load to the delta frame to which the pair of RTG's are mounted.

C. ELECTRICAL INTERFACE

1. Connector Receptacle

In order to accommodate efficient electrical connection of the generator output to the spacecraft power cable, a multi-pin receptacle was required. Calculations by NASA/Ames and TRW together with consideration of hardware availability suggested the selection of a 26 pin receptacle. As indicated in Fig. II-2, four of the pins are used for the temperature sensors and twenty pins supply the power circuit. The two unused pins separate the negative and positive power pins.

2. Temperature Sensors

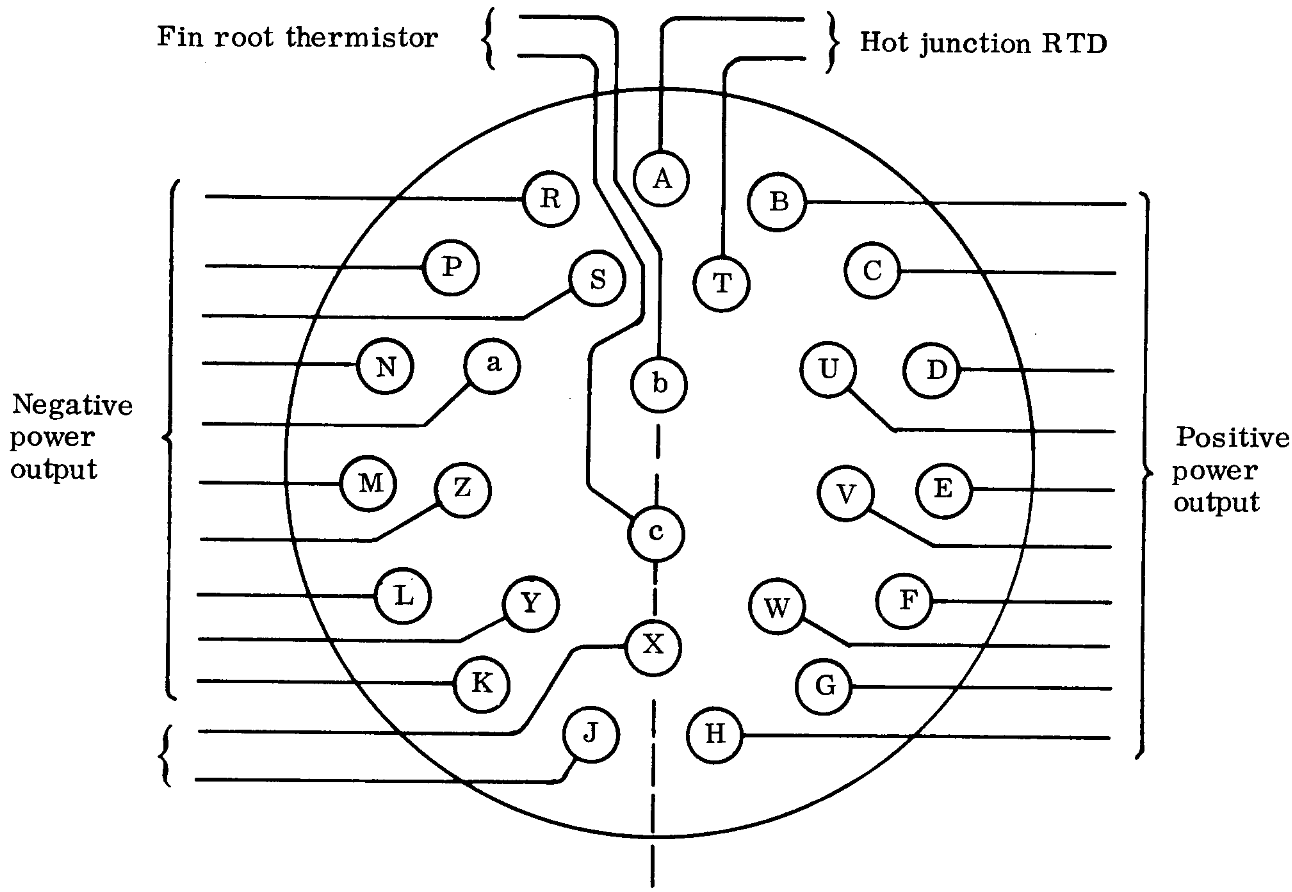
Spacecraft signal conditioning capability necessitated the use of resistance type temperature sensors instead of the thermocouple devices used for ground test generators. To this end, an RTD attached to the hot shoe of one thermoelectric couple provides a hot junction temperature sample, and a thermistor attached to the inside of the housing near the electrical receptacle is used to indicate the housing temperature (from which fin root temperature may be estimated).

This minimal instrumentation was adopted to simplify signal conditioning requirements for the spacecraft and to reduce the probability of generator malfunction from instrumentation failure. Further, the successful performance of RTD's and thermistors in the SNAP 19/NIMBUS generators lent confidence to the use of only a single pair of sensors for each RTG.

3. Magnetic Field Compensation

In order to reduce the magnetic field caused by current flow in the RTG, the internal circuitry of the generator was altered to provide a negating effect. A detailed calculational

FIG. II-2. RTG ELECTRICAL CONNECTOR PIN ASSIGNMENTS



View looking at mating face of pin connector pin 'A' toward mounting end of generator.

technique (MAGFIELD program) was developed to show that the field was mostly dipolar and that a relatively simple current loop at one end of the generator could provide a compensating dipole. The resulting quadrupole field was sufficiently low to enable satisfaction of the NASA specification of less than 2.5 gamma and 0.3 gamma in the axial and radial directions, respectively, at two meters from the RTG.

TABLE II-1

MAGNETIC FIELD CAUSED BY CURRENT FLOW IN THE SNAP 19 PIONEER RTG

	Field Strength in Gamma at Two Meters from the RTG Center	
	With Compensating Loop	Without Compensating Loop
Axial	0.44	3.0
Radial	0.22	1.5

Table II-1 shows that at two meters from the RTG center the magnetic field is reduced by about a factor of ten. Further, since the compensated field is quadrupolar ($1/r^4$), the field at ten meters is a factor of 50 lower than the original dipolar field which varies as $1/r^3$. Measurements of the current caused magnetic field by NASA/Ames verified that the compensated circuitry achieved this substantial reduction and thereby the RTG was well within the spacecraft requirements.

III. GENERATOR DESCRIPTION

The generators designed and fabricated for the SNAP 19/Pioneer program were designated Radioisotopic Thermoelectric Generators (RTG's) and Electrically heated Thermoelectric Generators (ETG's). The RTG's served as flight prototype test generators (S/N 37 through S/N 43) and flight generators (S/N 44 through S/N 53). ETG's were fabricated as engineering development models (S/N 32, 33, 33R, 34, and 35) and engineering prototypes (S/N 35R and 36). Features of these generators are described in detail in the following sections. A generator part number flow chart is included in Appendix A.

A. RTG's S/N 37 THROUGH S/N 53

Seventeen RTG's were fabricated on the SNAP 19/Pioneer program, seven of which were designated flight prototype generators, two were flight backup generators, and eight are flight generators aboard the Pioneer 10 and Pioneer 11 spacecrafts. A typical SNAP 19/Pioneer RTG is illustrated in Fig. III-1. The generator consists of three major subsystems, the heat source, the thermopile (converter), and the housing and radiator, plus miscellaneous hardware.

The significant differences among the RTG's are itemized in Table III-1. The first class contains the four prototype RTG's S/N 37 through S/N 40 which were fabricated and tested prior to the discovery of heat source and converter performance aberrations in S/N 37. Subsequent to the diagnostic disassembly of S/N 37 and S/N 39 and the incorporation of remedial design features, three additional prototype RTG's (S/N 41 through S/N 43) were fabricated to incorporate the revisions noted in Table III-1. Predicated upon the demonstrated success of the three prototype units, ten RTG's (S/N 44 through S/N 53) were fabricated, tested and delivered for flight use.

1. Heat Source

The heat source of all Pioneer RTG's (see Fig. III-2) consists of a radioisotope fuel, plutonium-238, which is contained in a multi-layered capsule. The capsule is supported by zirconia rings contained in a graphite heat shield.

Fuel Capsule

The overall capsule assembly is cylindrical in shape with hemispherical ends. It is

FIG. III-1. SNAP 19 PIONEER RTG

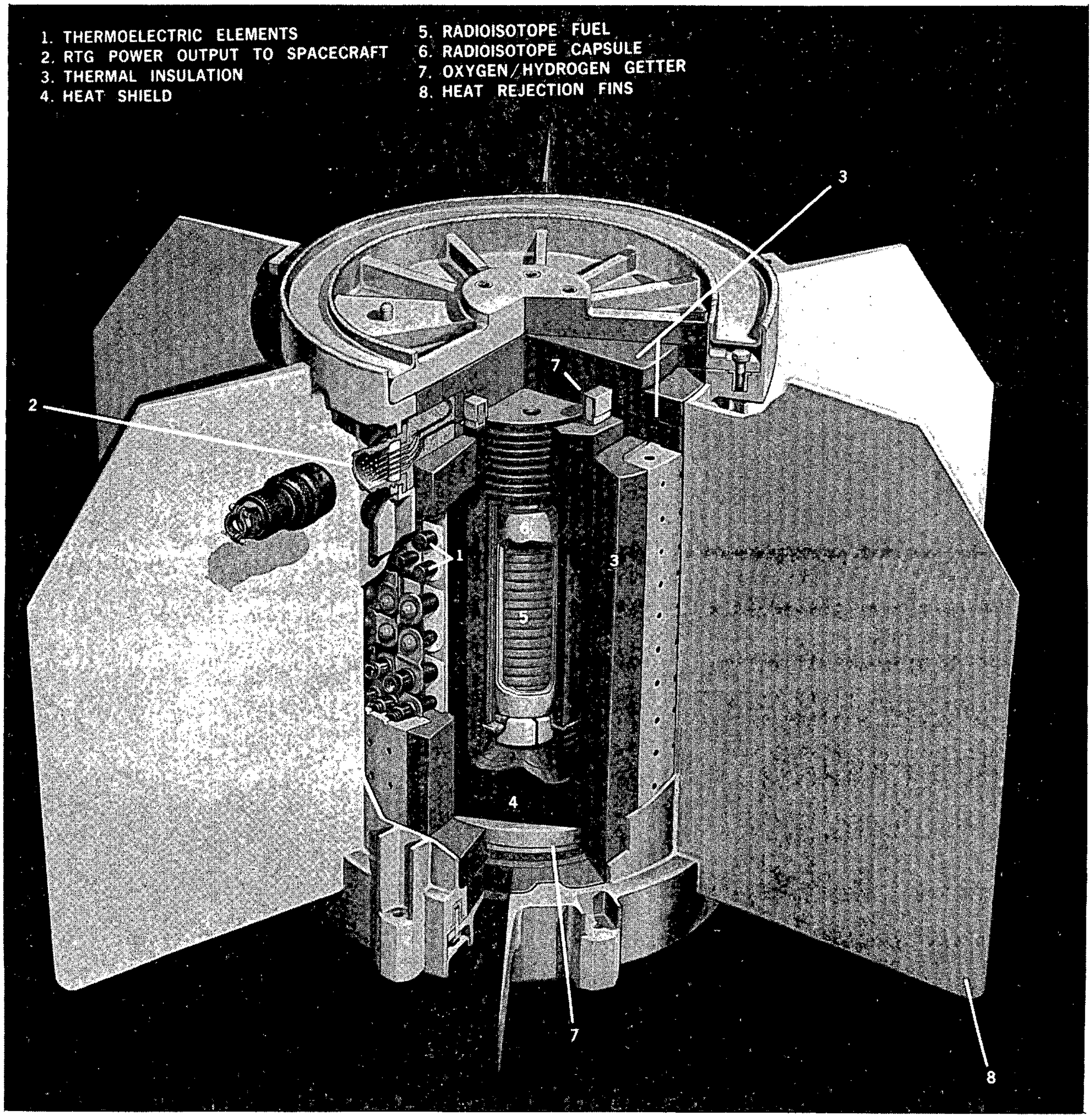
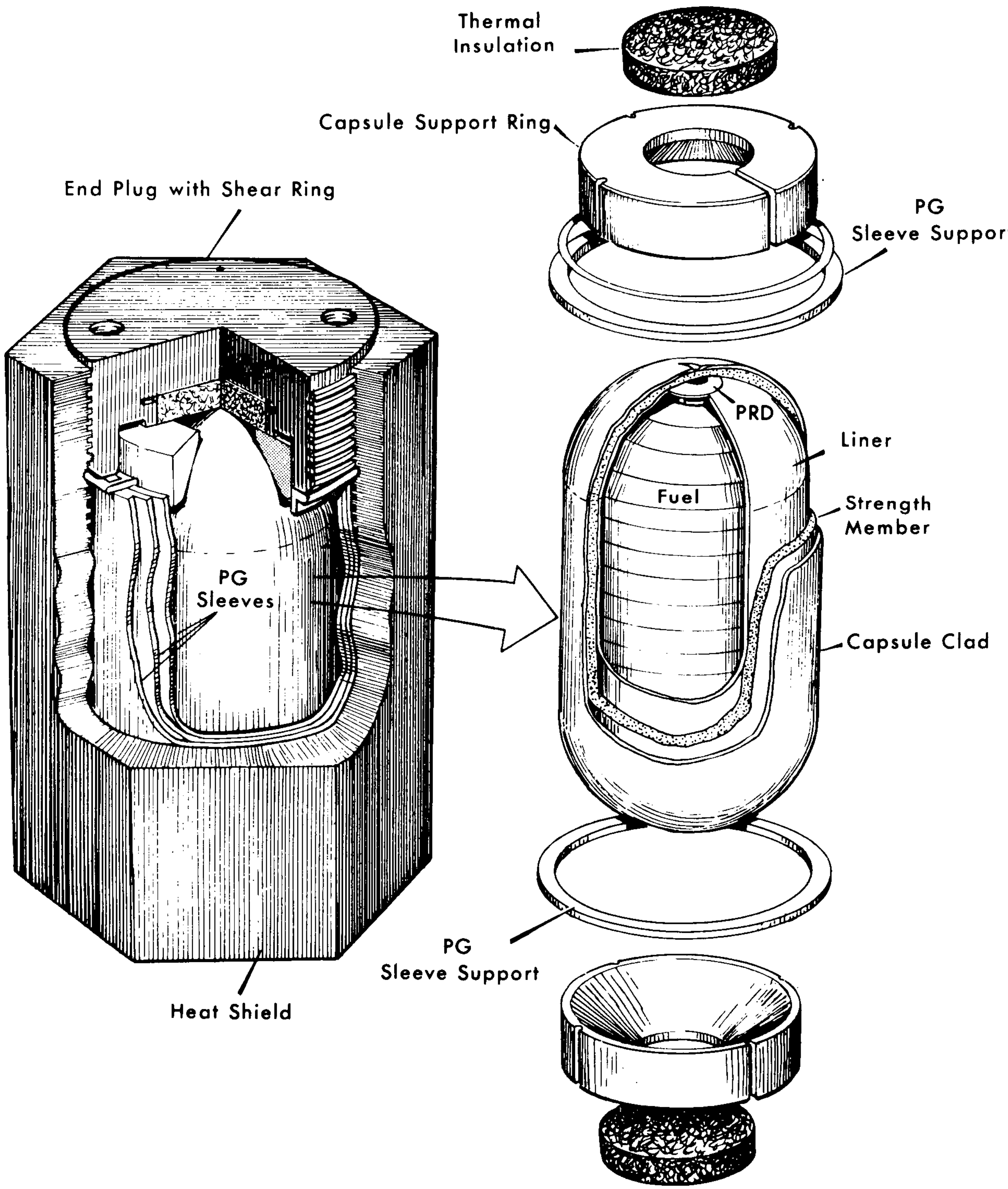


TABLE III-1

RTG CHARACTERISTICS SUMMARY

RTG Characteristic	RTG S/N 37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Heat Source																	
T-111 Capsule	x	x	x	x													
TZM Capsule						x											
T-111 Capsule with Inner Liner					x		x	x	x	x	x	x	x	x	x	x	x
Container																	
Tube in One Cover	x	x	x	x													
Tube in Both Covers					x	x	x	x	x	x	x	x	x	x	x	x	x
Fins 4.62 in. (root-tip)	x	x	x	x	x												
Fins 6.74 in. (root-tip)						x	x	x	x	x	x	x	x	x	x	x	x
Receptacle 321 CRES	x	x	x	x	x	x	x	x	x	x	x	x					
Receptacle 20CB3													x	x	x	x	x
O-Ring 77545	x	x	x	x	x	x	x	x	x	x	x	x					
O-Ring 74775													x	x	x	x	x
Miscellaneous																	
Getter					x	x	x	x	x	x	x	x	x	x	x	x	x
Outgassing (evacuate and backfill)	x	x	x	x													
Outgassing (purge)					x	x	x	x	x	x	x	x	x	x	x	x	x
Gas Fill (75% helium/25% argon)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Assembly in Air	x	x	x	x	x	x	x	x									
Assembly in Glove Box									x	x	x	x	x	x	x	x	x

FIG. III-2. SNAP 19 PIONEER HEAT SOURCE



2.468 inches in diameter and 4.797 inches long. The fuel is in the form of pucks, about two inches in diameter and 0.2 inch thick, of plutonium moly cermet (PMC). Eighteen pucks comprise a complete fuel stack for the capsule.

For RTG's S/N 37 through S/N 40, the fuel was encapsulated in a three layer capsule. The inner layer, the liner, is fabricated of 20 mil thick tantalum-10% tungsten. It is a welded assembly of a hemispherical head with a pressure release device (PRD) attached to a cylindrical section with an integral hemispherical head. The PRD allows the escape of helium which is created by the decaying fuel. The center layer, the strength member, is 90 mil thick tantalum alloy, T-111. The configuration is similar to the liner assembly and the joint is made by TIG welding. The strength member provides structural integrity of the capsule in the event of a mission abort with subsequent impact on the Earth's surface. The outer layer, the clad, is 18 mil thick platinum-20% rhodium. The configuration is similar to the liner and strength member assemblies and closure is made by a TIG weld. Both the clad and the strength member contain a small hole to allow the escape of helium. The clad provides limited protection against the effects of oxidation of the strength member and liner in the event of deposition following mission abort.

An inner liner was designed for RTG's S/N 41 through S/N 53 to provide an oxygen barrier between the fuel and tantalum base liner. The inner liner is fabricated of 5 mil thick molybdenum-46% rhenium and consists of two hemispherical heads tack welded to a cylindrical center section. An 0.6 inch diameter clearance hole at one end provides clearance for the liner PRD. An inverted "bishop's cap" covers the annular fuel puck at this end, thereby supplying an interface between the PRD and the fuel stack.

The fuel capsule design of RTG S/N 42 differed from other generators in that a TZM strength member without the outer platinum-rhodium shell was specified, while the fuel, inner liner and liner assemblies were unchanged. The strength member was fabricated of 101 mil thick TZM, formed into two taper threaded cylindrical sections with integral hemispherical heads. The complete fuel capsule assembly is 2.626 inches in diameter by 4.770 inches long, and it weighs about 0.6 pound less than the T-111 capsule.

Heat Shield and Capsule Support

The heat shield is a graphite container of hexagonal cross section with a central cylindrical cavity for the fuel capsule. Closure is effected by threaded graphite plugs at each end. The main body and end plugs are machined from blocks of fine grained, isotropic Poco graphite. Outer dimensions of the heat shield are 3.5 inches across the flats and 6.5 inches long. The central cavity is about three inches in diameter extending the full length of the heat shield with internal stub acme threads two inches long at each end. The external envelope of each end plug is a cylinder three inches in diameter by 1.33 inches long with external stub acme threads for engagement with the main body. Inside each end plug is a cavity for the fuel capsule end and an integrally machined shear ledge. The shear ledge provides a rigid bearing surface during normal operation, but allows thermal expansion of the fuel capsule without breakage of the heat shield during abnormal accident environments.

The fuel capsule is supported at each end by a ceramic load ring which bears against the end plug shear ledge. The load rings are made of zirconium oxide, 3% magnesium oxide stabilized, with an outside diameter of 2.44 inches, an inside diameter of 1.16 inches, a thickness of 0.64 inch, and an internal 45° beveled surface bearing on the capsule. The rings are cut radially in one place to allow thermal stress relief.

Between the fuel capsule lateral surface and the heat shield body are three concentric pyrolytic graphite sleeves. The assembly which provides thermal resistance during accidental reentry from space has an outside diameter of 2.934 inches, an inside diameter of 2.534 inches, and is 3.8 inches high. It is fitted inside the center (unthreaded) section of the heat shield with a one to two mil diametral clearance. To prevent damage through movement of the sleeve assembly during exposure of the RTG to dynamic environments, a 10 mil thick Poco graphite washer and a 20 mil thick (uncompressed) graphite felt washer are inserted between the sleeve assembly and the heat shield end plug.

A small disc shaped tantalum felt pad is inserted into the center of the shear ring in each heat shield end plug. The pad is 1.5 inches in diameter by 0.12 inch thick and provides a resistance to heat transfer from the heat shield end plug to the fuel capsule during potential accident conditions.

2. Thermoelectric Converter

The thermoelectric converter consists of six modules each of which bears against one of the flat faces of the heat shield. The modules are complete conversion assemblies of thermoelectric couples (fifteen), insulation, interconnecting electrical conductors (straps) and cold end hardware which provides loading force between the housing and heat shield. Assembly of the module occurs by insertion of the couples into pre-formed holes in the Min-K insulation, packing the space between thermoelectric material and Min-K with fibrous microquartz, and completion of the electrical path by soldering of copper straps to form a two couple parallel arrangement. The cold end hardware subassembly contains the springs and pistons which provide a compressive force to each thermoelectric element. Figure III-3 shows one module configuration with particular emphasis on the cold end hardware. One additional component (not shown) used in the placement of module against the heat shield is a 0.010 inch thick sheet of phlogopite mica to provide high temperature electrical insulation.

The construction of the 90 TAGS 85/2N thermoelectric couples in the SNAP 19 generator is illustrated in Fig. III-4. Each couple is 1.03 inches long, 0.5 inch wide, and 0.578 inch high. It consists of a 50 mil thick nickel 200 hot shoe, two braze wafers, two high purity iron cups, a tin telluride segment and a bonding wafer (P-side only), a TAGS-85 P-leg and a 2N N-leg, a bonding wafer (P-side only), two high purity iron cold shoes, two lead indium (85-15) solder discs and two oxygen free copper connector straps. The TAGS-85 part of the P-leg is 0.270 inch diameter and 0.395 inch long and the tin telluride segment (hot side) is 0.270 inch diameter and 0.100 inch long. The 3M-TEGS-2N N-leg is 0.377 inch diameter and 0.495 inch long.

A view of the electrical interconnection of the modules is illustrated in Fig. III-5. Shown is one of the two crimp-connection points of each module with the stranded oxygen free copper wires joined with an oval splice. A similar connection exists at the other end of the modules. In addition to these crimp connections, another connection is made by soldering a short length of copper wire to terminals located inside the envelope of Min-K insulation. This somewhat complicated interconnection scheme was necessitated by the odd number of couples in each module (15) and the desired arrangement of paralleled pairs of couples. Figure III-6 shows the magnetic compensation loop joined by routing the output wires in a channel at the end of the RTG before attachment to the connector receptacle pins.

FIG. III-3. THERMOELECTRIC MODULE AND COLD-END HARDWARE

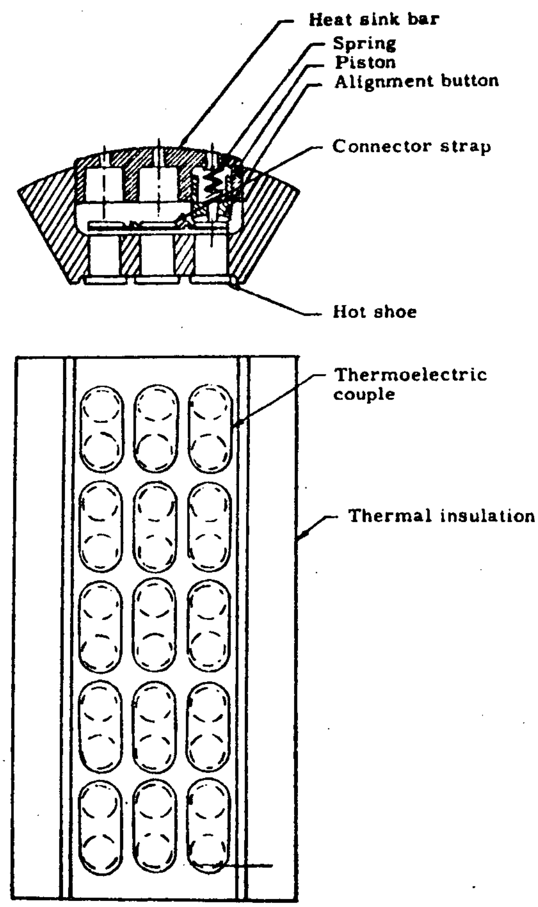


FIG. III-4. SNAP 19 TAGS-85/2N COUPLE CONFIGURATION

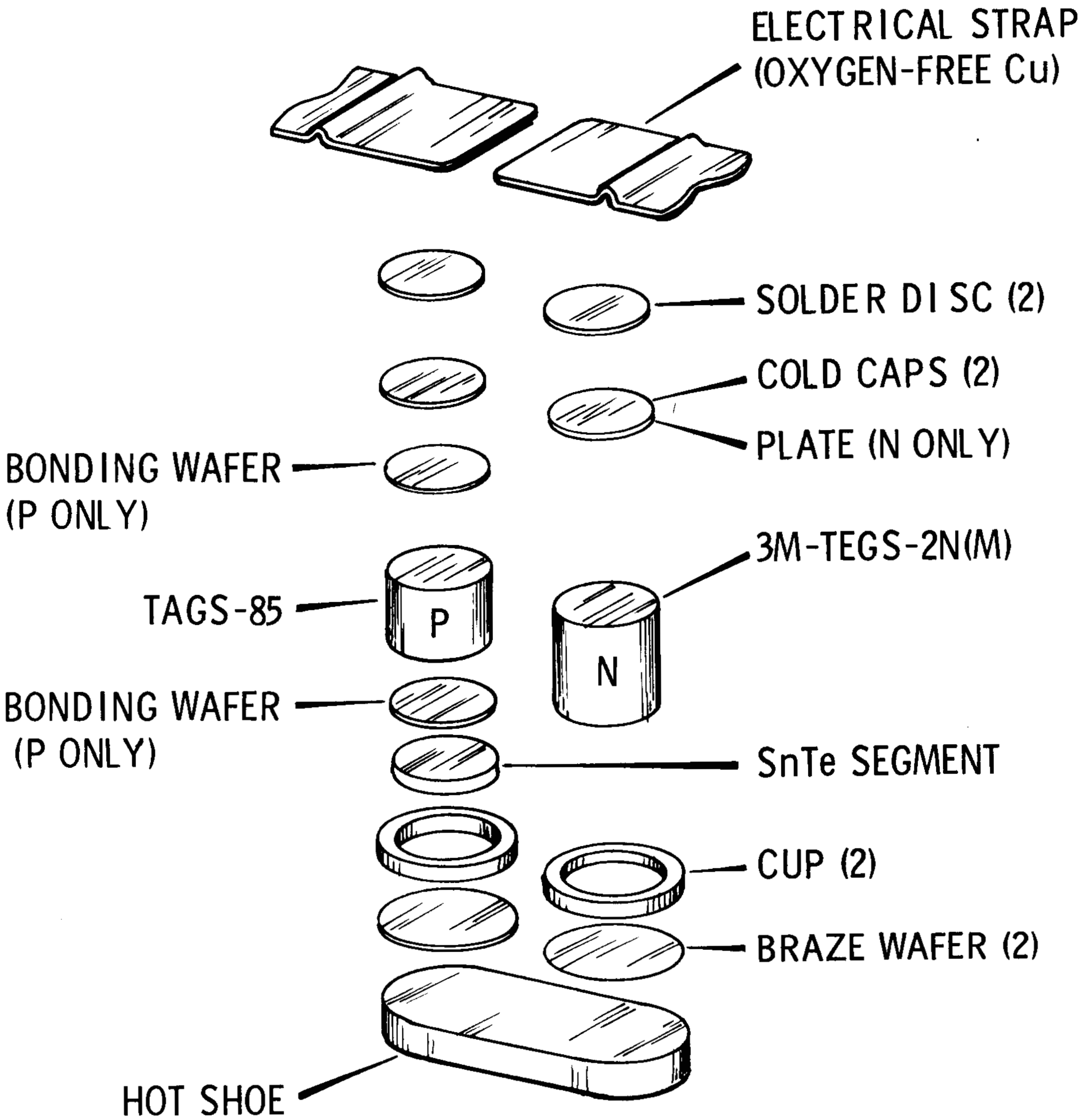


FIG. III-5. MODULE INTERCONNECTIONS

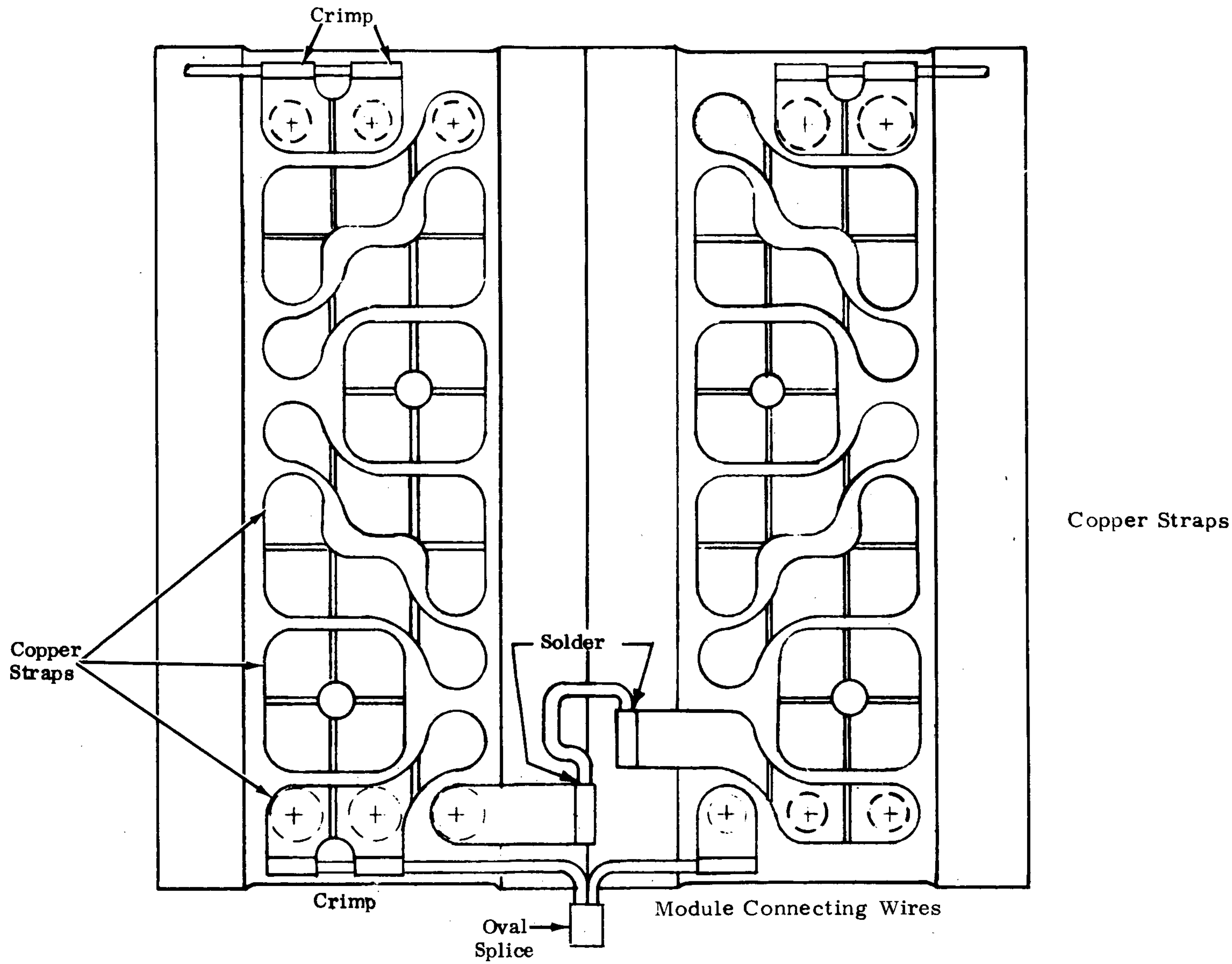
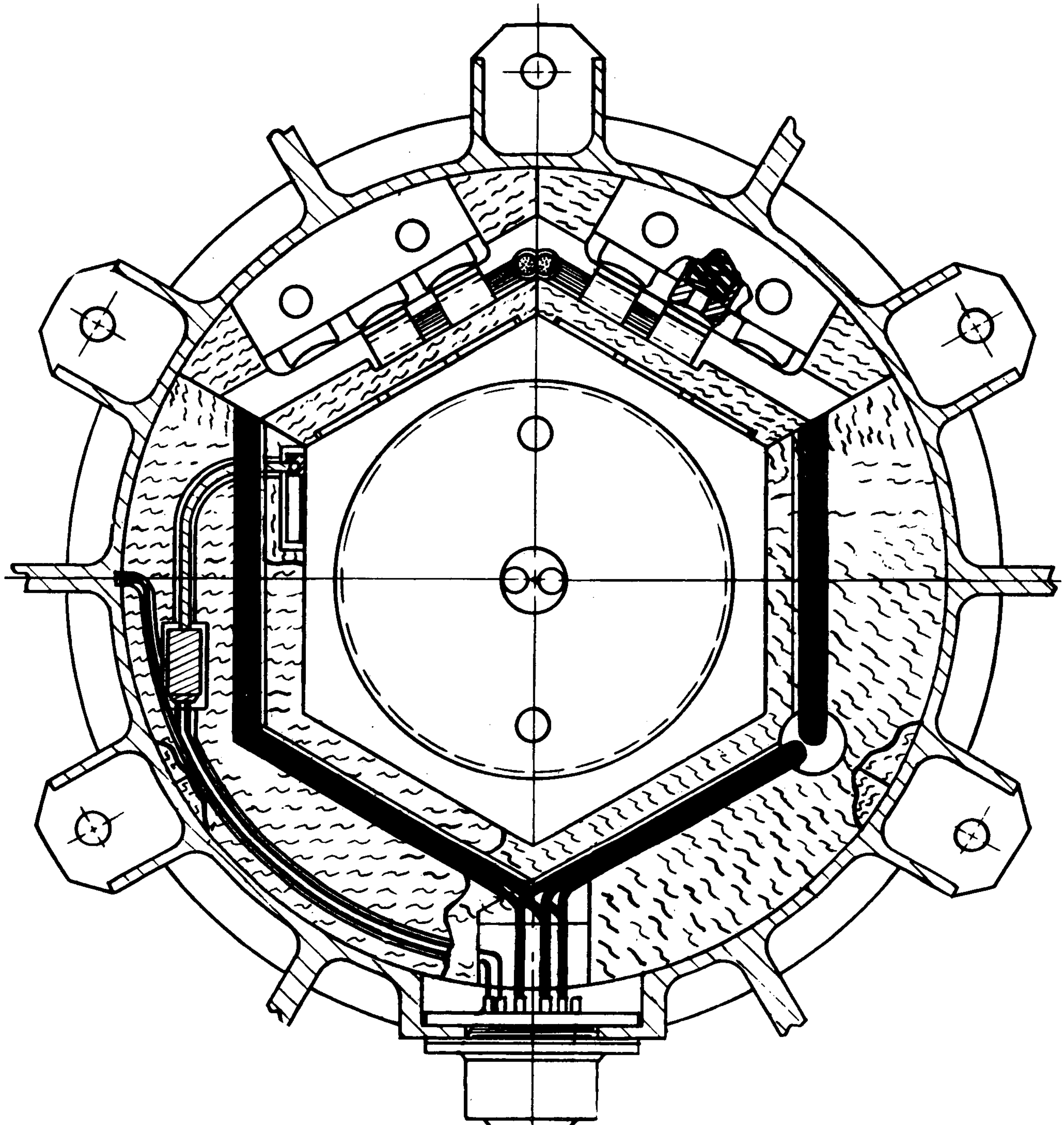


FIG. III-6. INTERMODULE CONNECTION AND MAGNETIC COMPENSATION LOOP



The cold end hardware is illustrated in Figs. III-3 and III-5. It consists of 180 alignment buttons, 180 pistons, 180 helical compression springs, and six heat sink bars. Upon generator assembly, the springs are compressed, preloading individual thermoelectric elements with about six lbs of load. This serves several purposes: (1) Allows small gaps, between unbonded surfaces, e.g., strap to button, button to piston. (2) Maintains low electrical and thermal resistance at bonded joints, e.g., element to cold shoe, cold shoe to connector strap. (3) Provides damping of vibration induced motion of the heat shield.

The alignment button is 0.44 inch diameter and 0.08 inch high, has one flat surface which mates with the connector strap and one spherical surface which is lapped with its matched piston. The button is fabricated of 6061-T6 aluminum alloy. A hardcoating process, resulting in an oxide coating, assures electrical insulation of the thermoelectric circuit at the cold side.

The piston is 0.435 inch diameter and 0.431 inch long, has a spherical surface which mates with the button and a cylindrical recess at the other end to retain the spring. Like the button, the piston is fabricated of 6061-T6 aluminum alloy and is hardcoated.

The spring, purchased as a controlled commercial item, is 0.3 inch diameter, 0.56 inch long, made from 0.038 inch diameter wire. It is fabricated of type 302 stainless steel, has a spring rate of 32.3 lb/in., an operating length of 0.361 inch, and a load at operating length of 6.5 lbs.

The heat sink bar is fabricated of 6063-T5 aluminum alloy bar and is 6.12 inches long, 1.87 inches wide, and 0.63 inch deep. It has a flat surface in which thirty 0.436 inch diameter by 0.419 inch deep holes are bored for the pistons. The piston holes are concentric with 0.125 inch diameter through holes for screw clearance. The opposite surface is a 3.125 inch radius cylindrical surface which mates with the inside of the housing. The heat sink bar is hardcoated to provide additional insulated surfaces between the pistons and generator housing.

3. Housing Assembly

The generator core is contained in a hermetically sealed housing, to which are welded six heat rejection fins. End covers are bolted and welded, and an electrical receptacle provides the interface for power output and instrumentation.

The housing is a thin walled cylinder 6.25 inches inside diameter with a 0.093 inch minimum wall thickness. Overall length is 11.06 inches. The housing is machined from an

HM-31A-F condition magnesium alloy forging. Six radial fin stubs equally spaced around the outside of the housing, 0.20 inch thick at the root, and 1.532 inches long are integrally machined in the housing. Two radial stiffening ribs are machined between each pair of fin stubs. The ribs are 0.08 inch thick and 0.746 inch long. At each end of the generator a seat flange and a weld flange are provided. The seat flange provides a seat for the cover and contains twelve blind ring locked inserts to which the cover is bolted. The weld flange provides a lip to which the cover is fusion welded to provide a hermetic seal.

Three equally spaced handling lugs are integrally machined between the fin stubs and the weld flange at one end of the housing. A boss which receives the electrical receptacle is machined at the mounting lug end of the housing between the stiffening ribs and the seat flange. Six mounting lugs are integrally machined on the ends of the stiffening ribs on the outside of the weld flange at the end of the housing opposite the three handling lugs. Holes, 0.28 inch diameter, are provided on a 7.656 inch diameter bolt circle in the mounting lugs.

Six fins, one welded to each of the fin stubs, provide the bulk of the heat rejection capacity. The fins are fabricated of HM21A-T8 magnesium alloy plate. The fins are 0.17 inch thick at the root and have a constant taper to a 0.03 inch thick tip. They are 10.44 inches long and 3.09 inches wide for RTG's S/N 37 through S/N 41. The fins for RTG's S/N 42 through S/N 53 are 5.21 inches wide. This equates to a root to tip fin width of 4.62 inches for RTG's S/N 37 through S/N 41 and a root to tip fin width of 6.74 inches for RTG's S/N 42 through S/N 53. As noted in Section II, the flight configuration fins of S/N 42 to S/N 53 have a 2.77 inch by 3.53 inch triangular cut out of the outboard corner.

End closure of the housing assembly is accomplished with bolted and welded upper and lower end covers. Both end covers are fabricated of HM21A-T8 magnesium alloy plate. The upper end cover is 7.935 inches diameter. It consists of a flat disc 0.16 inch thick, a center boss 2.16 inches diamater and 0.715 inch high atop the disc, a ring concentric with the center boss 6.25 inches outside diameter, 0.08 inch thick, and 0.79 inch high atop the disc, twelve equally spaced radial ribs 0.18 inch thick and 0.4 inch high extending from the center boss to the outer edge of the cover atop the disc, and a thickened flange extending from the ring to the outer edge of cover. The flange is 0.375 inch thick and has twelve equally spaced clearance holes centered between the ribs. The holes are 0.28 inch diameter. Four blind, ring locked inserts are provided in the center boss. A 0.246 inch inside diameter tube with a 0.065 inch wall is welded to the flat disc to provide a port for generator outgassing gas fill operations.

The lower cover is a disc 6.875 inches diameter and is nearly identical with the upper cover in configuration. Differences include a hollow center boss 1.78 inches outside and 1.38 inches inside diameter and a concentric ring which is 5.25 inches outside diameter.

RTG's S/N 37 through S/N 40 have tubes in one cover only, while RTG's S/N 41 through S/N 53 have tubes in both covers. The change to two tubes facilitated purge type outgassing of the generator.

The covers are bolted to the housing with 1/4 inch diameter titanium alloy bolts. These bolts are locked in place with HM21A-T8 magnesium alloy bolt retainers (see Fig. III-7). A channel shaped seal ring is placed in the void above the bolts, is welded to the housing on the outer lip, and is welded to the cover on the inner lip. The upper cover seal ring is fabricated of HM31A-F condition magnesium alloy and the lower cover seal ring is fabricated of HM21A-T8 magnesium alloy.

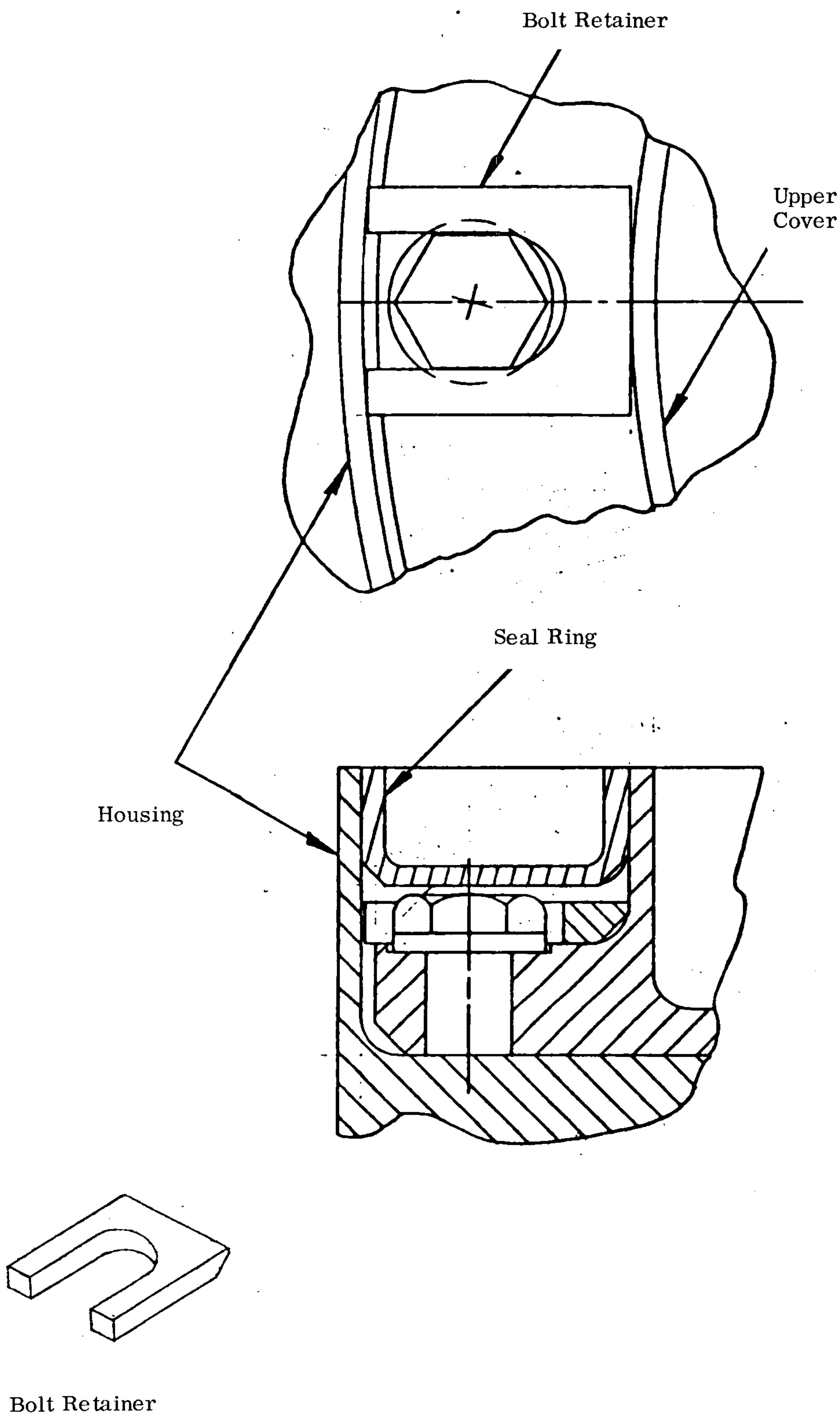
The electrical receptacle is a Deutsch hermetic 26 pin type. The seal between the receptacle and the housing is by a Viton rubber O-ring. Viton material 77-545 was used on RTG's S/N 37 through S/N 48 and improved Viton material 747-75 was used on RTG's S/N 49 through S/N 53. The change in materials was instituted to provide a better seal between the shell and the glass insert. The receptacle is retained on the housing with a standard receptacle nut which is wired to prevent loosening during vibration.

The housing, fins, and end covers, with the exception of interface surfaces such as mounting lugs, are sprayed with an emissive coating which augments the heat rejection capability The coating, which is applied after the surface has been specially prepared, consists of two to three mils of zirconia in a sodium silicate binder. The coated surface possesses an emissivity of about 0.9 and a solar absorptivity on the order of 0.2.

4. Instrumentation

SNAP 19/Pioneer RTG's contain two instrumentation sensors, a resistance temperature device (RTD) and a thermistor. These devices indicate the hot junction temperature and the fin root temperature, respectively.

FIG. III-7. BOLT RETAINER CONFIGURATION



The RTD (Fig. III-8) is a precision type surface temperature probe which exhibits calibration stability at high temperature. It consists of a coil contained in a housing, a barrel, a stem which joins the coil housing and barrel, a hermetic seal, and external lead wires. The temperature sensing element of the RTD is its sensing coil, which is a strain free platinum wire wound in the shape of an extension spring. The coil housing, 304 stainless steel, serves to protect and transfer heat to the sensing element. The mounting flap is an integral part of the coil housing. The stem connects the coil housing to the barrel. The RTD signal lead wires, inside the stem, are electrically insulated with magnesium oxide. The barrel protects and hermetically seals a transition from #30 AWG platinum signal wire to #28 AWG platinum lead wire. The RTD lead wires egress through a hermetic glass seal.

The RTD is spot welded to a tab on the hot shoe of a special thermocouple. Three such attachment tabs are available (one end thermocouple of each of three modules).

The thermistor is a thermally sensitive resistor. The temperature probe consists of metal oxides, sintered with a binder, and two signal lead wires. The SNAP 19/Pioneer generator thermistor is a glass encapsulated, hermetically sealed bead unit.

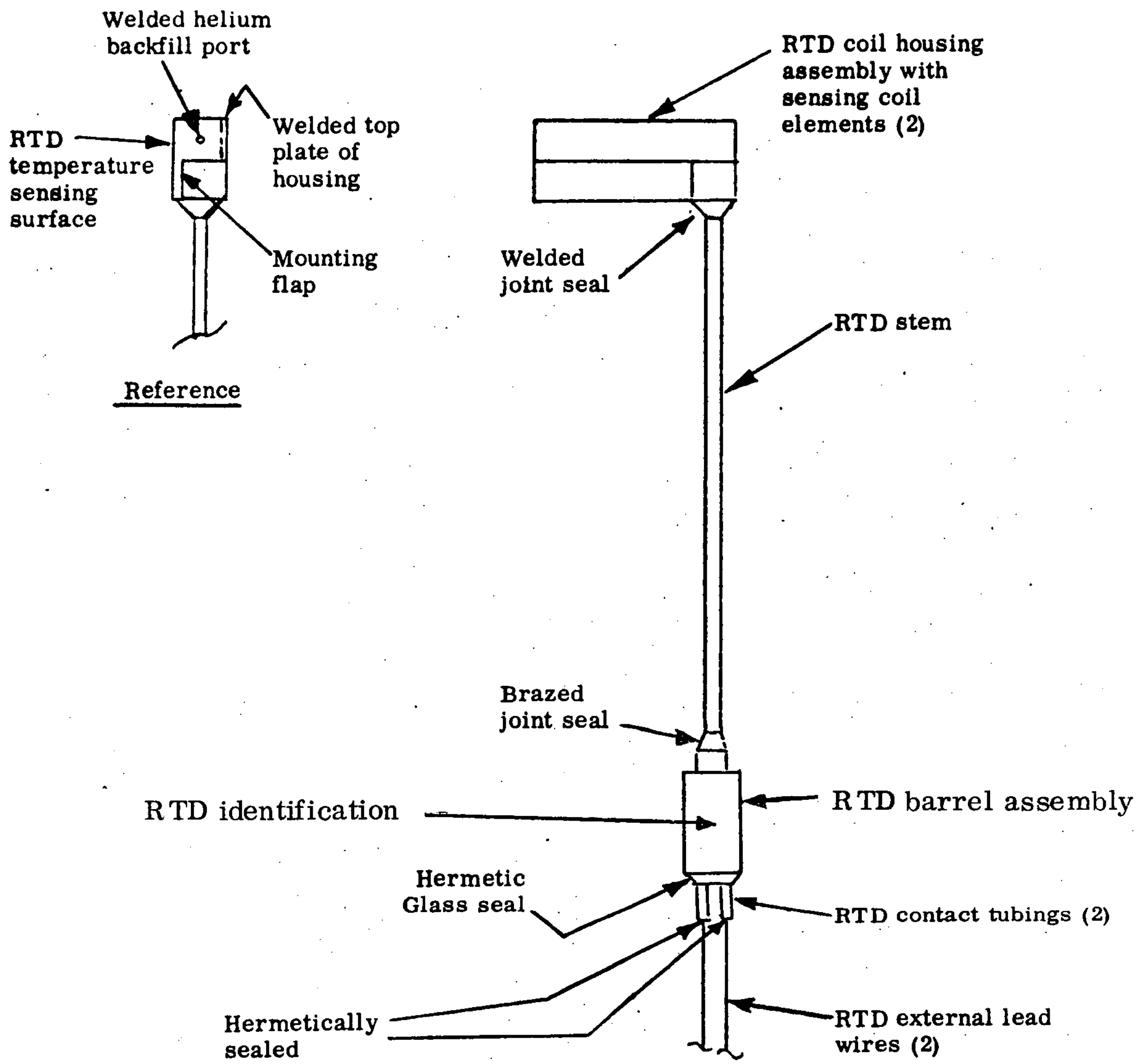
The thermistor is mounted in a slot on the inside surface of the housing about 2.5 inches from one end, and it senses fin root temperature. The thermistor is calibrated in the range 80 to 469°F.

5. Miscellaneous Components

RTD components which do not conveniently fall within one of the generator subsystems are included in this section. Components included are thermal insulation, the getter, and the generator fill gas.

All of the thermal insulation in the RTD, with the one exception of the microquartz insulation packed around the elements, is fabricated of Min-K 1301 insulation. The module insulation is a completely formed detail. End insulation discs and rings are cut from one inch and two inch thick sheets. End insulation discs are cut about 40 mils thicker than the cavity they fill. During generator assembly, when the discs are compressed, a preload in excess of the maximum expected dynamic load is applied to the heat source which restricts motion of the heat source.

FIG. III-8. NOMENCLATURE OF RTD CONFIGURATION



Due to the great affinity of Min-K 1301 for water vapor and the extensive procedure required to drive off the binder, a study was conducted early in the program to evaluate other insulations. Replacement insulations, which represented a technical improvement over Min-K 1301 in several categories, were selected. Min-K 1999 was selected as the molded module insulation and Min-K 2002 was selected as the load bearing insulation for end discs and rings. Fabrication of Min-K 1999 module insulation was unsatisfactory due to consistent breakage during handling. Because of this, the replacement program was discontinued.

The diagnostic disassembly of RTG S/N 37 suggested installation of a getter in the generator (see Section VI). A ring configuration one at each end of the heat shield was selected for RTG's S/N 41 through S/N 53.

Each getter consists of a ring of reactor grade zirconium pressed and sintered in the form of a ring to 70 to 80% density. The ring has a 3.062 inch inside diameter, a 3.5 inch outside diameter, and is 0.562 inch high. The zirconium is contained in a two piece housing fabricated of palladium. The container wall thickness is 0.012 inch.

The SNAP 19/Pioneer RTG is filled with an inert gas to inhibit sublimation of the thermoelectric materials and to permit satisfactory operating temperatures of heat source components. A gas mixture of 75% helium 25% argon was the initial fill of all RTG's. This mixture represents a compromise which offers low heat source temperatures, low ΔT across cold end hardware, and reasonable parasitic heat loss through the Min-K insulation.

6. Outgassing Tool

All RTG's are outgassed prior to the fueling operation. Outgassing removes unwanted entrapped gases from within the generator, e.g., oxygen and water vapor, so that when the final gas change is accomplished, the fill gas is nearly contaminant free. RTG's S/N 37 through S/N 40 were outgassed by the evacuation and backfill method. Subsequent to diagnostic disassembly of S/N 37, an improved method of generator outgassing was developed which consists of continuous evacuation of the RTG up to a hot junction temperature of 600°F and a continuous helium purge from 600°F to 1050°F. RTG's S/N 41 through S/N 53 were outgassed using the evacuation and purge method.

The outgassing tool consists of an electrical heater block, a graphite end plug, thermal insulation, and an end plate to which an electrical receptacle and valve assembly are mounted. The heater block is similar to that used in an ETG except that one end is flat to mate with the graphite end plug. The end plug is unthreaded to slip fit into the heat shield body. A Min-K 1301 thermal insulation disc provides a thermal interface between the heater block and the end cover. The end cover is a flat aluminum alloy plate which mounts in the upper end of the generator. A large diameter Viton O-ring provides a seal between the outgassing cover and the housing flange. The cover is bolted to the generator and an electrical receptacle mounted in the center of the cover provides a hermetically sealed feedthrough for the heater lead wires. A tube and valve a assembly mounted in the cover provide a means for evacuating and purging the generator.

B. ETG'S

Five Electrically heated Thermoelectric Generators (ETG's) were fabricated as engineering models (S/N 32 through S/N 35) and prototype (S/N 36). Two of these units were rebuilt (S/N 33R, S/N 35R) because of test induced failures. The designs evolved from the first ETG, S/N 32, through the prototype units, S/N 35R and S/N 36 which were the first to employ welded end cover closures.

1. Engineering Models

Four engineering model ETG's, S/N 32 through S/N 35, were fabricated. One of these, S/N 33, was rebuilt as an engineering model, S/N 33R, and one, S/N 35, was rebuilt as a prototype ETG, S/N 35R. The engineering models are similar to the RTG's described in Section III. A.

ETG S/N 32 was the first engineering model ETG designed and built on the SNAP 19/ Pioneer program. The electrical heater block for this generator is fabricated of nickel 200 and simulates the fuel capsule in configuration and weight. Heat source restraint consists of tantalum felt compliant pads which are preloaded by torquing of the graphite heat shield end plugs. The housing assembly differs from the RTG in that the covers are bolted to the housing and sealed with two concentric O-rings. There are no stiffening ribs on the housing between fins. A zirconium sponge getter contained in a nickel 200 shell located at one end of the heat only. Thermal insulation is the same as RTG's. A pressure transducer is mounted external to and atop the cover at the getter end of the generator. A magnetic compensation loop is not provided. Instrumentation includes 14 thermocouples and two voltage taps. Thermocouple locations include eight hot junction, three cold junction, and three fin root. The fill gas is 100% argon.

S/N 33 is nearly identical to S/N 32. The one exception is that a heat shield retaining sleeve was added as an interface between the heat shield and the thermopile. It was thought that separation of the thermopile and heat source would assure survival of the thermoelectric couples by isolating the couples from the longitudinal motion of the heat source during vibration. However, lateral motion of the heat source associated with failure of the getter housing induced electrical shorting in the thermopile. S/N 33 was rebuilt following diagnostic disassembly as S/N 33R without a restraining sleeve.

S/N 34 is the same as S/N 32 except the O-ring grooves are in the covers instead of the housing.

ETG S/N 35 was similar to S/N 34. The electrical heater block was enlarged to more closely weight simulate the Pioneer fuel capsule. In order to provide a tighter hermetic seal, a bolted and welded end closure was developed to eliminate the large O-rings. The end closure design evolved for S/N 35 is identical to that of all RTG's. The pressure transducer was eliminated and in order to reduce the magnetic flux caused by current flow, a compensation loop was provided at one end of the generator. Generator instrumentation was revised to include nine thermocouples, one RTD (hot junction) and one thermistor (fin root). Thermocouple locations include one heater block, one hot junction, five fin root, and two cover.

Anomalies during the vibration testing of S/N 35 resulted in a diagnostic disassembly which highlighted inadequate heat source support. A series of eight tests, known as the cold vibration test series (INSD-2873-64, SNAP 19/Pioneer Cold Vibration Test Report, dated March 1972), were conducted which yielded evolution of the heat source support system described previously.

Upon completion of this series of tests, S/N 35 was reassembled as S/N 35R without the getter and with a fill gas of 75% argon and 25% helium. S/N 35R is the first prototype RTG.

IV. RTG OPERATING CHARACTERISTICS

This section describes the significant electrical and thermal characteristics of the Pioneer RTG's during flight operation and other applicable environments such as pre-launch and accident conditions. To this end, a detailed description of the method for deriving power-reliability performance predictions is given together with comparison to observed behavior of the Pioneer 10 and Pioneer 11 generators. It should be noted that the thermal and electrical parameters for these analyses are based largely upon macroscopic data. For example, thermoelectric degradation characteristics are derived from complete generator test data, and temperatures and gas generation effects are based upon measurements of generators at test conditions with corrections for the seal operating environments. It will be seen that this approach yields predictions which are in very good agreement with observed performance.

On the other hand, thermal analyses of the heat source are based upon basic thermal transport properties such as conductivity and emittance with little direct experimental verification of temperature determined for the particular configurations under investigation. Thus, the accuracy of these results is quite dependent upon manufacturing and materials properties variations. It was necessary to consider the resulting uncertainty of heat source component temperatures in the nuclear safety assessment of the Pioneer mission.

A. POWER-RELIABILITY

1. Power Performance

a. Calculational model

A calculated power assessment was performed for the generators designated for the Pioneer 10 and Pioneer 11 missions. The analysis considered:

i. Measured power and leak rate and the indicated flight fin root temperature data for each RTG.

ii. An evaluation of generator power degradation data from ground-based electrically heated test generators.

iii. The effect of uncertainty in hot junction temperature/thermoelectric degradation rate.

A method labeled Parameter Variation Analysis Technique was used for this study as coded in Teledyne Isotopes computer program PDF 10. A description of the method and the input parameters follows:

Parameter Variation Analysis Technique

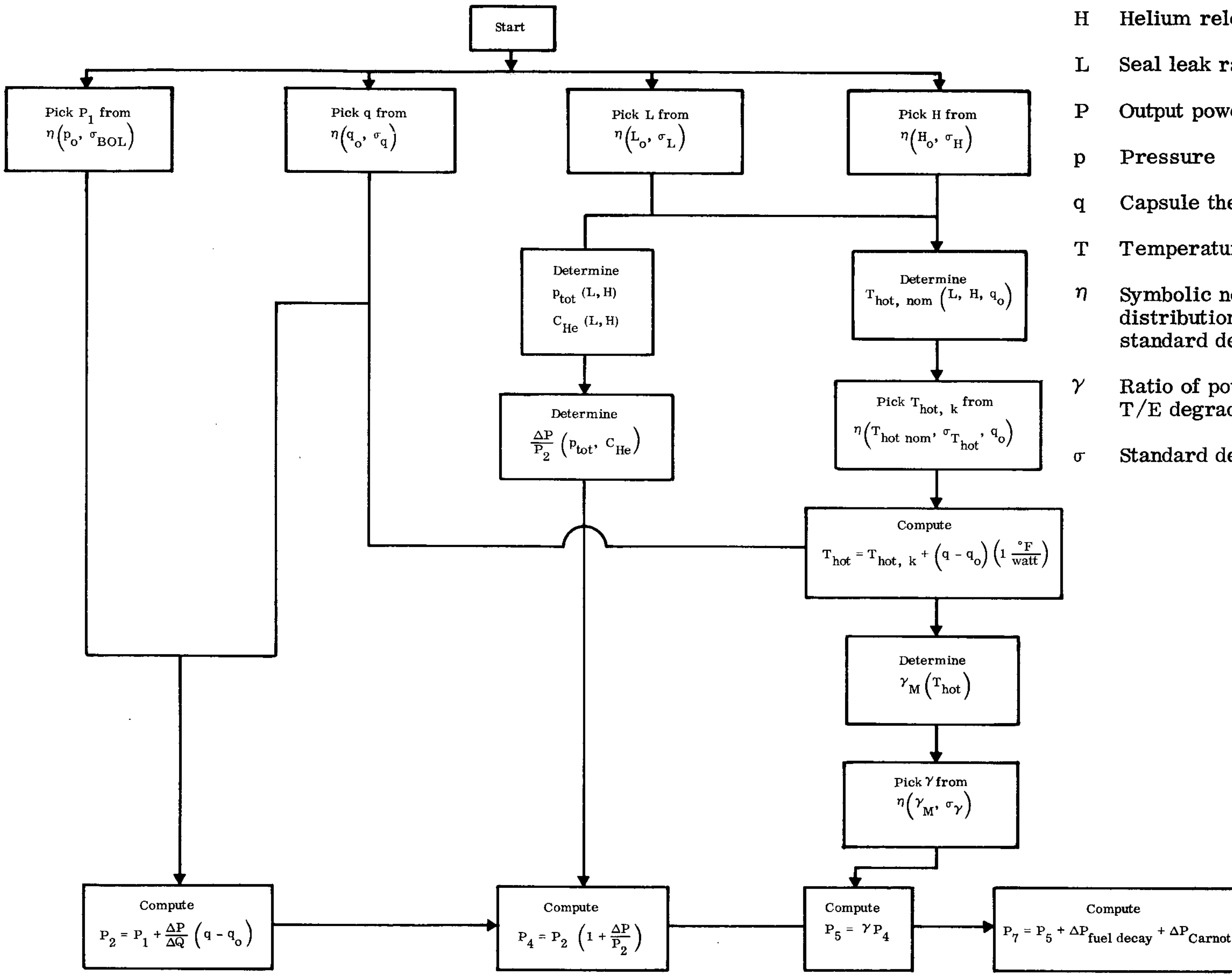
The parameter variation analysis technique was developed to provide a means of combining values of non-linearly related variables (e.g., fuel capsule helium release rate, generator housing leak rate, initial power, thermoelectric degradation rate, fuel inventory) selected at random from appropriate distributions. The form of solution is a probability density function (pdf) which gives the probability that the answer is x, as contrasted with more conventional analyses which predict a unique or nominal value of x.

A Monte Carlo technique is used in a computer program (PDF 10) to randomly sample input distributions and to produce the pdf of RTG output power. For a given set of input parameters, corresponding to a specific time during the mission, the non-linear input functions are evaluated and the corresponding generator power is computed. For each such "Monte Carlo history," the resultant power is tallied. Repetition of this process a large number of times yields the pdf of output power. The 0.995 reliability requirement for Pioneer dictates that about 10,000 histories be calculated to yield sufficient accuracy at the extremes of the output power distribution.

The process of a Monte Carlo history is shown in Fig. IV-1 where the notation "pick" refers to random selection of a parameter value from the prescribed input distribution. Input parameters are the T/E degradation, the fuel capsule percent helium release, the generator gas leak rate, the heat source thermal loading, and the initial generator output power (P_o).

The notation "determine" means to evaluate the non-linear functions pressure, concentration, temperature, degradation and power. The required functions p(H,L), C_{He}(H, L), T_{hot}(H, L), $\gamma(T_{hot})$ and $\frac{\Delta P}{P2}$ (p, C_{He}) are input in tabular form with interpolation providing specific values. Additionally, the worth of fuel decay ($\Delta P_{fuel\ decay}$) and the Carnot effect (ΔP_{Carnot}) is provided.

FIG. IV-1. CALCULATION OF A HISTORY IN PDF 10



NOMENCLATURE

C	Concentration
H	Helium release rate from fuel
L	Seal leak rate
P	Output power
p	Pressure
q	Capsule thermal loading
T	Temperature
η	Symbolic notation for a modified normal distribution with a mean value and standard deviation indicated in parenthesis
γ	Ratio of power at time t to power initially, T/E degradation factor
σ	Standard deviation

b. Inputs to parameter variation analysis

(1) Temperatures

Flight data have provided generator housing temperature information which includes the effects of trajectory, sun orientation, and heat conduction to the mounting boom. From this data, fin root temperature vs. time profiles are shown in Figs. IV-2 and IV-3 for the outboard units and the inboard units, respectively. The significant contribution of this data is that temperatures are about 15°F lower than predicted from extrapolated cold wall thermal vacuum test data. A possible cause of this reduction is heat conducted into the mounting structure in the amount of 40 thermal watts per RTG.

The mean hot junction vs. time profiles are based on life data from ETG's, the fin root temperature profile discussed above, the effect of load voltage operation at 4.0 and 4.1 volts (inboard and outboard, respectively) and the calculated internal RTG gas conditions. The temperatures are not given for each RTG but rather only for inboard or outboard position. The reason for this generic treatment is that a single RTD reading, such as exists on each flight RTG, is not deemed sufficiently accurate to depict the hot junction temperature of any given generator.

The values in Figs. IV-2 and IV-3 are taken to be the mean of a truncated normal distribution with a standard deviation of 15°F. The variation is introduced to accommodate the following effects:

(a) Thermal variations from unit to unit in cold end hardware, insulation, and thermoelectric elements.

(b) Fin root uncertainty.

(c) Load voltage uncertainty of ± 0.1 volt.

(d) Hardware differences between flight units and generator life test units.

(e) True thermoelectric degradation variance

(2) Initial power

"Initial" power on each RTG is taken to be the value measured at RTG acceptance (< one month heated time) and is shown in Tables IV-1 and IV-2 normalized to the appropriate fin root temperature. The corresponding gas fill is very close to 75% helium/25% argon.

The power measurement uncertainty, σ_{BOL}, is taken as 0.1 watt.

FIG. IV-2. TEMPERATURE VERSUS TIME; Q = 645 WATTS; WITH GETTER; INITIAL GAS FILL: 75% He/25% Ar; 100% HELIUM RELEASE RATE; OUTBOARD RTG

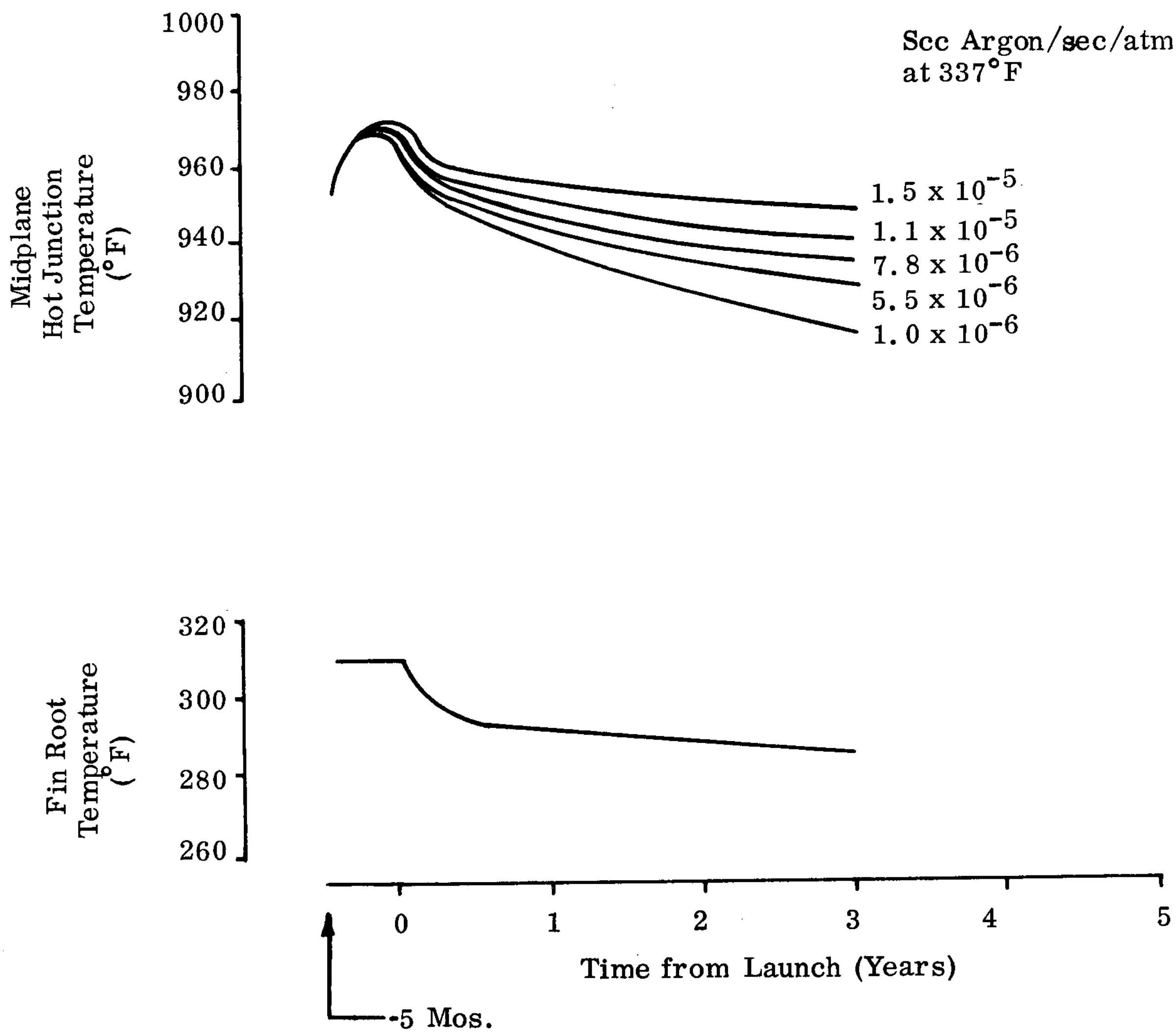


FIG. IV-3. TEMPERATURE VERSUS TIME; Q=645 WATTS; WITH GETTER; INITIAL GAS FILL: 75% He/25% Ar;100% HELIUM RELEASE RATE; INBOARD RTG

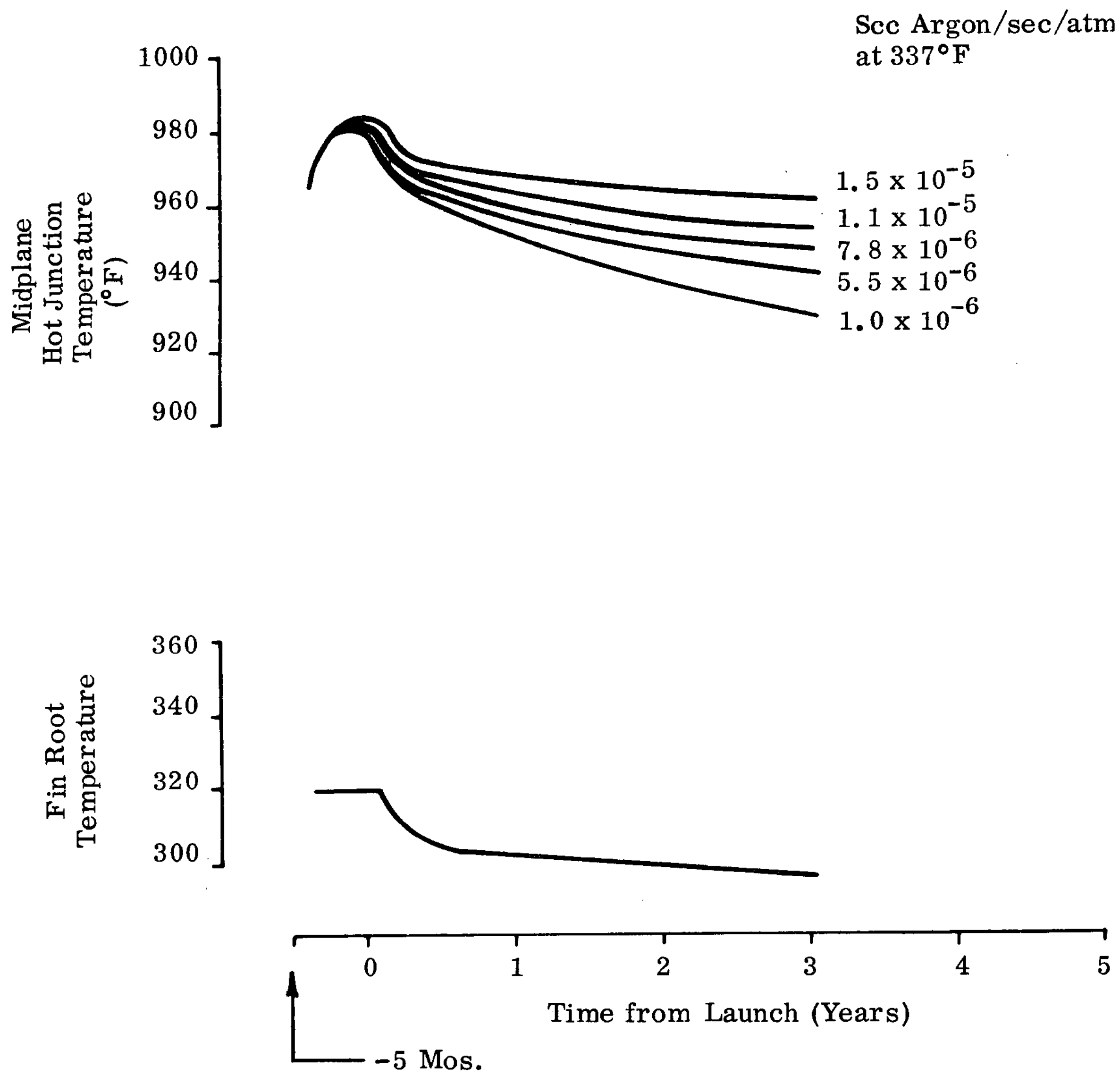


TABLE IV-1

SELECTED ANALYSIS INPUT DATA

PIONEER 10 RTG'S

RTG S/N	Leak Rate* (scc He/sec-atm)	Fuel Inventory (watts)	Heated Time at Acceptance (hours)	Spacecraft Location	Power (watts), Voltage (volts) and Fin Root Temperature (°F) at Acceptance
44	2×10^{-5}	649	635	Outboard	41.62 at 4.1 and 310
45	1.9×10^{-5}	646	610	Inboard	40.58 at 4.0 and 320
46	2.2×10^{-5}	647	400	Outboard	40.95 at 4.1 and 310
48	3.2×10^{-5}	649	500	Inboard	41.04 at 4.0 and 320

* Leak rate of argon ≈ one-third leak rate of helium. Indicated values were measured after acceptance vibration and are referenced to 337°F.

TABLE IV-2

SELECTED ANALYSIS INPUT DATA

PIONEER 11 RTG's

RTG S/N	Leak Rate* (scc He/sec-atm)	Fuel Inventory (watts)	Heated Time at Acceptance (hours)	Spacecraft Location	Power (watts), Voltage (volts) and Fin Root Temperature (°F) at Acceptance
49	1.5×10^{-5}	649	1090	Outboard	40.57 at 4.1 and 310
51	2.3×10^{-5}	650	1064	Inboard	40.35 at 4.0 and 320
52	2.0×10^{-5}	649	930	Outboard	40.80 at 4.1 and 310
53	2.6×10^{-5}	649	1065	Inboard	40.00 at 4.0 and 320

* Leak rate of argon ≈ one-third leak rate of helium. Indicated values were measured after acceptance vibration and are referenced to 337°F.

(3) Fuel inventory

The fuel inventory is not of consequence in this analysis since the power is measured for each RTG and hot junction temperature for either the inboard or outboard position is treated generically. For reference, the nominal fuel inventory is shown in Tables IV-1 and IV-2.

(4) Helium release rate

Helium release rate from the fuel is assumed to be 100% based on the data from LASL and examination of early-life performance on all Pioneer RTG's. This analysis does not consider temporary retention of helium within the fuel followed by sudden expulsion. Such behavior may lead to temporary departure of performance from the predicted trend but will have a negligible effect in the long term.

(5) Leak rate

Generator leak rate is measured on each RTG after vibration testing. This value is used in the analysis as the mean leak rate. One standard deviation is taken to be ten percent of the mean based on an examination of the raw leakage data combined with a judgment on the worth of other factors, e.g., data normalized uncertainty, operator variance. The assumption is made in this analysis that leak rate remains constant with time.

(6) Fuel decay

The loss in initial power from fuel decay is given in Table IV-3 for three specific times.

(7) Carnot effect

The fin root temperature decreases with time because of fuel decay and diminishing solar input after launch. As a result of this temperature decrease, a small power increase occurs as shown in Table IV-3. It may be noted that the values are different for generators S/N 44 and S/N 45 at 5000 hours, but at later time the power increase is the same for all RTG's. This is caused by the age difference (a few hundred hours) among generators at the time of launch and the rapidly changing fin root temperatures early in the flight. By the 15,000 hour point, the generators are far from earth and multiplication of the slow rate of change of fin root temperature by the relatively small age difference yields a negligible temperature difference.

TABLE IV-3

RESULTS OF FUEL DECAY AND CARNOT EFFECT

Total Heated Time for Generator (hrs)	Loss in Thermal Power Due to Fuel Decay Per RTG (watts)	Loss in Electrical Power Due to Fuel Decay Per RTG (watts)	Power Increase Due to Carnot Effect Per RTG (watts)
5,000	2.9	0.29	0.15 (RTG S/N 44)
			0.25 (RTG S/N 45)
			0.30 (RTG's S/N 46, 48, 49, 51, 52, 53)
15,000	8.6	0.86	0.53 ((All RTG's)
30,000	17.2	1.72	0.60 ((All RTG's)

(8) Gas pressure/concentration vs. time

At fueling, the generator gas fill is 75% helium/25% argon at 16 psia. The gas pressures and compositions as a function of time thereafter are shown in Figs. IV-4 and IV-5 for seven different gas leakage rates from the generator housing. These results were obtained by consideration of Viton seal permeation characteristics in conjunction with helium release rate from the fuel.

(9) Power-gas relationship

Through parasitic heat loss effects, output power of a Pioneer RTG is a function of its gas composition and pressure. This relationship is shown in Fig. IV-6 for the binary gas system helium/argon. The data were developed experimentally on ETG S/N 41.

(10) Thermoelectric degradation

Figure IV-7 gives the fractional generator power remaining (thermoelectric degradation only) at 30,000 hours as a function of hot junction temperature. The data points represent results from four life test ETG's: HPG S/N 1 (960°F), ETG S/N 29 (980°F), ETG S/N 31 (1015°F) and ETG S/N 26 (1055°F). The curve indicated through the data is a least squares parabolic fit. Values of P/P_o at other times than 30,000 hours may be linearly interpolated since the four ETG's used for the derivation of this data have degraded linearly with time.

FIG. IV-4. GAS CHARACTERISTICS;75% HELIUM/25% ARGON INITIAL FILL;OUTBOARD; 100% HELIUM RELEASE RATE

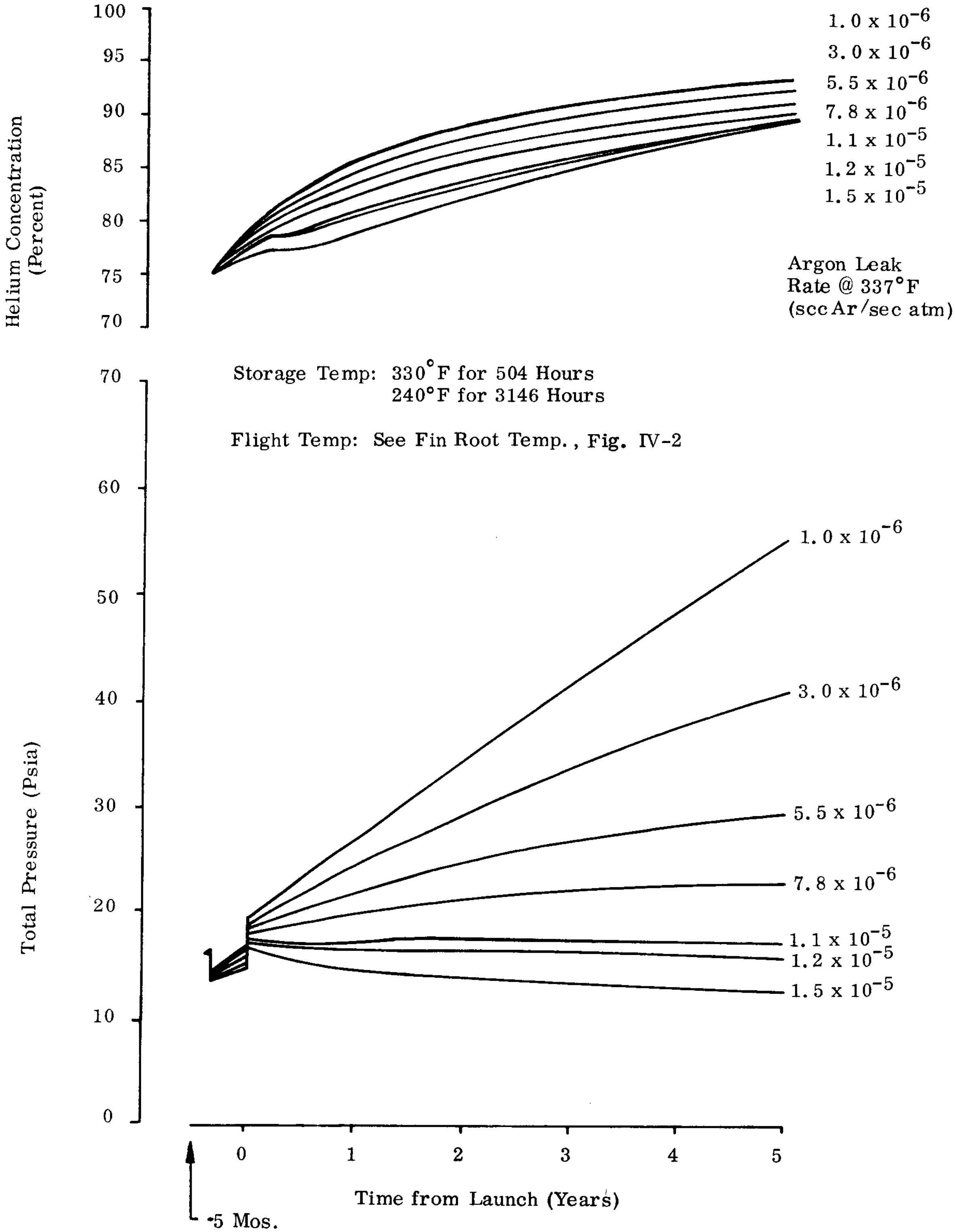


FIG. IV-5. GAS CHARACTERISTICS; 75% HELIUM/25% ARGON INITIAL FILL; INBOARD; 100% HELIUM RELEASE RATE

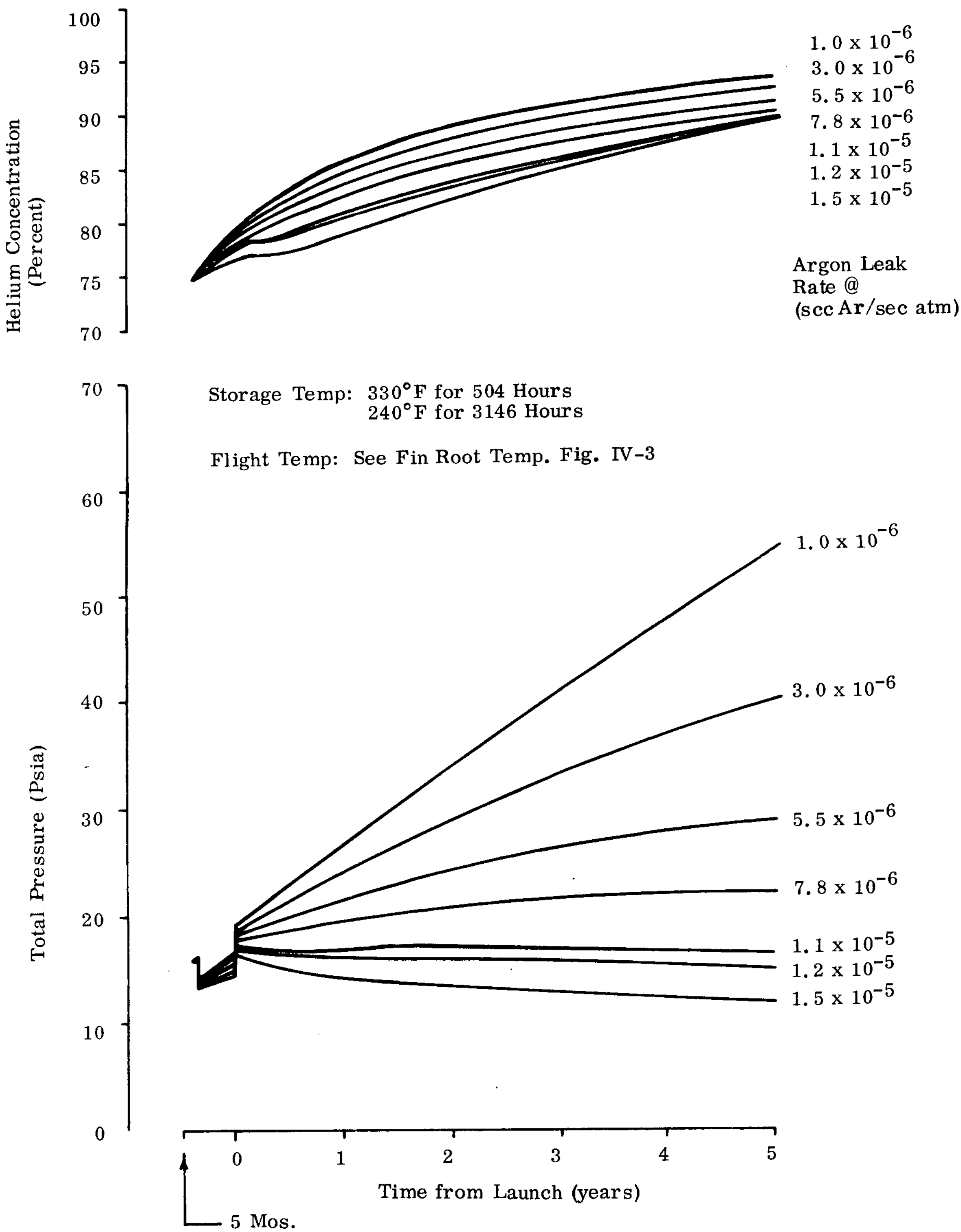


FIG. IV-6. S/N 41 POWER CHANGE WITH GAS COMPOSITION AND PRESSURE

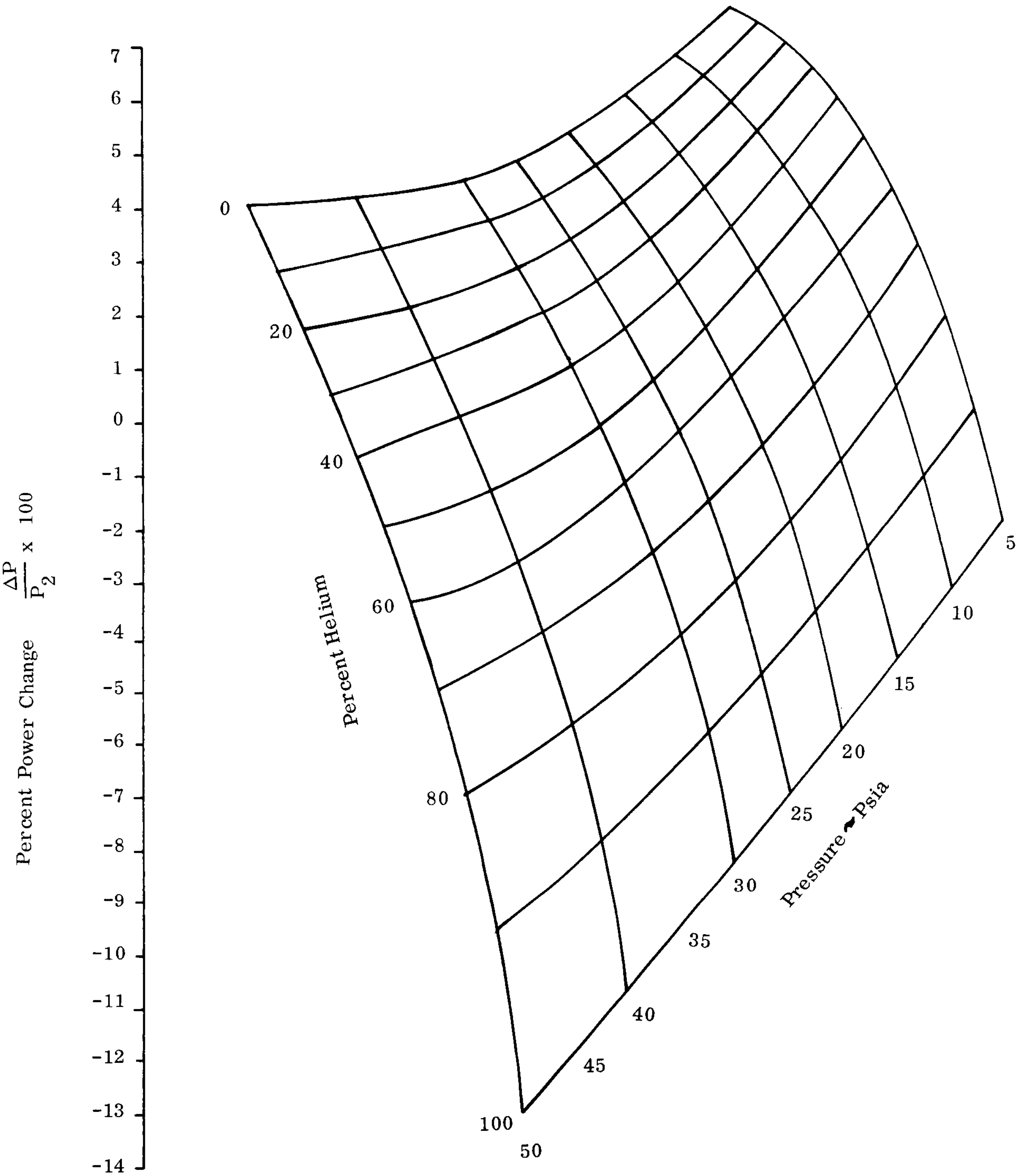
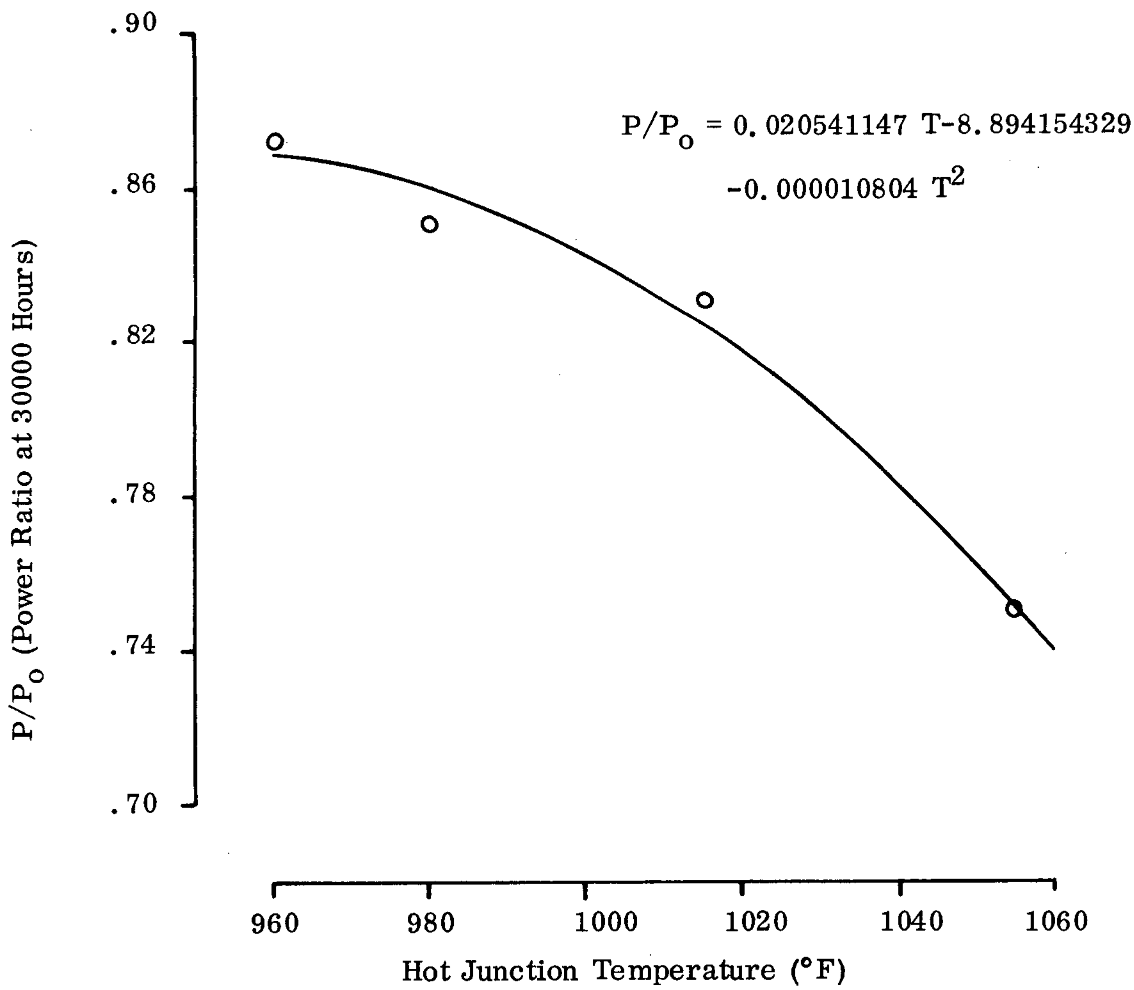


FIG. IV-7. THERMOELECTRIC DEGRADATION RATE
P/P_o AT 30,000 HOURS



b. Power-probability results

Pioneer 10 RTG System

Results for each Pioneer 10 RTG are presented in Figs. IV-8 through IV-11 in the form of RTG output power vs. time, parametric in probability. For reference, hot junction and fin root temperatures are also given. The graphs shown for fin root temperature were taken directly from Figs. IV-2 and IV-3. In the case of hot junction temperature, the appropriate curves in Figs. IV-2 and IV-3 were vertically translated to "fit" spacecraft data from the single sensor installed in each RTG. It is observed that the predicted power is in good agreement with data interpreted from spacecraft telemetry. The only significant discrepancy exists for generator S/N 45 where the spacecraft data is believed high as revealed by a comparison of the initial flight data with numerous earlier measurements. Hot junction temperature behavior is essentially as expected except in the case of RTG S/N 48. It appears that some malfunction in the signal reduction/transmission has occurred since the unchanging temperature indication is not a probable failure mode for the RTD sensor.

The total RTG system power is shown in Fig. IV-12. In order to provide a basis for continuous evaluation of performance, a band representing the predicted power trend is superimposed. The band width approximates the 0.99 probability range (0.005 to 0.995) and encompasses a nominal predicted system power indication of 142 watts at Jupiter encounter in December 1973. It may be observed that this nominal value is about one watt higher than that observed from summing the individual generator predictions of Fig. IV-8 through IV-11. This difference is caused mainly by the data discrepancy of S/N 45 shown in Fig. IV-9.

Pioneer 11 RTG System

The predicted performance trends of the Pioneer 11 RTG's are shown in Figs. IV-13 through IV-16. It is apparent that the behavior of these generators is similar to that of the Pioneer 10 generators. As of this writing, data indicates satisfactory agreement with predictions. Thus, the anticipated RTG system power at Jupiter encounter in December 1974 is 138 watts.

c. RTG launch transients

Prior to launching of the first Pioneer spacecraft it was of interest to determine whether the RTG's would experience temperatures in excess of equilibrium space operation during the

FIG. IV-8. PIONEER 10 RTG S/N 44 (OUTBOARD) PERFORMANCE

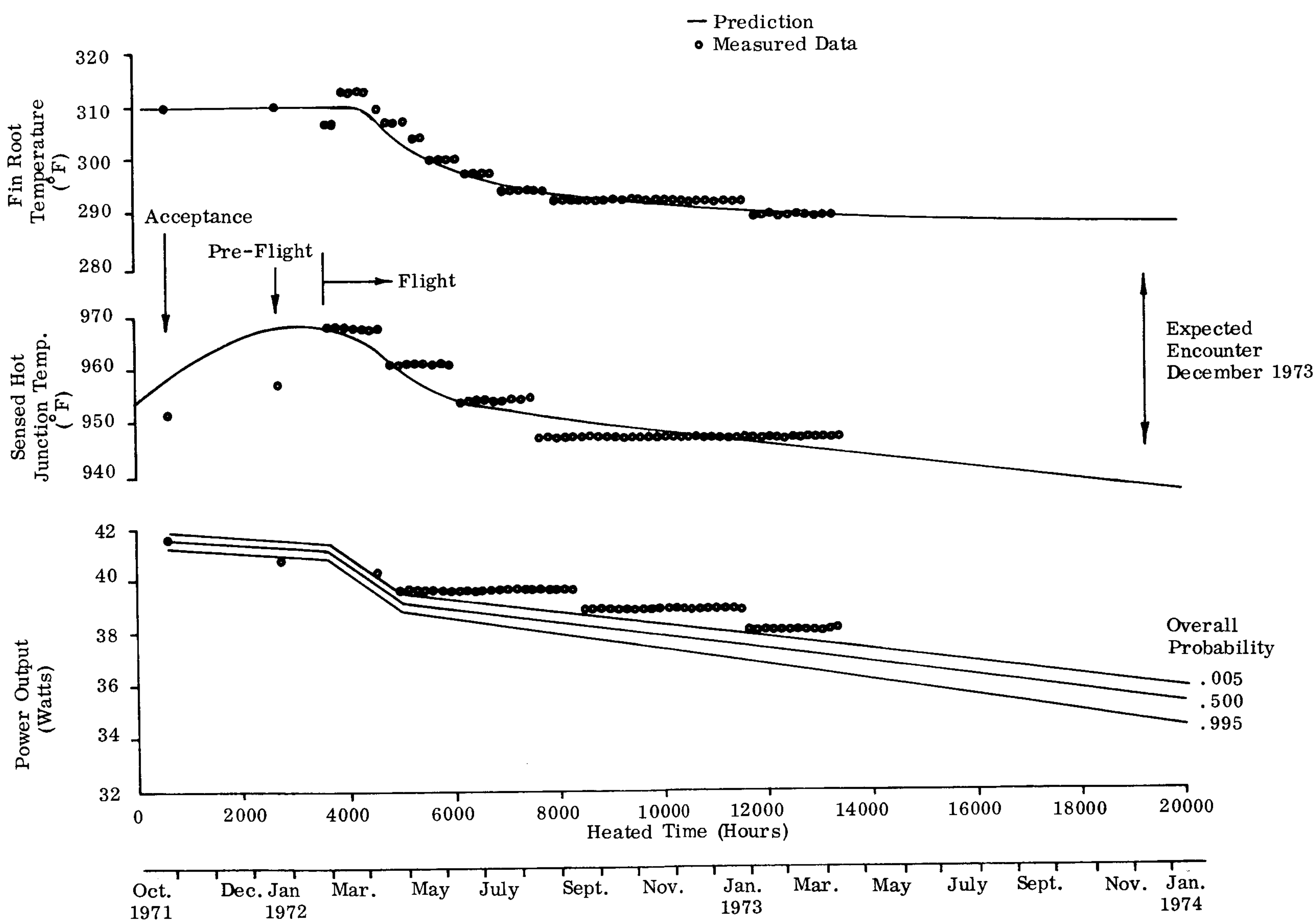


FIG. IV-9. PIONEER 10 RTG S/N 46 (INBOARD) PERFORMANCE

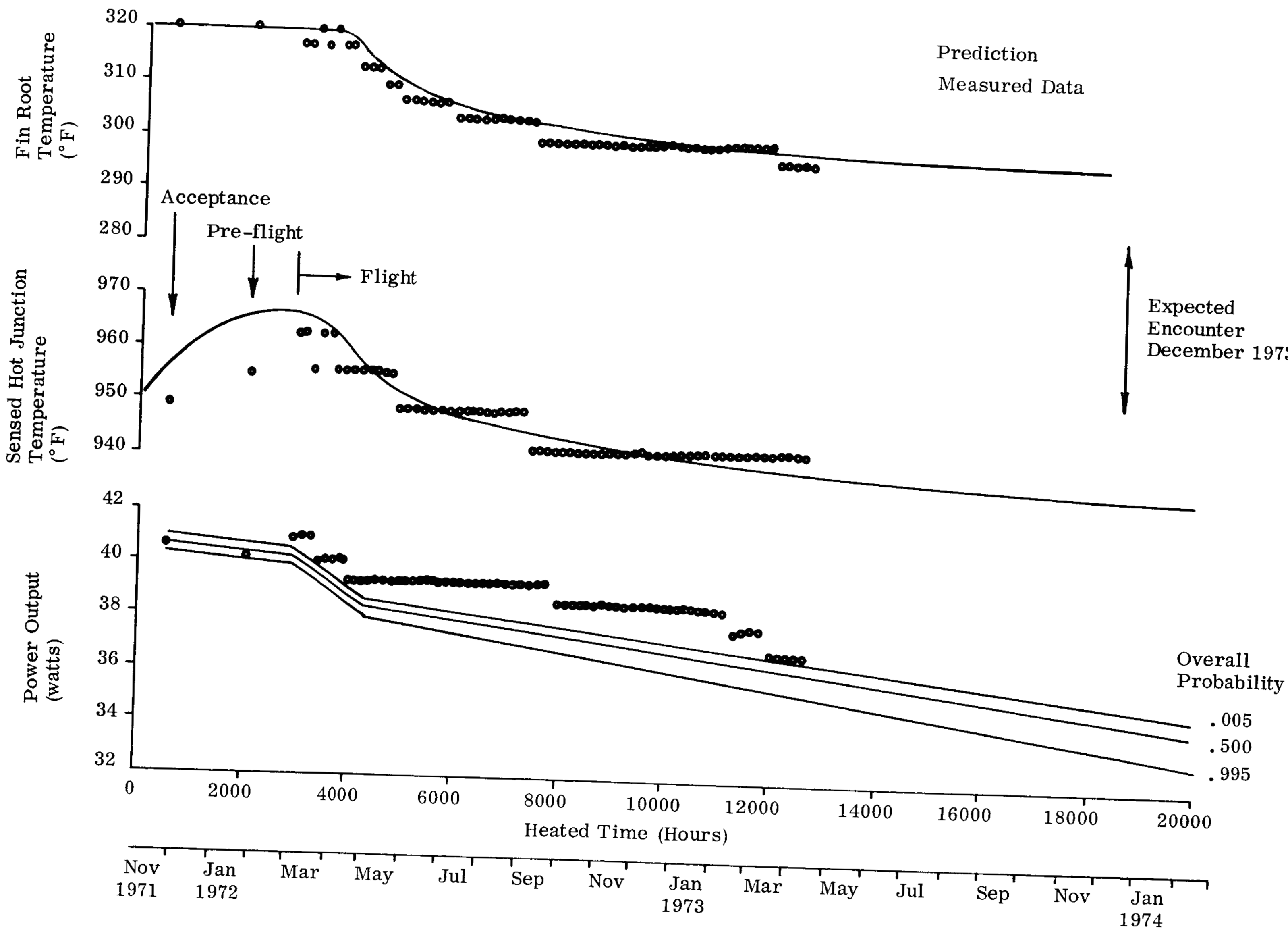


FIG. IV-10. PIONEER 10 RTG S/N 46 (OUTBOARD) PERFORMANCE

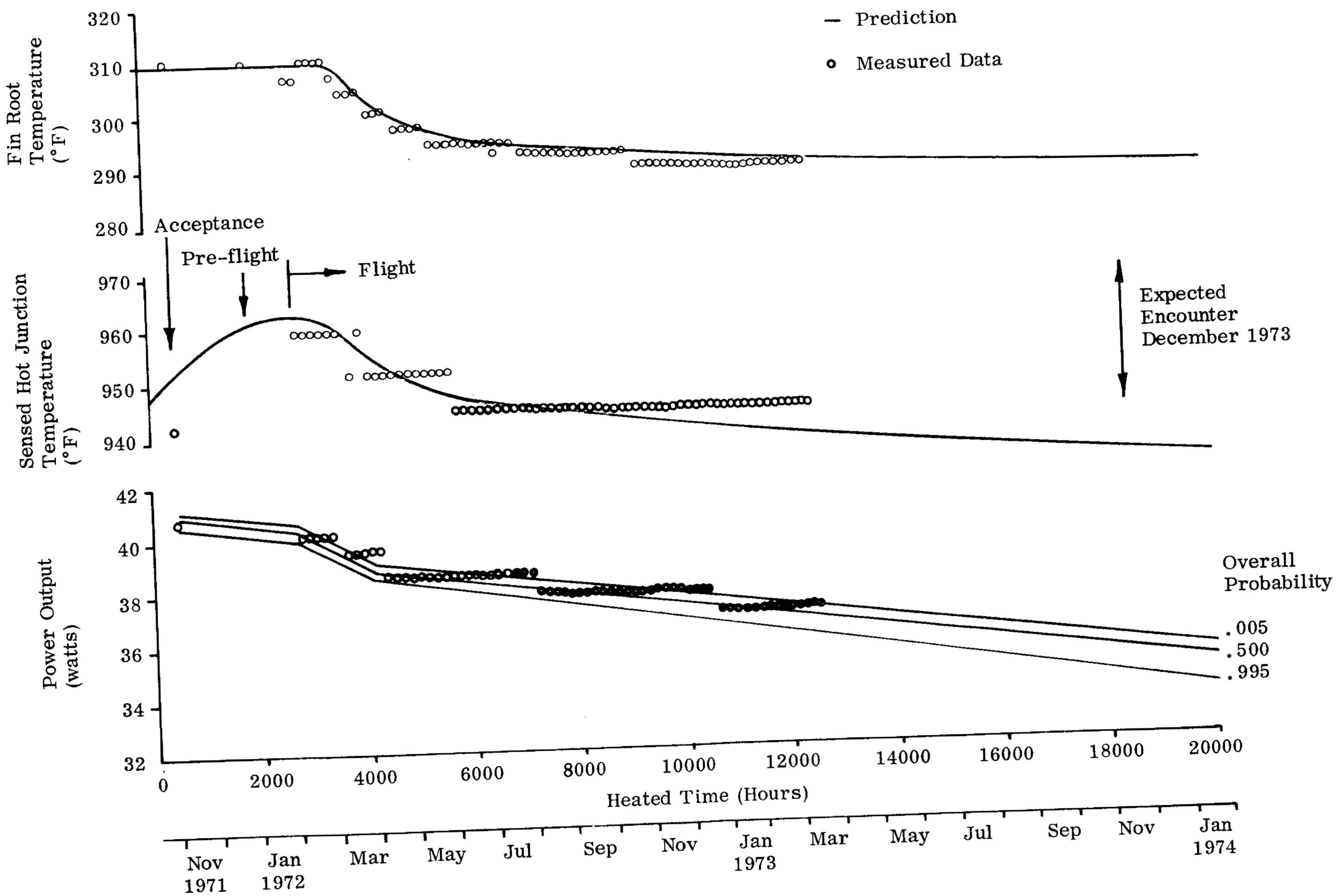


FIG. IV-11. PIONEER 10 RTG S/N 48 (INBOARD) PERFORMANCE

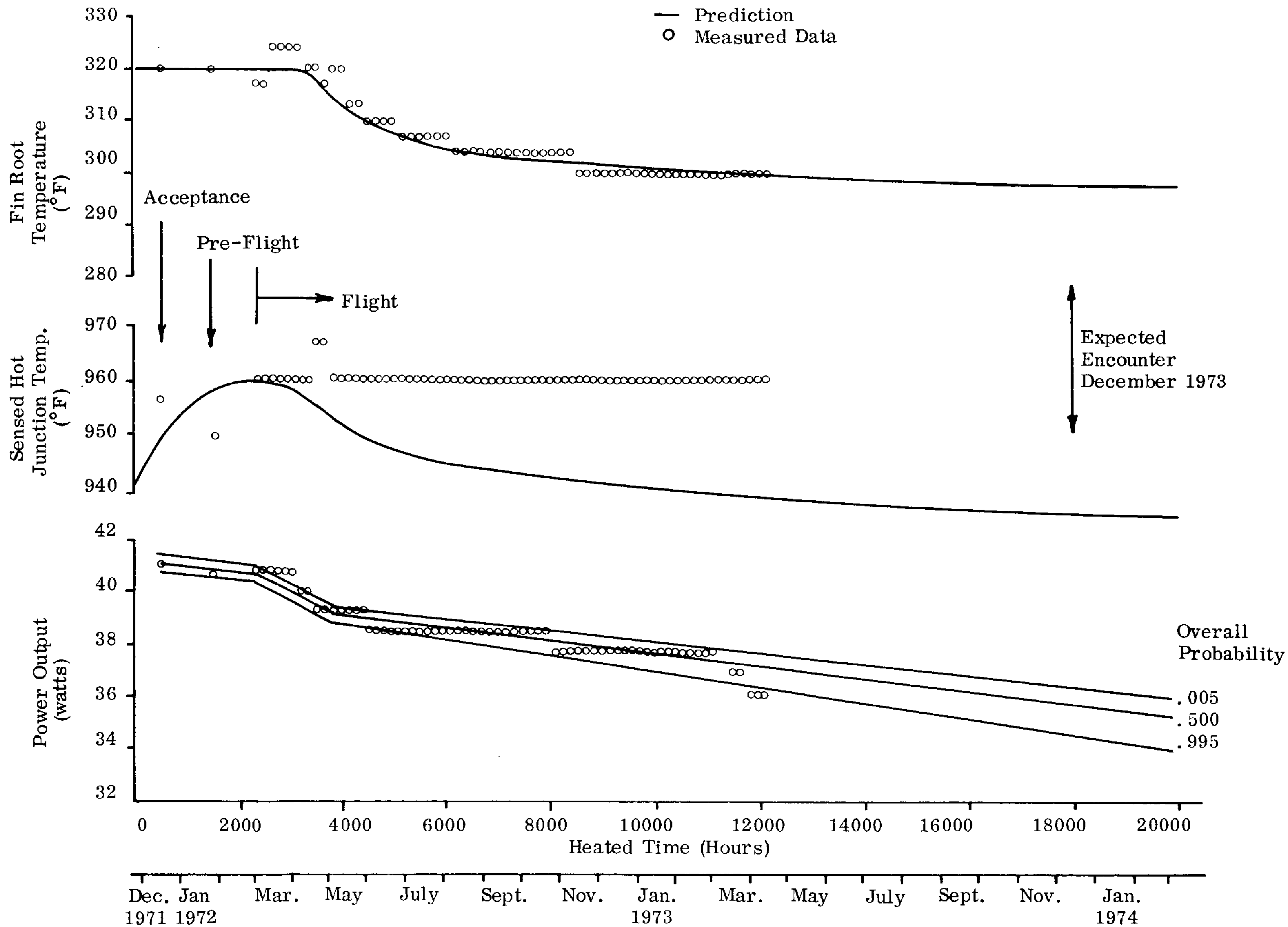


FIG. IV-12. TOTAL RTG SYSTEM POWER COMPARISON OF FLIGHT DATA WITH PREDICTED POWER BAND

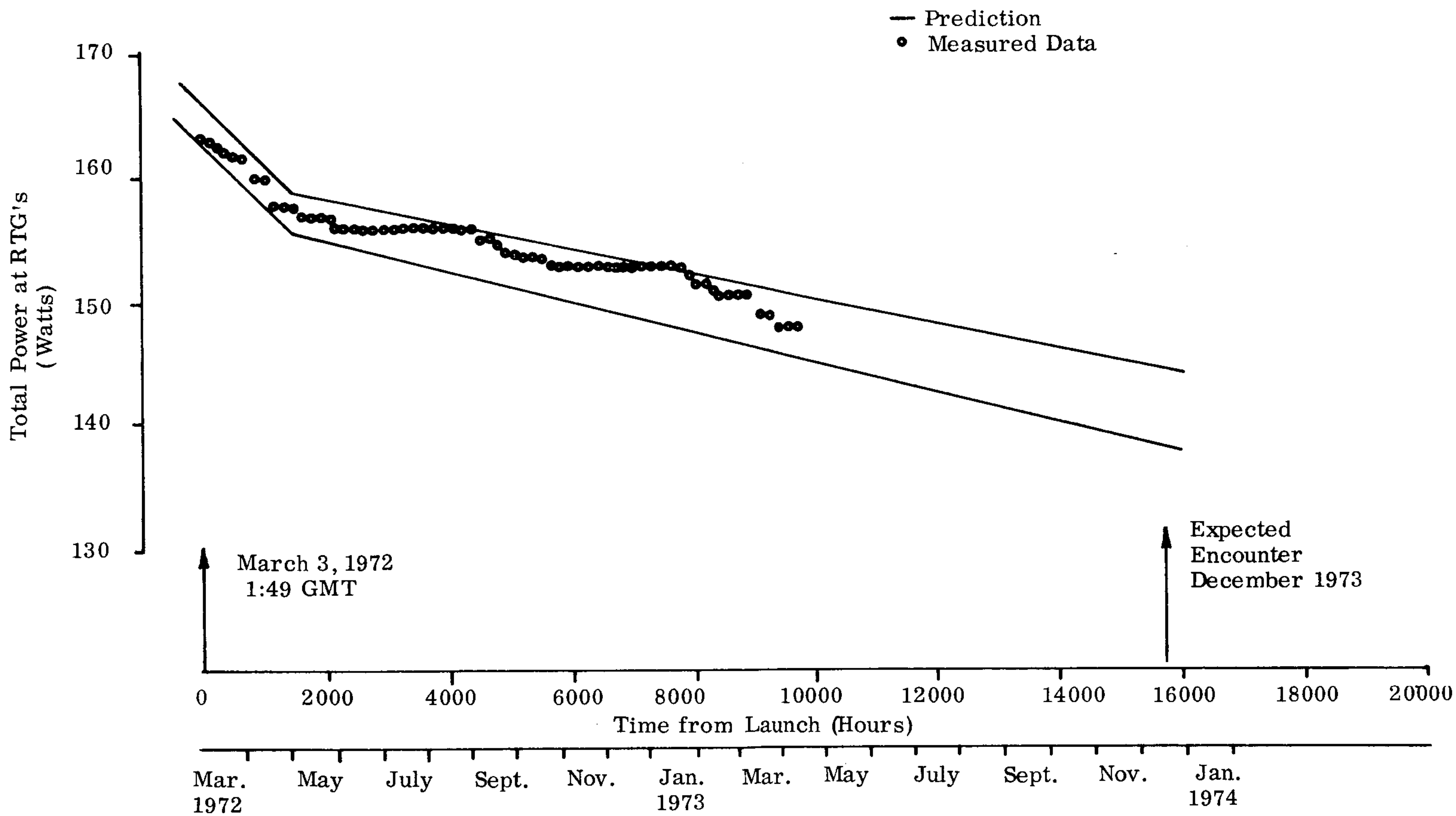


FIG. IV-13. PIONEER 11 RTG S/N 49 (OUTBOARD) PERFORMANCE

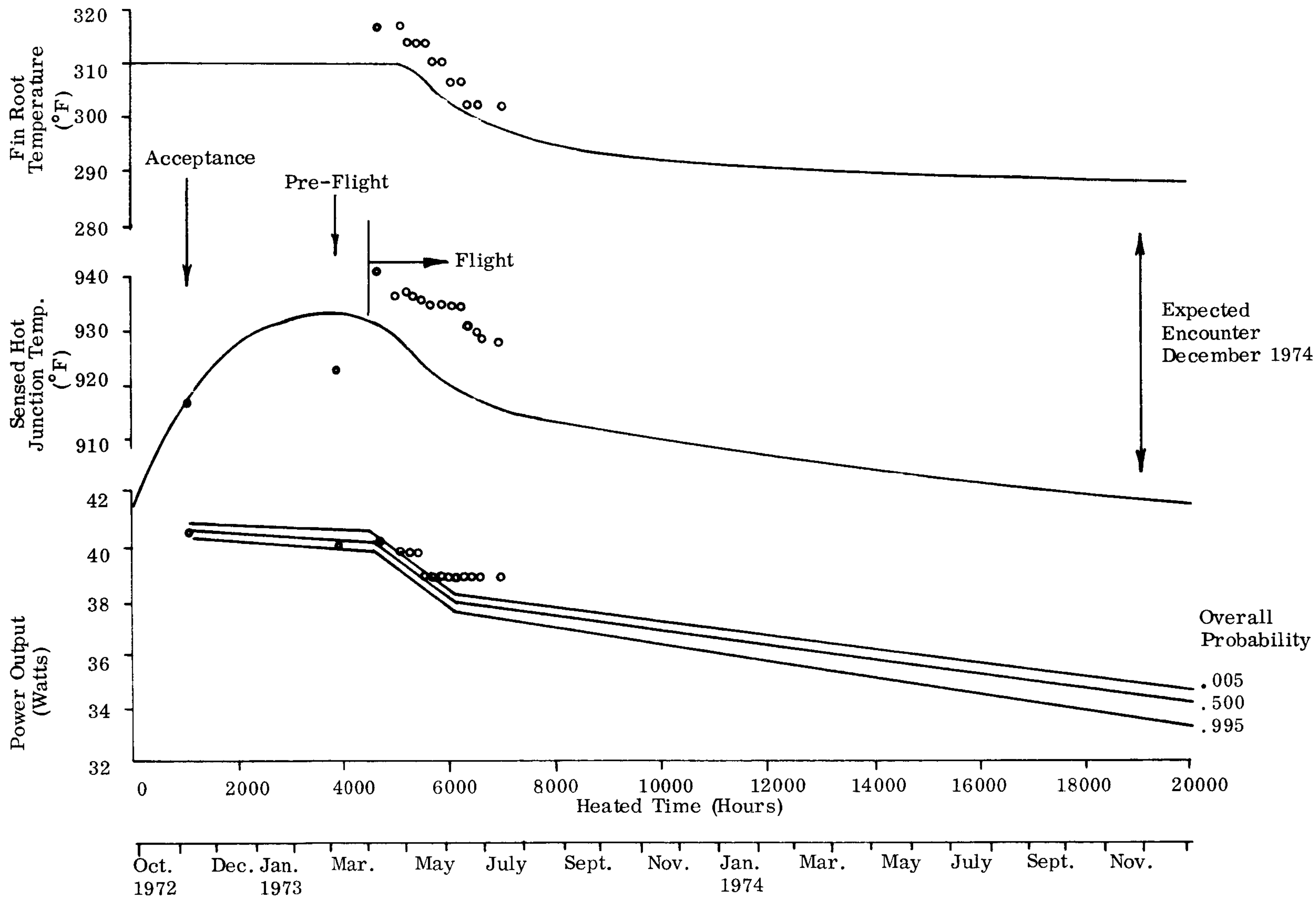


FIG. IV-14. PIONEER 11 RTG S/N 51 (INBOARD) PERFORMANCE

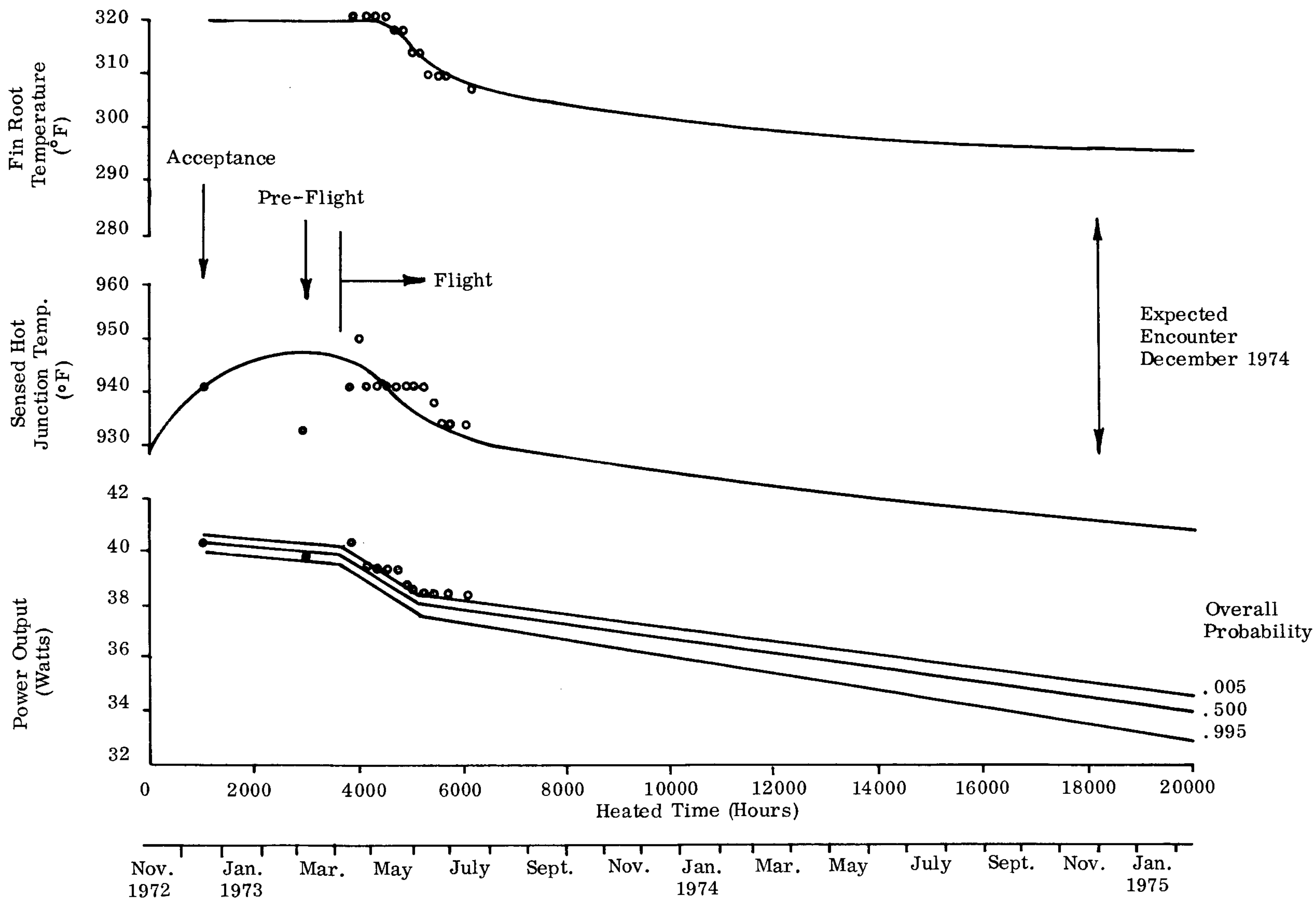


FIG. IV-15. PIONEER 11 RTG S/N 52 (OUTBOARD) PERFORMANCE

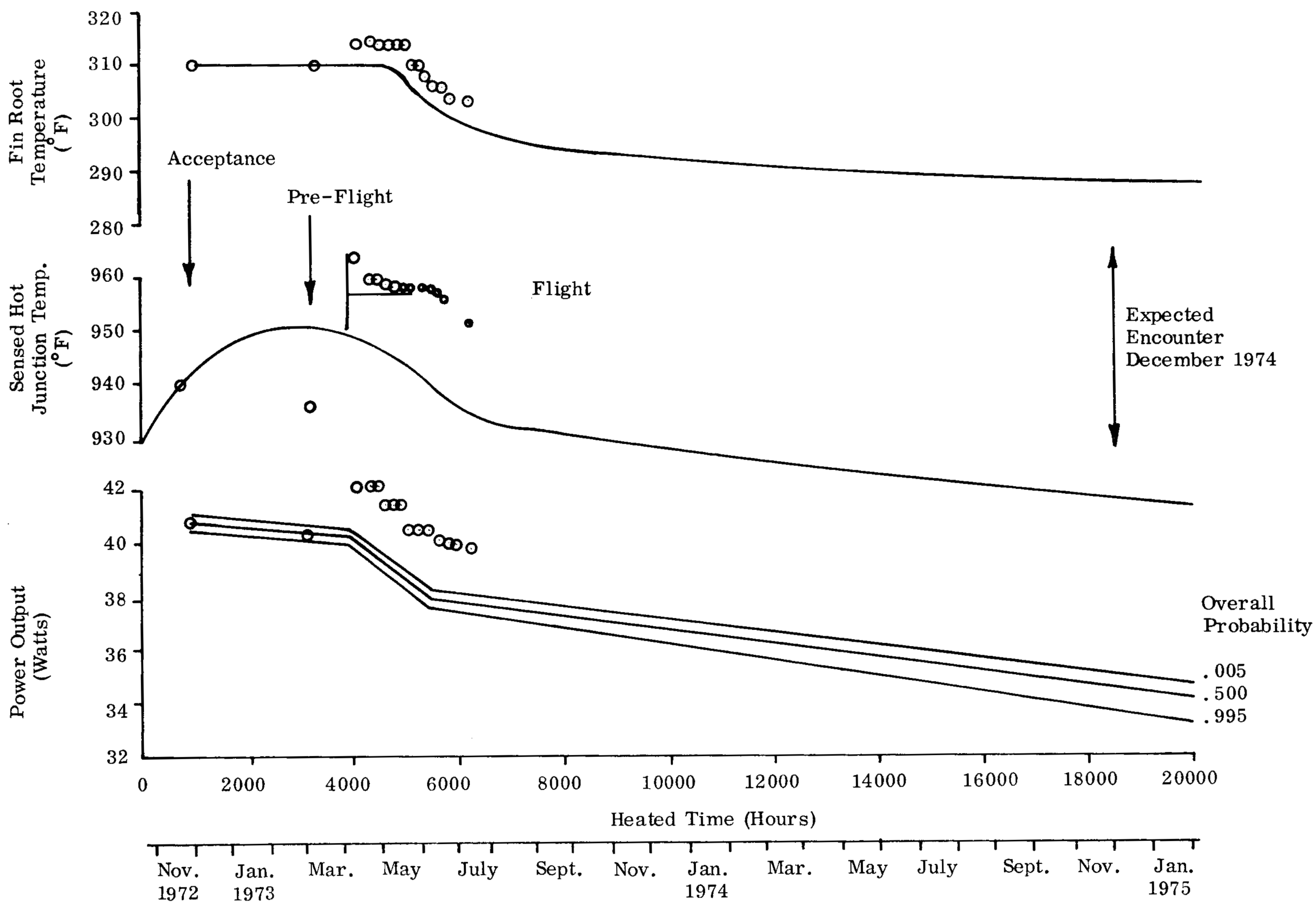
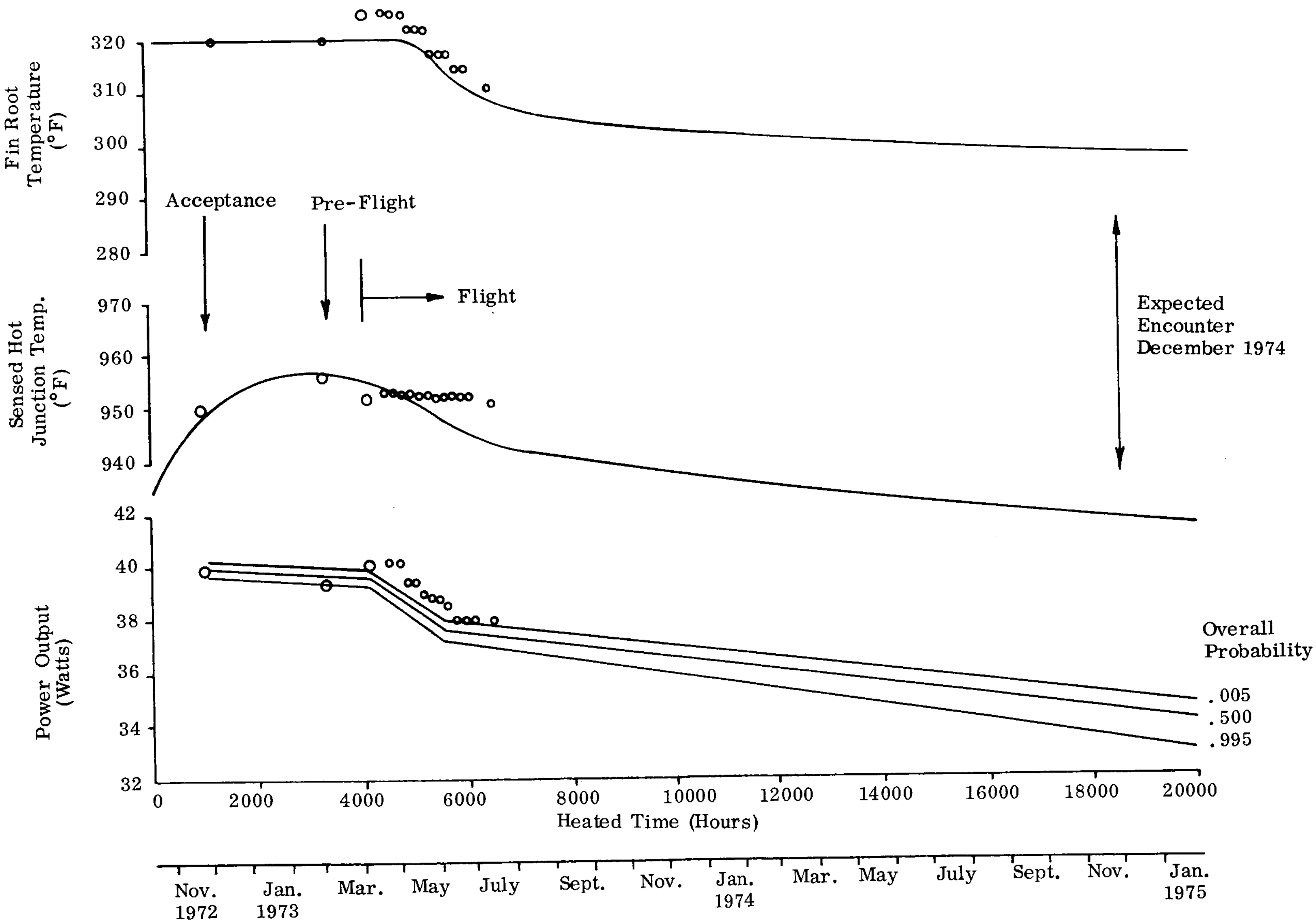


FIG. IV-16. PIONEER 11 RTG S/N 53 (INBOARD) PERFORMANCE



ascent phase of the mission. Experiments performed at JPL indicated that the approach to equilibrium would be gradual without overshoot and flight data confirmed this behavior.

Power and temperature data received from the Pioneer spacecraft shows the RTG behavior from liftoff to equilibrium operation in space. It can be seen in Fig. IV-17 that upon termination of on-pad cooling at liftoff the RTG housing (fin root) temperature rises relatively quite rapidly until RTG boom deployment. Thereafter the rate of increase slows and 90% of the change occurs within one hour from liftoff. This elevation of the heat rejection temperature is accompanied by an immediate large reduction of output power because of the hot junction temperature lag. The output power reaches its minimum value about one-half hour after liftoff, but thereafter, a sharp recovery is observed. After about one hour, the power increase follows the hot junction temperature increase since the housing temperature is nearly at its equilibrium value. Equilibrium of power and hot junction temperature occurs by about four hours after liftoff.

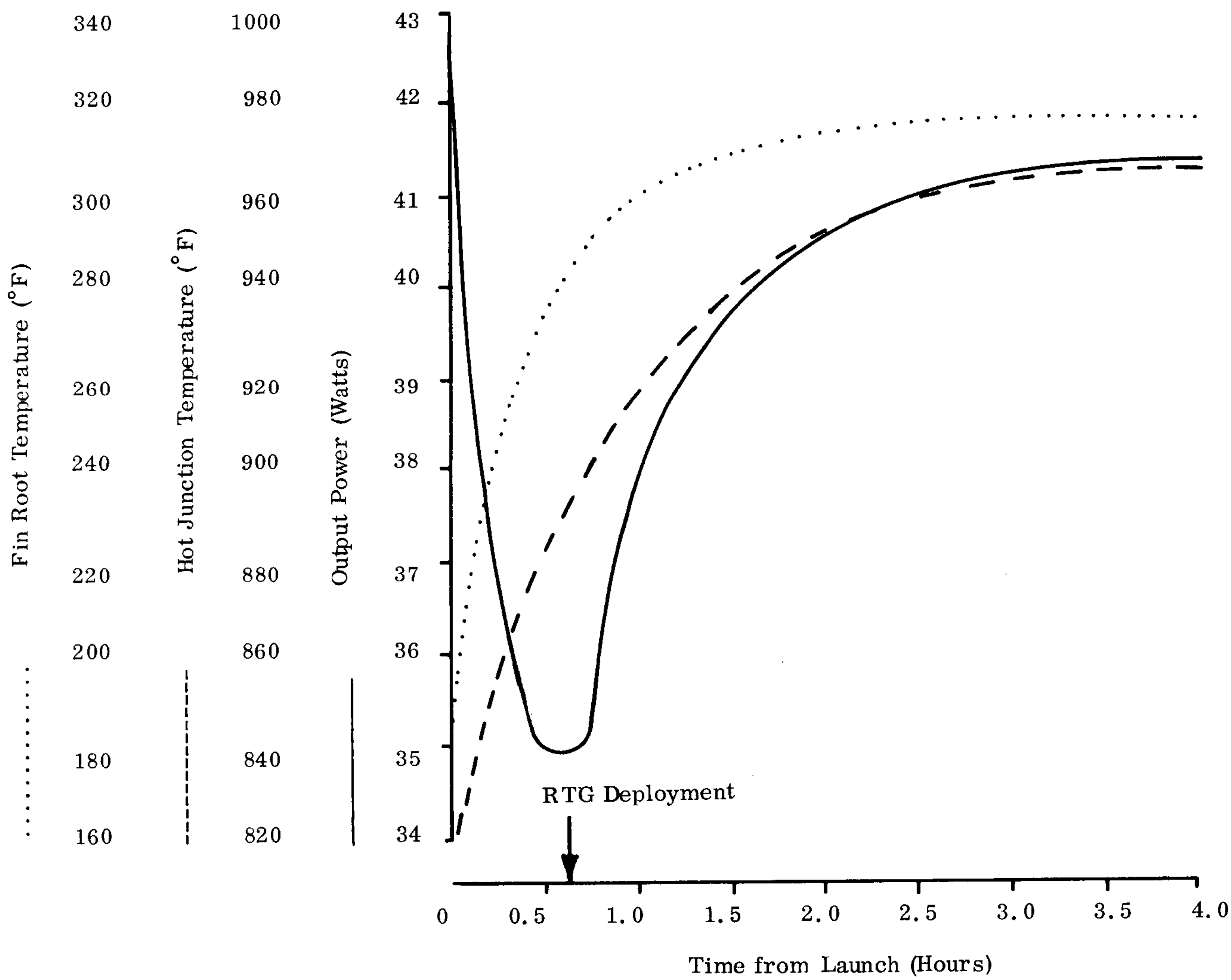
B. STEADY STATE TEMPERATURES OF RTG HEAT SOURCE

A steady state thermal analysis of the heat source was performed for the SNAP 19/ Pioneer RTG's. Internal temperatures were calculated as a function of average heat shield surface temperatures at selected times of interest between fueling and launch. Analytical results are presented as heat source temperature distributions and component peak temperatures versus heat shield temperature.

1. Conditions Studied

Heat source temperatures were determined for normal RTG operations with inert gas and under accident conditions with loss of gas and subsequent vacuum around the heat source. Normal operation is defined as an 0.75 He/0.25 Ar gas fill at one atmosphere pressure, since the small increase in helium concentration between fueling and launch does not appreciably affect heat source temperature. The accident conditions are defined as vacuum inside the generator (fin root temperature = 330°F)and a separated heat source viewing space. The first vacuum condition could exist if RTG seal failure occurred after launch, whereas the second case is associated with release of the heat source from the RTG during a multi-orbit reentry.

FIG. IV-17. PIONEER RTG POWER SYSTEM LAUNCH TRANSIENT



2. Method of Analysis

A two-dimensional thermal model was constructed for use with the Teledyne Isotopes TAP-3C digital computer program. The nodal arrangement of this model is presented in Fig. IV-18. Material properties (thermal conductivity and emissivity) are presented graphically in Figs. IV-19 and IV-20.

A uniform conductance was used between the nodes representing the heat shield surface (nodes 124 to 128) and the sink temperature (node 135) which would result in a desired average heat shield surface temperature. Heat shield temperatures at various times between beginning-of-life and launch, presented in Table IV-4, are derived by adding 40 F° to the midplane hot junction temperature. The hot junction temperatures were determined from evaluation of generator performance, helium leak rate and PMC helium release rate data. Test data from ETG's S/N 035 and S/N 036 indicated that the heat shield temperature is about 40°F higher than the hot junction temperatures.

TABLE IV-4

SELECTED PIONEER RTG TEMPERATURES

		Temperature (°F)		
	Circuit	Fin Root	Midplane Hot Junction	Heat Shield
B.O.L.	Load	329	973	1013
(Vacuum Test Chamber)	S.C.	329	873	913
B.O.L.	Load	250	900	940
(Air Operation)	S.C.	250	800	840
Pre-launch (5 months)	Load	~160	835	875
(Operation in Spacecraft Shroud)	S.C.	~160	735	775
Post-launch (5 months)	Load	310[1]	970	1010
(Normal Operation in Space)	Load	320[2]	980	1020

[1] Outboard RTG's

[2] Inboard RTG's

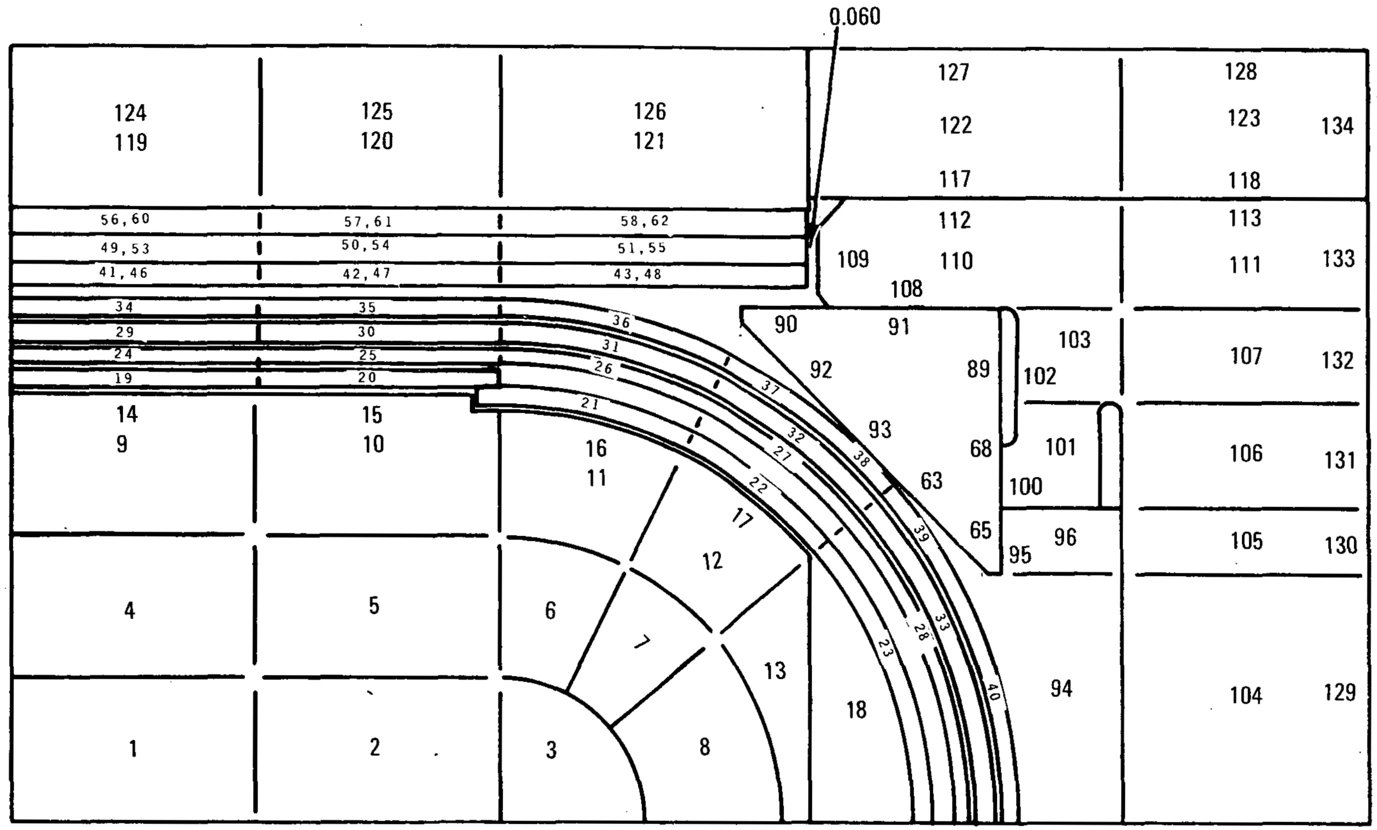


FIG. IV-18. SNAP 19 PIONEER T-111 HEAT SOURCE THERMAL MODEL

1-13	Fuel (PMC)
14-18	Fuel Surface
19-23	Inner Liner (Mo-50Re)
24-28	Liner (Ta-10W)
29-33	Strength Member (T-111)
34-40	Clad (Pt-20 Rh)
41-62, 97-99	3 Pc. Sleeve (Pyrolytic Graphite)
63-93	Load Ring (ZrO_2)
94-96	Insulation (Ta Felt)
100-113, 129-133	End Plug (Poco Graphite)
124-128, 134	Heat Shield Body (Poco Graphite)
135	Boundary Node

FIG. IV-19. THERMAL CONDUCTIVITY SNAP 19 HEAT SOURCE MATERIALS

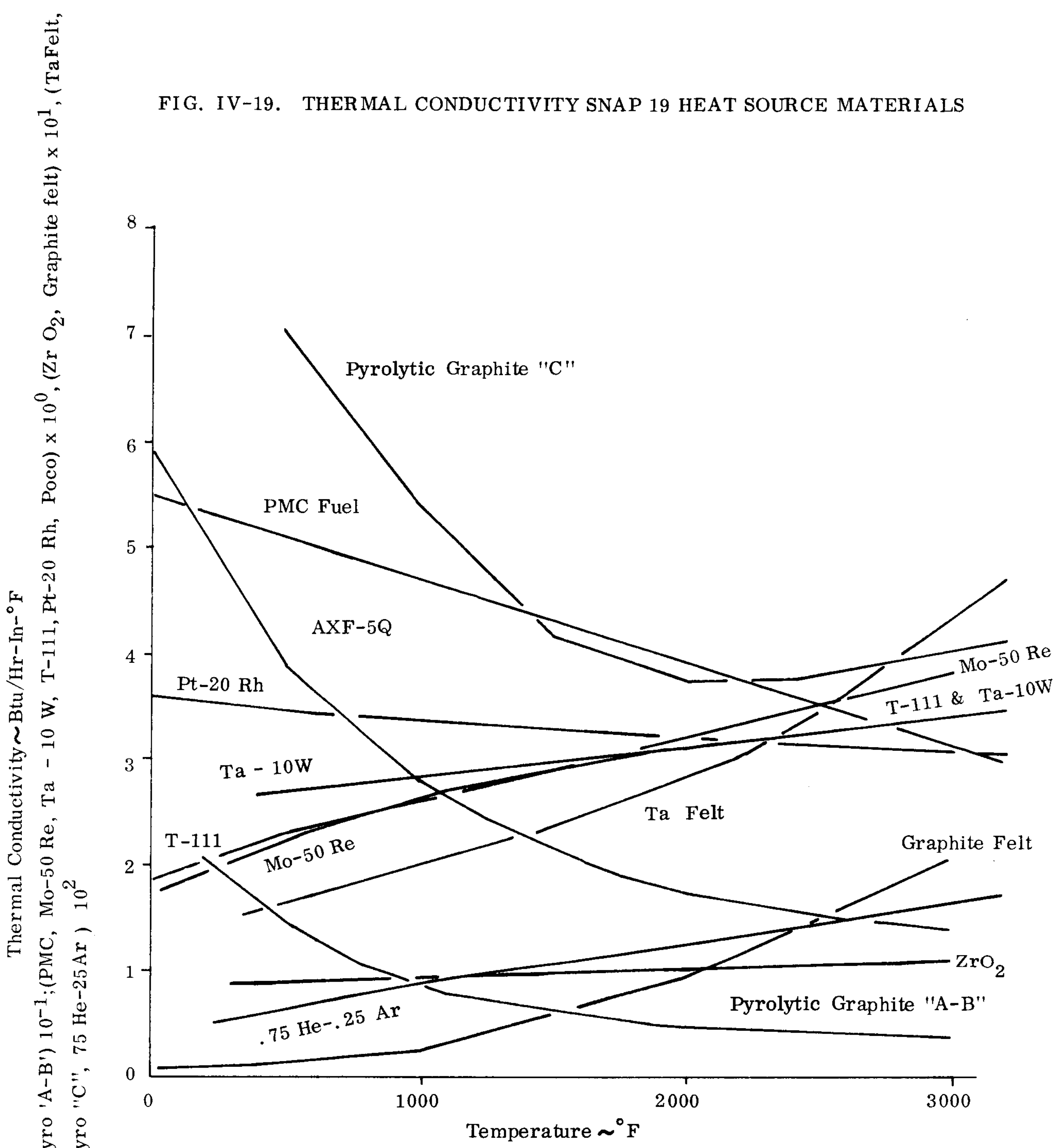
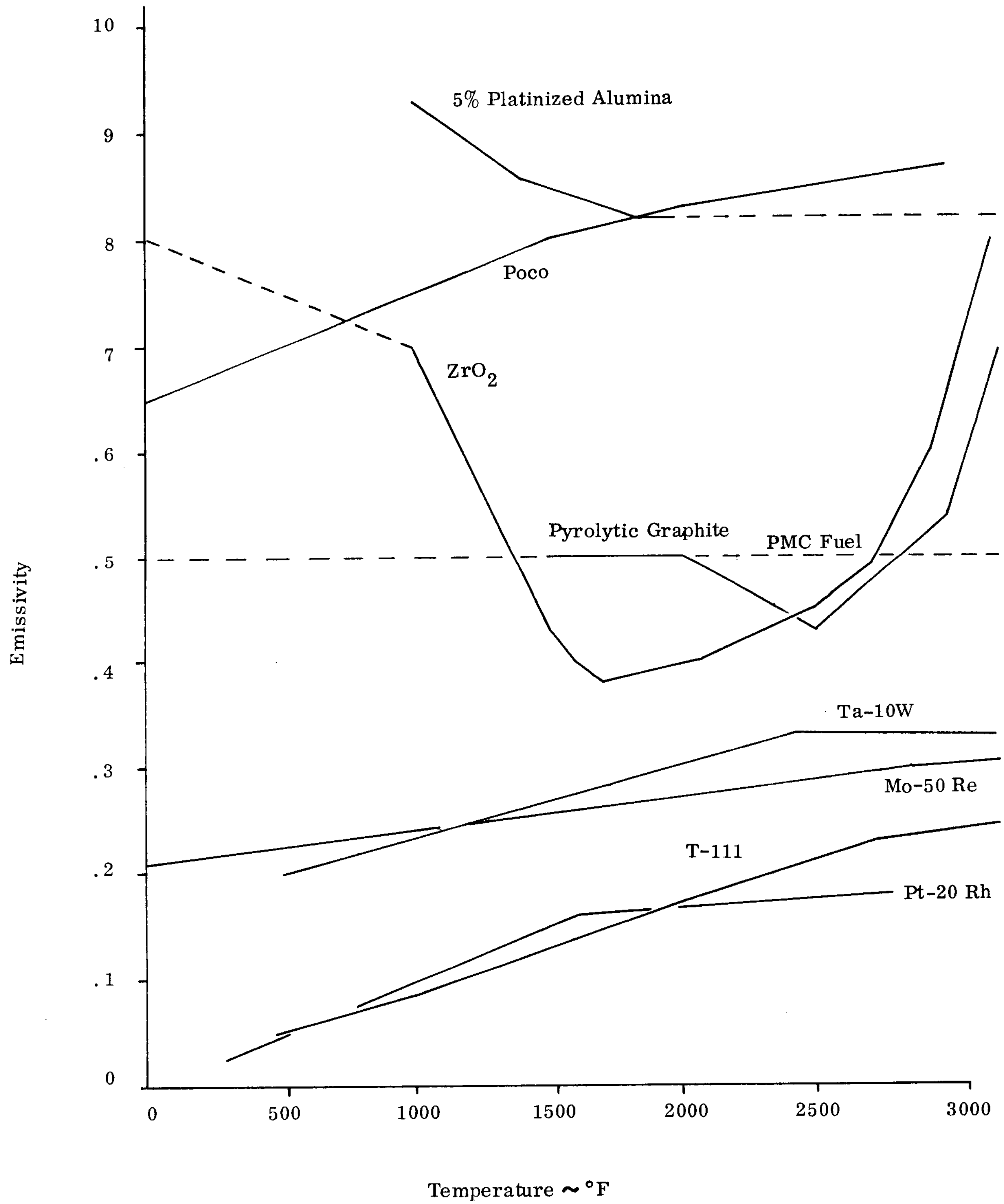


FIG. IV-20. SURFACE EMISSIVITY SNAP 19 HEAT SOURCE MATERIALS



Parametric calculations of the heat source thermal profile were made prior to establishment of the Pioneer RTG temperatures. In order to cover the potential range of operation, surface temperatures of 850°F, 1050°F and 1250°F were studied. For the case of the heat source exposed directly to a space environment, the heat shield body and end plug surface nodes (124 to 134 of Fig. IV-18) were assumed to radiate to a -460°F sink.

3. Results

Calculated temperature distributions for the heat source in the 0.75 He/0.25 Ar gas filled generator are presented in Figs. IV-21, IV-22 and IV-23 for the average heat shield temperatures of 850°F, 1050°F and 1250°F, respectively. In addition, Fig. IV-22 shows the gaps used in the analysis for RTG operation nearest post launch conditions. The maximum calculated temperature of each heat source component from Figs. IV-21 to IV-23 is presented in Fig. IV-24.

The temperature distribution of a heat source in vacuum is depicted in Figs. IV-25 and IV-26. Figure IV-25 gives the results for an RTG with internal vacuum and Fig. IV-26 shows the predicted temperature when the heat source is exposed directly to space.

C. OPERATIONAL RELIABILITY ASSESSMENT

1. Analysis

The operating reliability (probability of no catastrophic power loss) for the Pioneer RTG was evaluated for the three functional subsystems inherent to the generator, namely mechanical, thermal and electrical.[1] The mechanical subsystem considers the structural integrity of the overall housing and fin assembly to mount the RTG to the spacecraft, to support and constrain the thermoelectric modules and heat shield and to seal the internal T/E converter cover gases under the mission environments. The thermal subsystem considers the functions of "heat generation" within the isotopic fuel capsule, "heat conduction" through the thermal distribution sleeves and heat shield, and "heat rejection" through the module cold end bars and radiating fins. The electrical subsystem relates to the generation of electrical power "electric-generate" utilizing the thermoelectric (T/E) couples and conduction of the power to the electrical power receptacle as "electrical-conduct."

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(1) No reliability analysis was performed on the AGE.

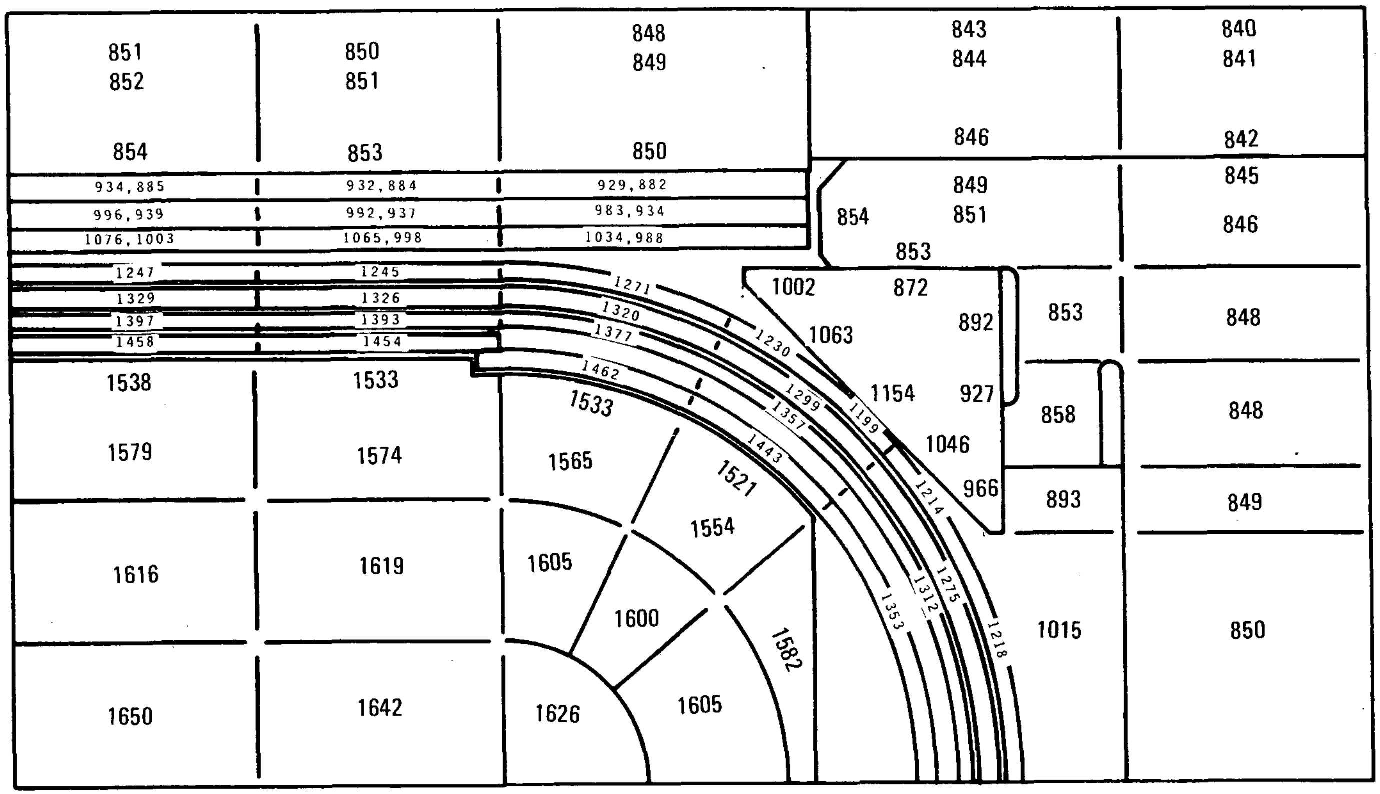


FIG. IV-21. SNAP 19/PIONEER HEAT SOURCE TEMPERATURE DISTRIBUTION 650 W. THERMAL INVENTORY 75% He - 25% Ar FILL GAS; AVERAGE SURFACE TEMPERATURE 850°F

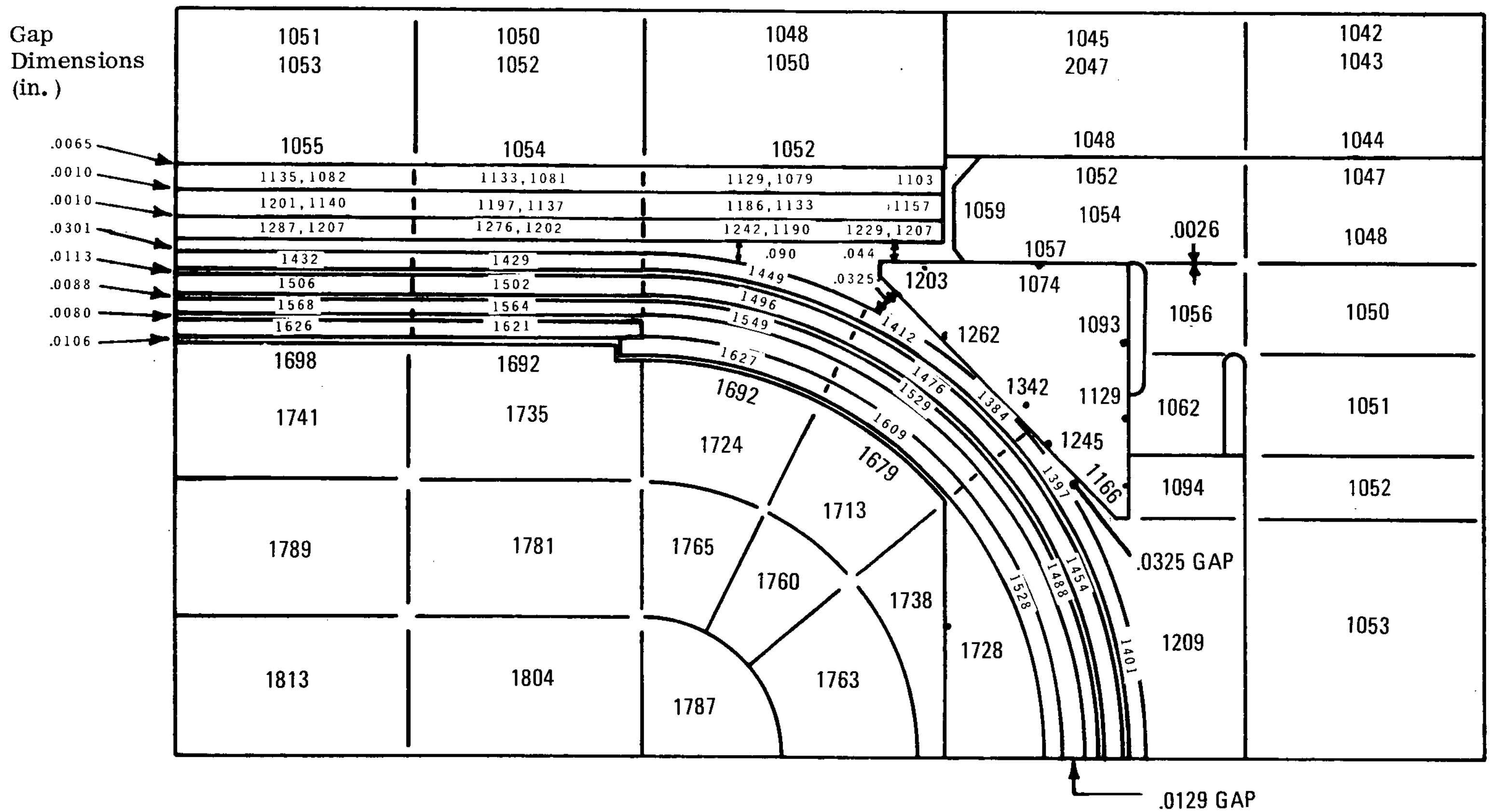


FIG. IV-22. SNAP 19/PIONEER HEAT SOURCE TEMPERATURE DISTRIBUTION T-111 CAPSULE DESIGN WITH .005" Mo-50Re FOIL; 650 W THERMAL INVENTORY 75% He - 25% Ar FILL GAS; SURFACE TEMPERATURE = 1050°F

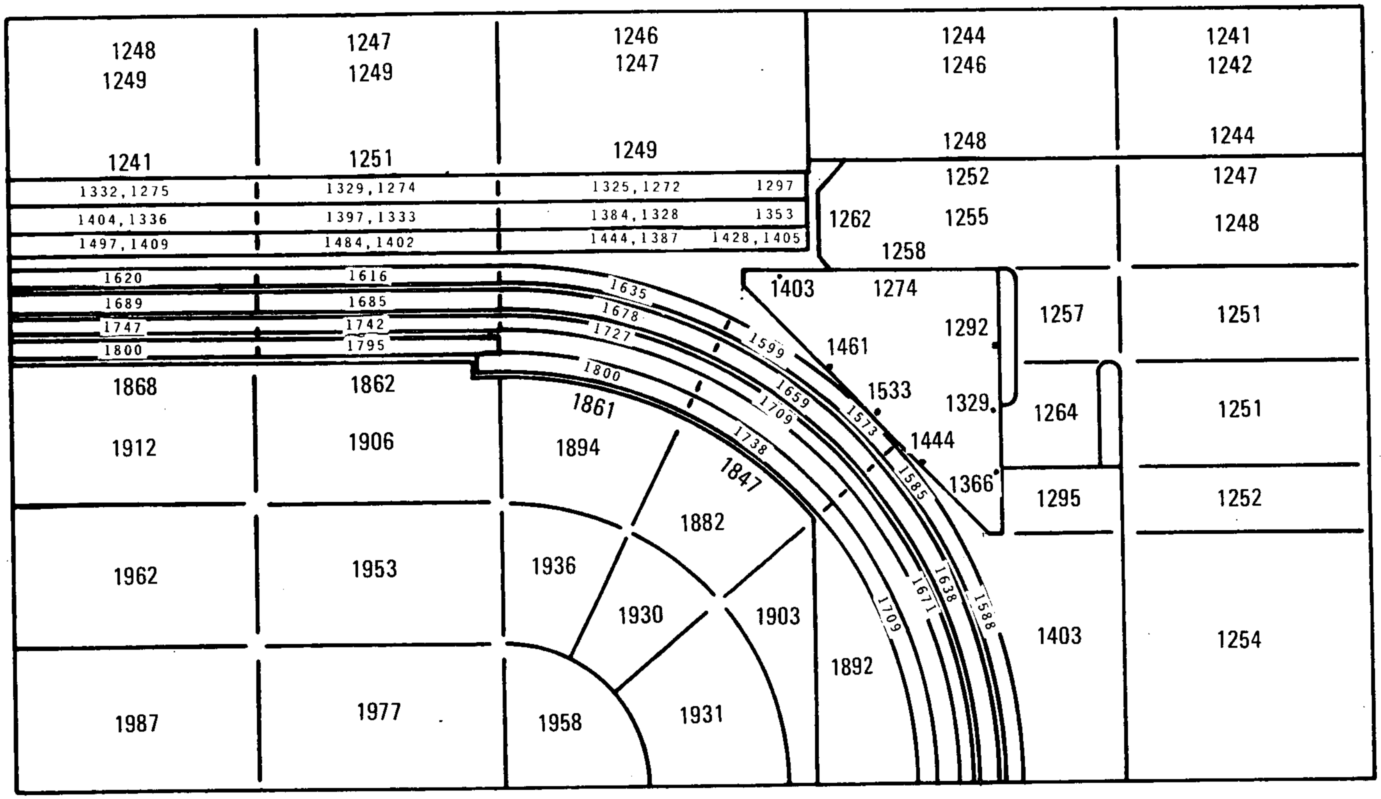
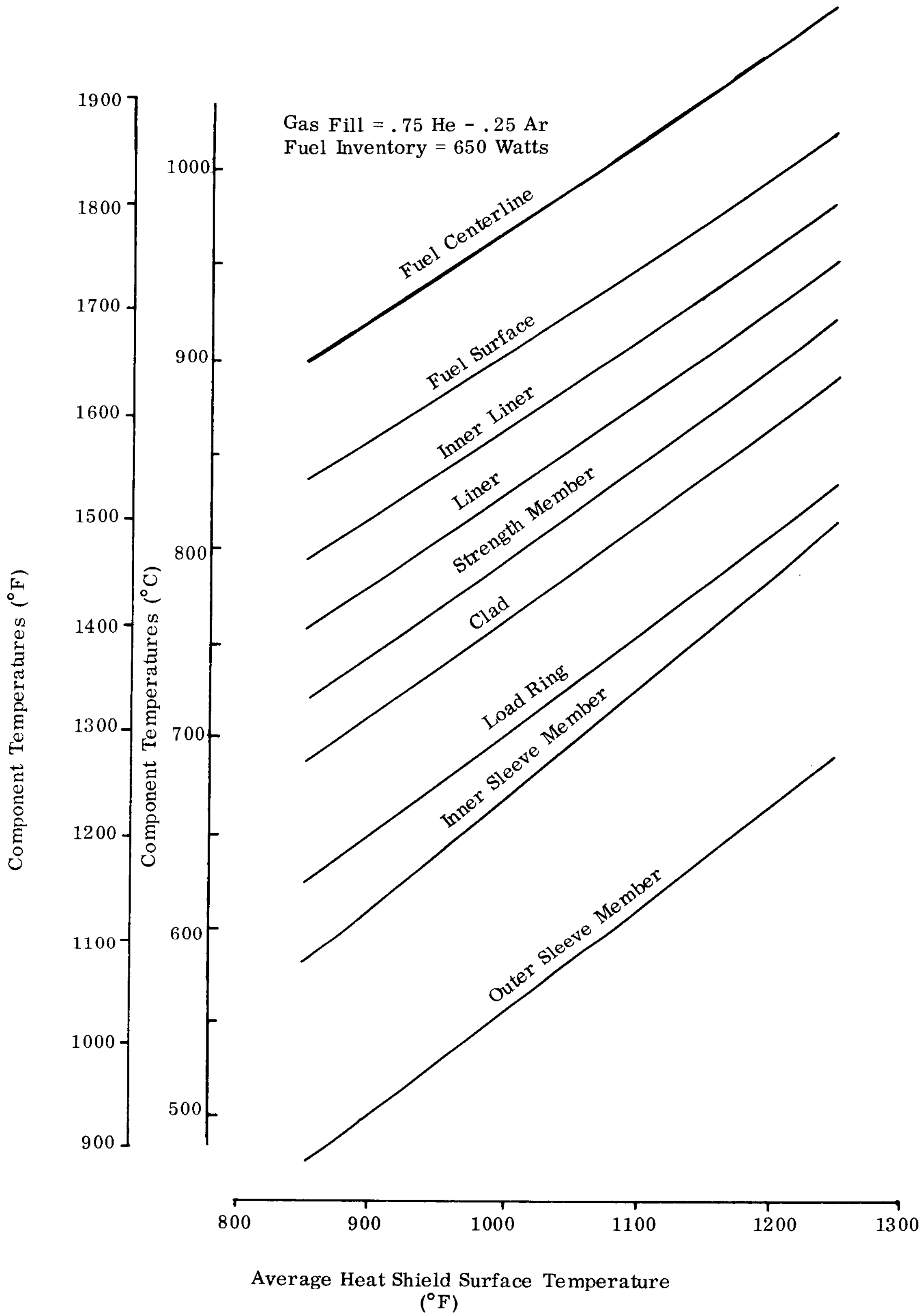


FIG. IV-23. SNAP 19/PIONEER HEAT SOURCE TEMPERATURE DISTRIBUTION 650 W THERMAL INVENTORY 75% He - 25% Ar FILL GAS: AVERAGE SURFACE TEMPERATURE 1250°F

FIG. IV-24. MAXIMUM HEAT SOURCE TEMPERATURES



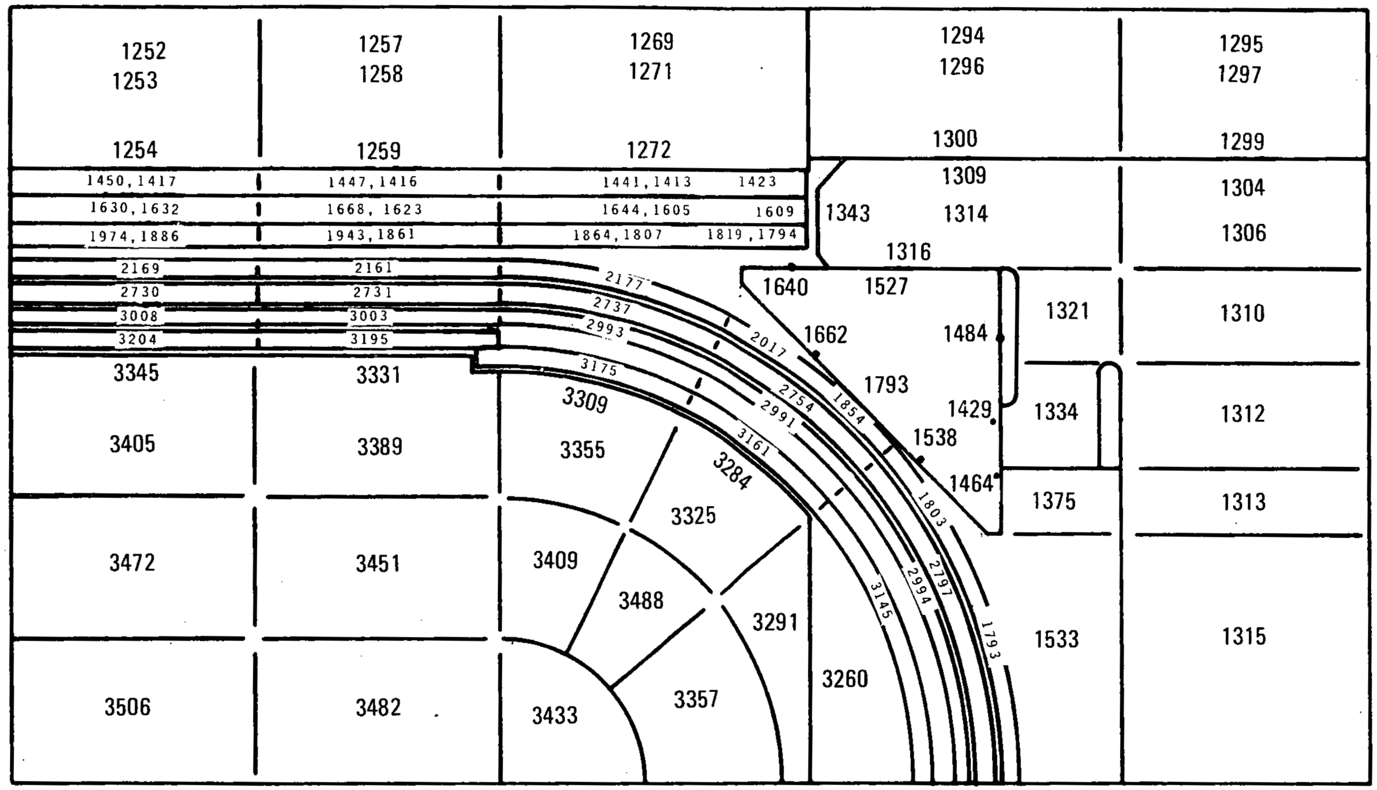


FIG. IV-25. SNAP 19/PIONEER HEAT SOURCE TEMPERATURE DISTRIBUTION
RTG INTERNAL VACUUM: VACUUM IN ALL GAPS OF HEAT SOURCE
FUEL INVENTORY = 650 W TFIN ROOT = 330°F RTG CIRCUIT ON LOAD

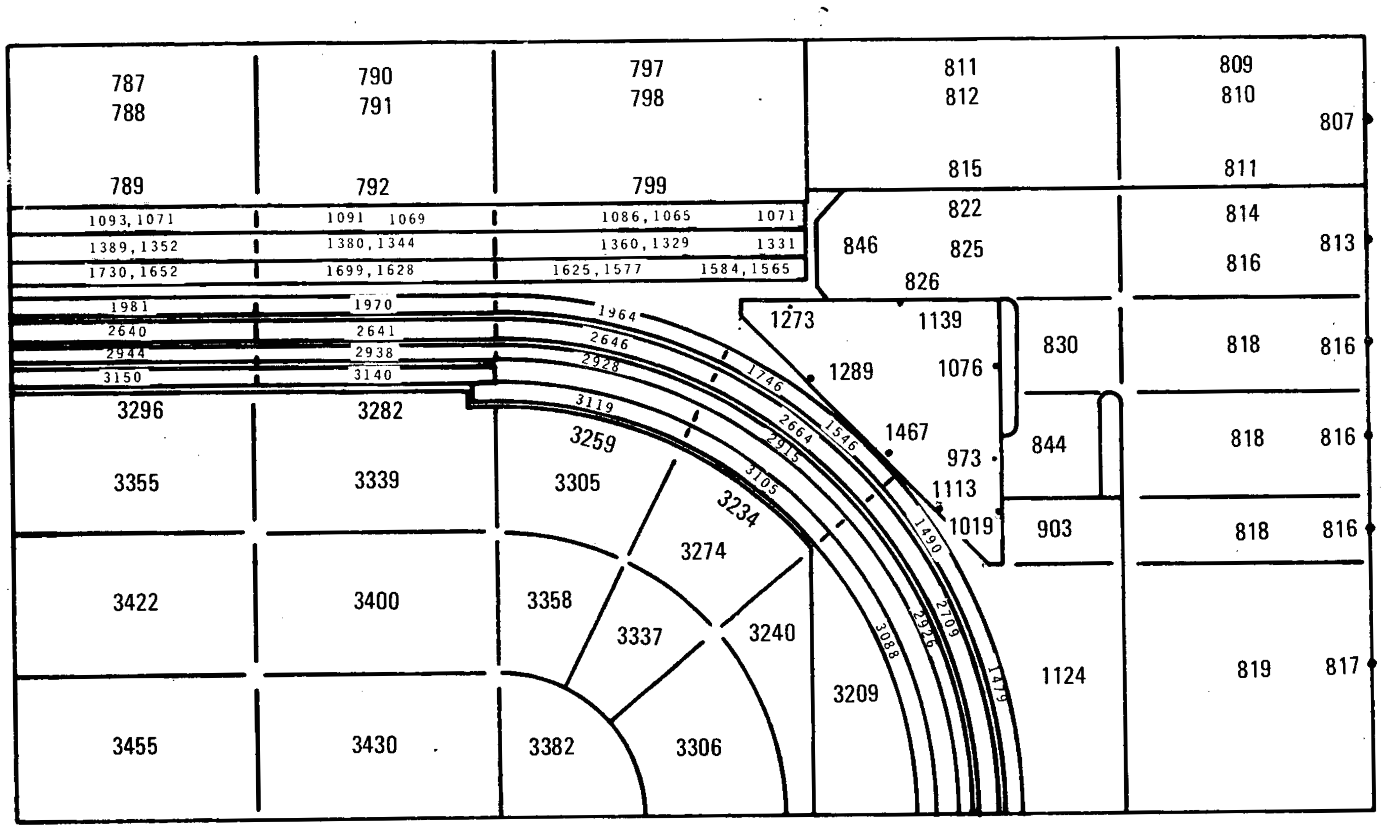


FIG. IV-26. SNAP 19/PIONEER HEAT SOURCE TEMPERATURE DISTRIBUTION
HEAT SOURCE VIEWING SPACE; VACUUM IN ALL GAPS
SINK TEMPERATURE = -460°F FUEL INVENTORY = 650 W

RTG Subsystem Failure Mode and Effect Analysis

(a) Mechanical

The mechanical subsystem has two primary catastrophic failure modes: loss of structural integrity and loss of T/E converter gas.

Structural failure of the RTG may result at the mounting lugs or fins, at the fuel capsule heat shield support and the preloaded Min-K insulation and at capsule support within the heat shield due to flight dynamic stresses encountered at earth launch, booster staging and from internal pressure exerted by the cover gas. Other structural loads are imposed by springs in the thermoelectric conversion system and preload forces for the heat source assembly. The design provides a minimum 1.5 safety factor on all loads generated by internal gas, springs, Min-K preload and acceleration loads using the 90 percentile allowable material strength from MIL-HDBK-5A. Using a worst case, all safety margins have a positive value. The structural analysis is supported by a pressure test to failure of a Pioneer housing. It failed at 360 psi where the failure occurred by pullout of the Rosan inserts used in conjunction with bolts to attach the cover to the housing. The normal operating perssure and mechanical loads in the RTG have a significant margin over the above test failure point of 360 psi.

The loss of the converter cover gas results from a leak in the housing assembly cover and related seal areas. The critical leak areas are shown in Table IV-5.

TABLE IV-5

SINGLE LEAK FAILURE POINTS

	Quantity
Viton O-ring (electrical receptacle seal)	1
Electrical receptacle (glass insert seal)	1
Housing material	1
Cover material (upper and lower)	2
Lower cover/housing weld	2
Upper cover/housing weld	2
Lower cover purge tube welds	2
Upper cover evacuation tube welds	2
	13

Of these, the electrical receptacle and Viton O-ring constitute, by far, the highest contribution to loss of the cover gas.

(b) Thermal

The thermal subsystem has three catastrophic failure modes: loss of isotope fuel source, loss of thermal circuit and loss of heat rejection.

Loss of the thermal energy source is considered to have an extremely low failure probability insofar as it contributes to the loss of electrical power. Heat will be produced regardless of the integrity of the fuel capsule. Capsule integrity is assured by the inherent margins included in the design as a result of nuclear safety criteria. The safety dictated design criteria require fuel containment under considerably more rigorous environment conditions than those encountered during normal mission conditions and are dictated primarily by environments which include launch accidents, atmosphere reentry heating and earth impact.

Heat conduction from the fuel capsule to the T/E couples which bear against the six flat sides of the heat shield is highly redundant. Ample experience confirms the reliability of Min-K and microquartz insulation to channel heat through the T/E elements. The high number of multiple paths assures heat flow to the thermoelectric couples. Mechanical failures, other than total disintegration, will impact the uniformity of the heat distribution.

The heat rejection function includes the cold end hardware which consists of module bars, alignment buttons, pistons, springs, and the housing/cooling fins. These hardware items perform the function of rejecting the waste heat from the T/E couples to ambient environments.

The thermal subsystem has no critical design areas due to the reliability of the heat source and the high number of redundant paths.

(c) Electrical

The electrical subsystem is composed of two functions of "generate" and "conduct." The electric generate function consists of the six thermoelectric module-90 T/E couple network. The failure probability of the T/E couple network is related primarily to the open circuit mode. Short circuits are extremely improbable due to the physical configuration employed in the design of the module. The T/E network design employs both mechanical and electrical redundancy. Connections between the thermoelectric couples are redundant by virtue of the series-parallel ladder network. Each couple connection, in addition to being bonded, is pressure-loaded through a piston spring arrangement which minimizes the resistance in the thermal path and provides mechanical redundancy to the bonded connections through pressure loading.

The design may tolerate a number of individual couple failures without resulting in an open circuit. A failure results in a step reduction in available power nearly double that which would be expected for a single couple failure since it affects the heat flow and resistance of the adjacent couple in the parallel branch. Over 75 million couple hours, with associated pistons and springs, have been accumulated in generators having series connected couples without a countable open circuit failure.

The electrical-conduct function comprises the wiring and connections. The failure probability is related to the open and short circuit modes. Three factors have been considered with relation to these modes: (1) mechanical strength of the electrical conduction in relation to routing and support; (2) electrical insulation characteristics of the wire in relation to temperature and environmental gases; and (3) the types of termination devices and the method by which they are applied. The heavy nine gauge wire conductor used in the generator and the supporting and routing of these conductors which are buried in Min-K and other insulating materials greatly minimize the possibility of a failure due to the first two factors.

The design incorporates nine redundant circuits through the electrical receptacle for both the positive and negative leads. Two series and three parallel connections are used to interconnect the receptacle and the six modules. The two series connections are identified critical design areas for the open failure mode. Rigid in-process controls have been applied to this area. Table IV-6 is a summary of the catastrophic failure mode analysis for the RTG broken down by subsystem.

The most critical design areas relate to the loss of T/E converter cover gas during space operation. The primary contribution to this loss is associated with the electrical receptacle/O-ring seal installation. For the Pioneer 11 RTG's the receptacle shell material was changed from 321 type to a 20CB3 type shell material to provide a higher design margin between mission operating temperatures and temperature at which the receptacle leaks. In addition, the Viton V77-545 O-ring material was replaced with a V747-75 material for reduced compression set at elevated temperatures and time. Tests have demonstrated a considerable design margin improvement. No failures have been experienced. Twenty receptacles have accumulated an average of 5000 hours at 370°F and eight of these have seen an average of 1200 thermal cycles between 370-150°F. Eighteen O-rings have accumulated an average of 8000 hours between 360 and 400°F and six of these have seen an average of 350 thermal cycles between 365-140°F. These test temperatures are well in excess of those seen by the receptacle seal installation in the Flight 10 and 11 RTG's which is less than 330°F.

TABLE IV-6

RTG FAILURE MODE AND EFFECTS SUMMARY

Mechanical	
Loss of T/E converter cover gas	Leak in housing/cover/seals, i.e., welds, O-ring, receptacle.
Loss of structural integrity	Physical damage from dynamic environmental forces.
Thermal	
Loss of isotope fuel source	
Loss of thermal circuit	Negligible effect and low probability of occurrence.
Loss of heat rejection	
Electrical	
Loss of electrical power circuit	Open in T/E couple redundant network.
	Open in receptacle, intermodule wiring.
	Insulation breakdown between RTD and T/E couple circuit.
	Insulation breakdown between T/E couple circuit and RTG structure.

2. Fabrication Control

An in-process manufacturing test and control program was established to assure that the quality of the RTG components was compatible with the high reliability goal. Tests and controls were established for all component parameters which significantly contributed to variation of power. Fuel capsule inventory, converter gas leak rates and other power parameters were treated using parameter variation and statistical methods. Certain results are presented in the previous section on power performance. The thermoelectric program which was considered to be the major contributor to performance is described herein.

Table IV-7 presents a summary of the in-process thermoelectric product manufacturing control program. It lists the component identity (generator, module, couple, element), the type test performed (power, resistance, voltage, resistivity), the test conditions (sequence, assembly stage, etc.), the test criteria, test sampling (quantity, individual or lot rejection, etc.), the statistical characteristics computed (Pioneer "F" and "G" generators (10) for comparison with the Pioneer 10 (4) and Pioneer 11 (4) flight RTG's). The program starts at the acceptance level of the thermoelectric couple elements and progressively follows through the assembly of the couples, modules, through the final assembly of the generator.

A compression of the electrical parameter statistical results obtained on thermoelectric elements, couples, modules and generators during fabrication, assembly and acceptance tests on the ten Pioneer "F" and "G" series RTG's with the statistical results of the four Pioneer 10 and the Pioneer 11 flight RTG's groups is presented. The results show the power is equal or less than one standard deviation from the mean of the contract acceptance requirements of 38.0 to 42.5 watts. The average values for all other electrical parameters of these two flight groups also exhibits little difference from the results for all ten RTG's. In all cases, the results are within one standard deviation.

3. Assessed Operating Reliability

The SNAP 19 generators S/N 1 through 53, S/N 100 through 102 and HPG S/N 001 have accumulated over 600,000 generator operating hours through April 30, 1973 without a countable catastrophic failure. These hours are projected to increase to slightly over one million by Pioneer 11 Jupiter encounter in December 1974. Pioneer generator hours alone (S/N 32 through S/N 53) are 200,000 by April 30, 1973, and 380,000 by December 1974.

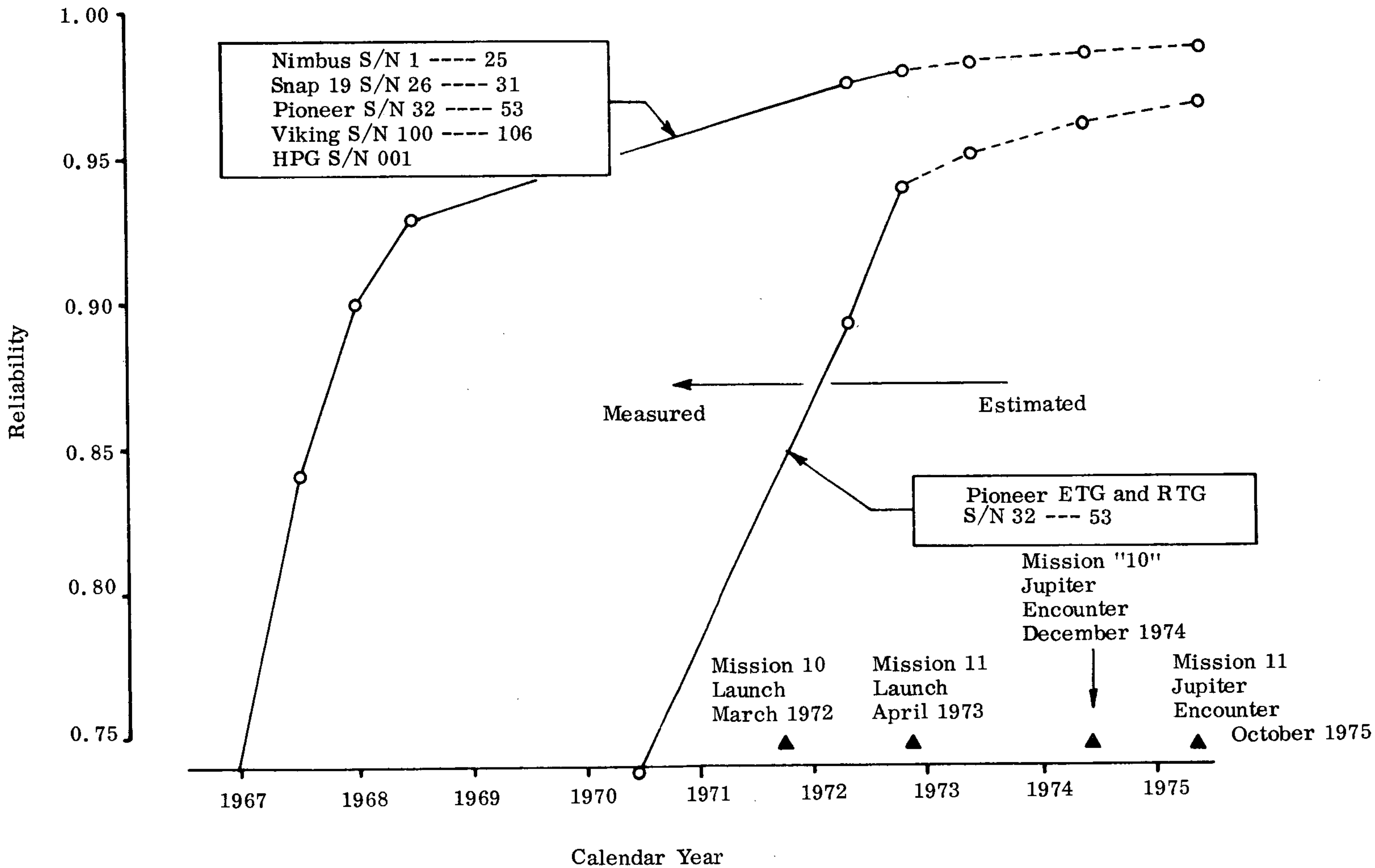
Demonstrated RTG reliability is computed (at 50% confidence) to be 0.98 for the 600,000 hour experience and 0.94 for the 200,000 hour experience. By December 1974, the demonstrated reliability is expected to increase to 0.99 when all SNAP 19 generators are considered and 0.97 for the Pioneer generator experience only.

The foregoing data is included in Figure IV-27.

TABLE IV-7 IN-PROCESS THERMOELECTRIC PRODUCT MANUFACTURING CONTROL

Component Identity	Test Type	Test Conditions	Test Criteria	Test Sampling	Statistical Characteristics Pioneer F & G	Pioneer 10	Pioneer 11
Generator	Power (watts)	Acceptance Test After Thermal Vacuum	Range 38.0 - 42.5 Ref. to 337°F Fin Root	100% Individual Rejection	$\bar{x}$ = 40.13 s = 0.4570 r = 39.1-41.1 n = 10 s/$\bar{x}$ = 0.0114	$\bar{x}$ = 40.6 s = 0.392 s/$\bar{x}$ = 0.010	$\bar{x}$ = 40.0 s = 0.294 s/$\bar{x}$ = 0.007
	Resistance (Milliohms)	Performed at Final Assembly Measured at Electrical connector in ambient Temperature	73.7 Maximum Corrected to 75°F	100% Individual Rejection	$\bar{x}$ = 70.55 s = 0.7757 r = 69.0-71.6 n = 10 s/$\bar{x}$ = 0.0110	$\bar{x}$ = 70.1 s = 1.036 s/$\bar{x}$ = 0.015	$\bar{x}$ = 70.85 s = 0.810 s/$\bar{x}$ = 0.0110
Module	Resistance (Milliohms)	Performed After Module Bonding In Ambient Temperature	14.4 Maximum Corrected to 75°F	100% Individual Rejection	$\bar{x}$ = 13.61 s = 0.2324 r = 12.64-14.26 n = 60 s/$\bar{x}$ = 0.0171	$\bar{x}$ = 13.55 s = 0.2206 s/$\bar{x}$ = 0.0163	$\bar{x}$ = 13.62 s = 0.301 s/$\bar{x}$ = 0.0221
Couple	Power (watts)	Performed at 1050/400 of and Matched Load subsequent to Ambient Temperature Resistance Test	0.535 Minimum Corrected to 1050/400°F	Sample (2) 5-15 (3) 16-50 (4) 51-90	$\bar{x}$ = 0.567 s = 0.0132 r = 0.534-0.593 n = 90 s/$\bar{x}$ = 0.0233	$\bar{x}$ = 0.568 s = 0.006 s/$\bar{x}$ = 0.011	$\bar{x}$ = 0.568 s = 0.010 s/$\bar{x}$ = 0.018
Couple	Resistance (Milliohms)	Performed at 75 ± 5°F Temperature Prior to Power Test Includes Total Couple and both Legs	2.75 Maximum	100% Individual Rejection	$\bar{x}$ = 2.504 s = .0442 r = 2.27-2.67 n = 1250 s/$\bar{x}$ = .0176	$\bar{x}$ = 2.524 s = 0.035 s/$\bar{x}$ = 0.014	$\bar{x}$ = 2.505 s = 0.046 s/$\bar{x}$ = 0.019
TAGS-85 Element	Seebeck Voltage (Millivolts)	Performed at 900/150 °F Subsequent to Annealing of the completed elements	Range 60.0-71.0	AQL=1.00 Lot Rejection	$\bar{x}$ = 65.12 s = 0.629 r = 60.7-68.9 n = 170 s/$\bar{x}$ = 0.010	$\bar{x}$ = 64.84 s = 0.576 s/$\bar{x}$ = 0.009	$\bar{x}$ = 65.31 s = 0.207 s/$\bar{x}$ = 0.003
TAGS-85 Element	Resistivity (Microhm-Cm)	Performed at 75 ± 5 °F prior to Seebeck Voltage Test, Test of Element Stick as cast from Material melt.	600 Maximum	AQL=1.00 Average of Three (3) Readings per Stick	$\bar{x}$ = 548.52 s = 8.4751 r = 514-581 n = 304 s/$\bar{x}$ = .0155	$\bar{x}$ = 555.23 s = 7.94 s/$\bar{x}$ = 0.014	$\bar{x}$ = 547.6 s = 10.5 s/$\bar{x}$ = 0.019
2N Element	Seebeck Voltage (Millivolts)	Performed at 900/150 °F Subsequent to Resistivity Test performed in Addition to 3M Co. Tests.	Range 87.0-106.0	AQL=1.00 Lot Rejection	$\bar{x}$ = 90.80 s = 1.9979 r = 86.7-96.0 n = 510 s/$\bar{x}$ = 0.0220	$\bar{x}$ = 91.8 s = 0.85 s/$\bar{x}$ = 0.009	$\bar{x}$ = 91.8 s = 1.98 s/$\bar{x}$ = 0.021
2N Element	Resistivity (Microhm-Cm)	Performed at 75 ± 5°F Temperature prior to Seebeck Voltage Test.	584 Maximum	AQL=1.00 Lot Rejection	$\bar{x}$ = 499.29 s = 21.9735 r = 400-586 n = 370 s/$\bar{x}$ = 0.0440	$\bar{x}$ = 490.0 s = 28.3 s/$\bar{x}$ = 0.058	$\bar{x}$ = 483.0 s = 29.9 s/$\bar{x}$ = 0.062

FIG. IV-27. SNAP 19 PIONEER RTG PREDICTED RELIABILITY AT JUPITER ENCOUNTER (MISSION TIME = 17530 HOURS AND 50% CONFIDENCE LEVEL)



V. GENERATOR TESTING

A. QUALIFICATION AND ACCEPTANCE

Seventeen fueled generators, S/N 37-53, were tested under the Pioneer program. The test descriptions and results for these RTG's are presented below. Detailed test chronologies for all 2N-TAGS SNAP 19 type generators since NIMBUS are presented in Tables V-8 through V-10.

All fueled units were subjected to acceptance level performance tests, leakage tests, vibration, vacuum exposure and radiation survey. Additionally, dynamic qualification testing for shock, vibration and acceleration was conducted on three fueled prototype units, S/N 37, S/N 41 and S/N 42, and one electrically heated generator, S/N 36.

1. Performance Tests

The relationship between output power and load voltage ("parametric test") was measured for all Pioneer generators at least three times before delivery. The first measurement was usually performed within 24 hours after fueling and two more were conducted later during thermal vacuum testing. The last performance test was used for determination of the characteristic power of each generator. Results of these parametric tests in load voltage are presented in Figs. V-1 through V-17. It is apparent that hot junction temperature, internal resistance and open circuit voltage increase with time, and, therefore, the maximum power occurs at higher load voltage with increasing time. A summary of this optimum voltage time behavior is given in Fig. V-18. It is seen (from this logarithmic presentation) that the rate of rise in peak power load voltage dimishes with time, and by delivery (about 1000 hours) a degree of stability is achieved which allows satisfactory characterization of each generator. All data are presented at actual fuel inventory but normalized to a constant fin root temperature of 330°F. The test procedure used is identified in Reference 4.

2. Hot Gas Leakage Tests

Gas leakage measurements were performed following fueling and the weld closure of the RTG upper cover. This was repeated after exposure to dynamic environmental testing and again during operation in the thermal vacuum chamber. Results of post fueling and post

FIG. V-1. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 37
FIN ROOT TEMPERATURE: 330°F
644 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

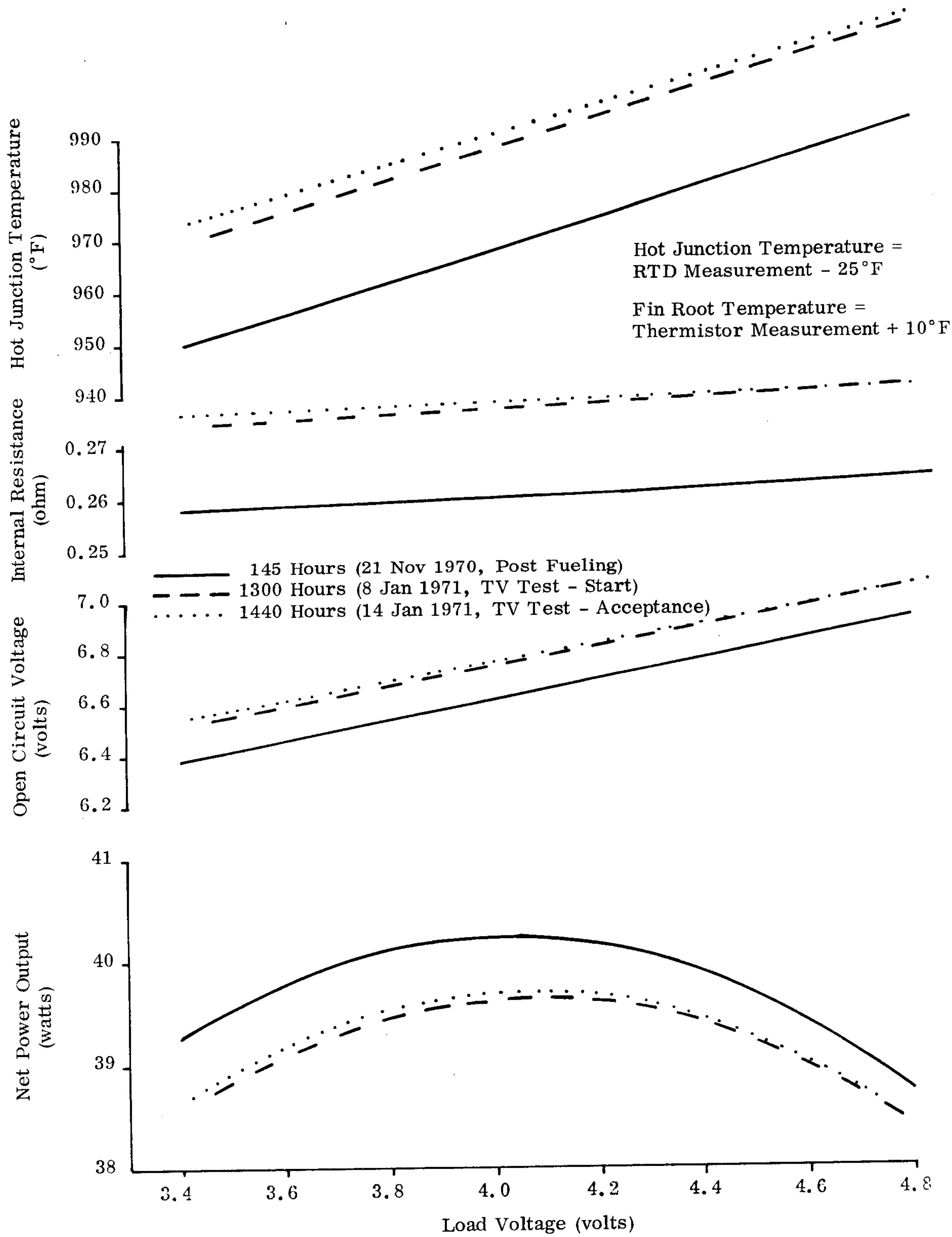


FIG. V-2. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 38
FIN ROOT TEMPERATURE: 330°F
647 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

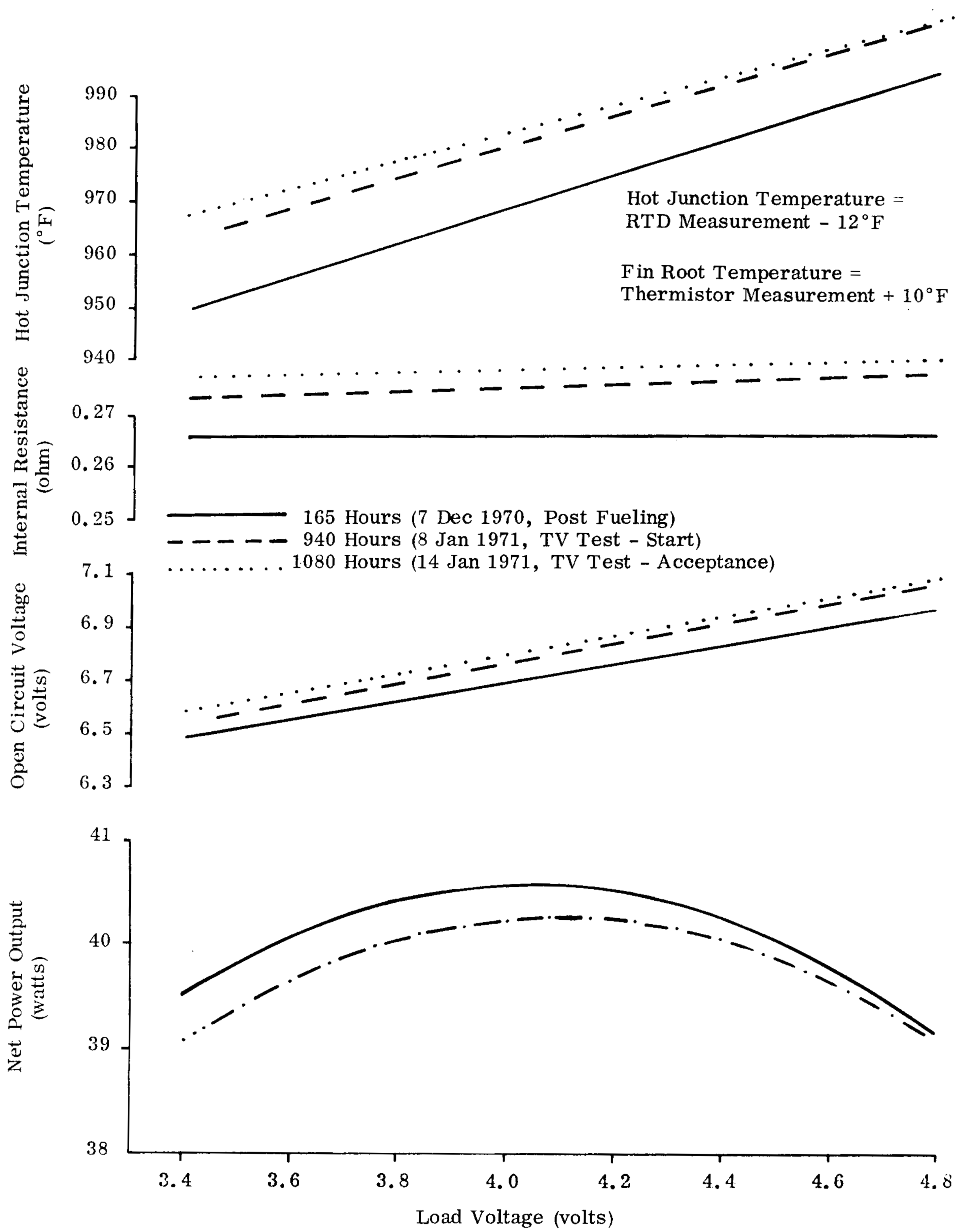


FIG. V-3. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 39
FIN ROOT TEMPERATURE: 330°F
643 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

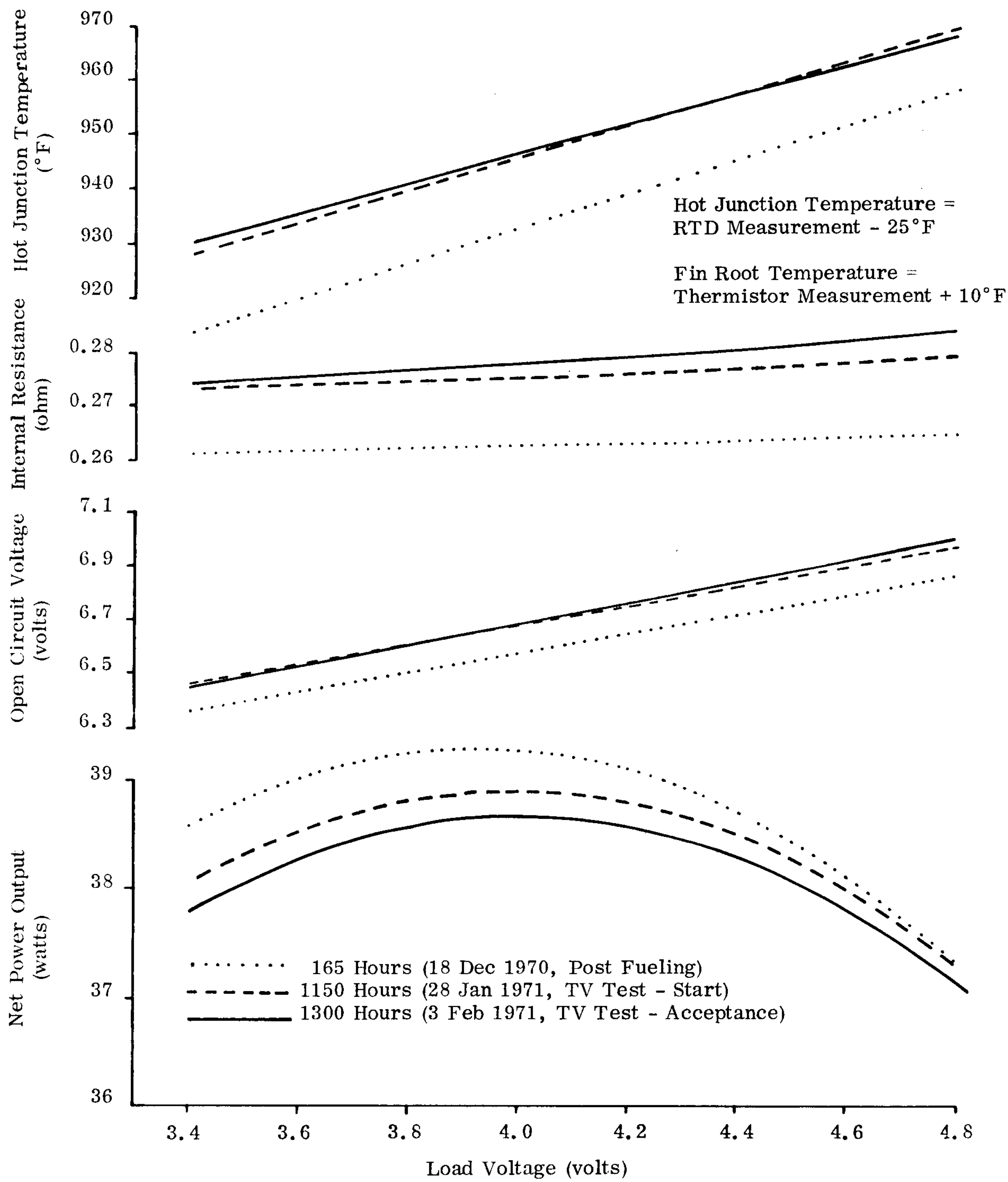


FIG. V-4. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 40
FIN ROOT TEMPERATURE: 330°F
646 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

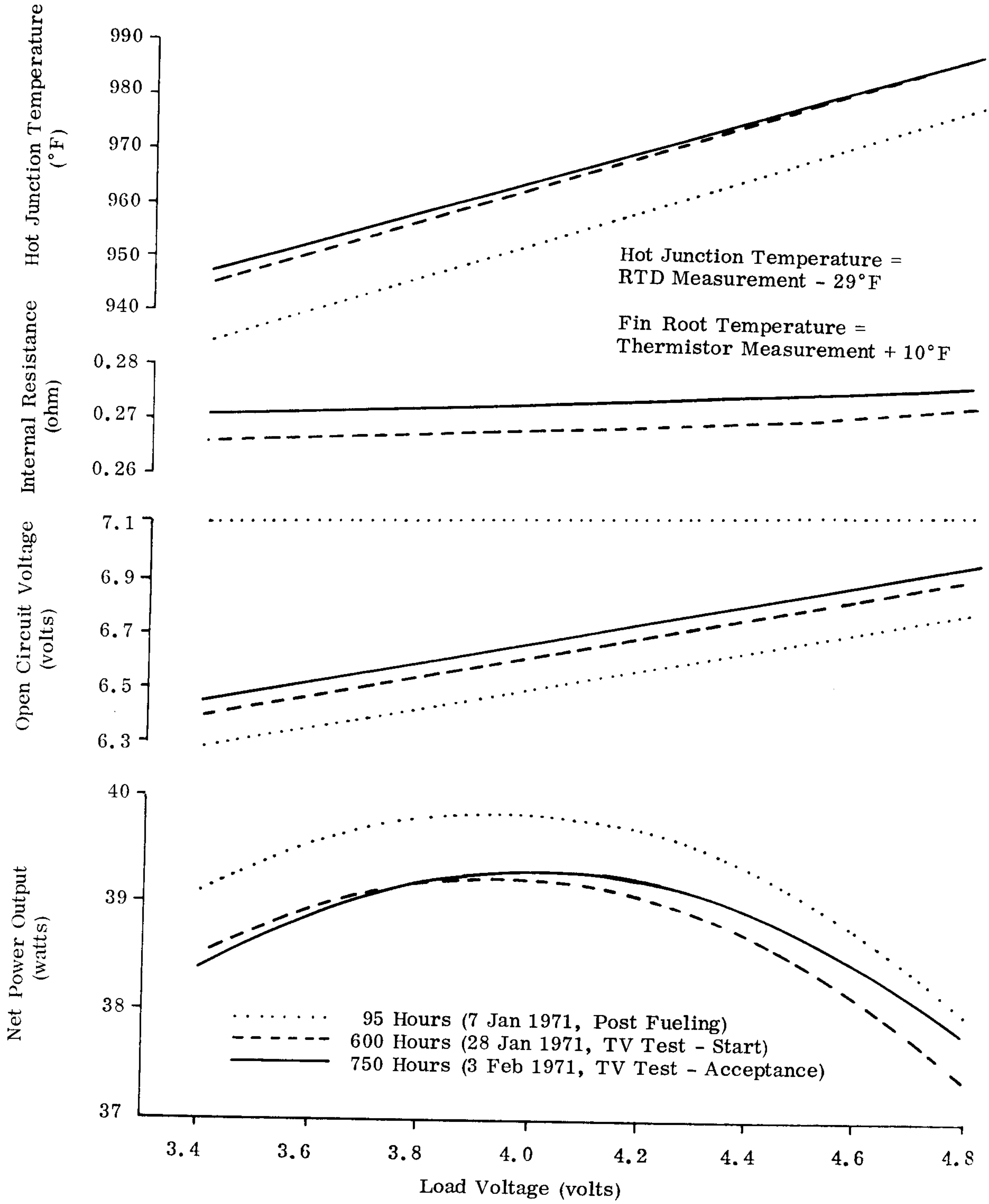


FIG. V-5. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 41
FIN ROOT TEMPERATURE: 330°F
641 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

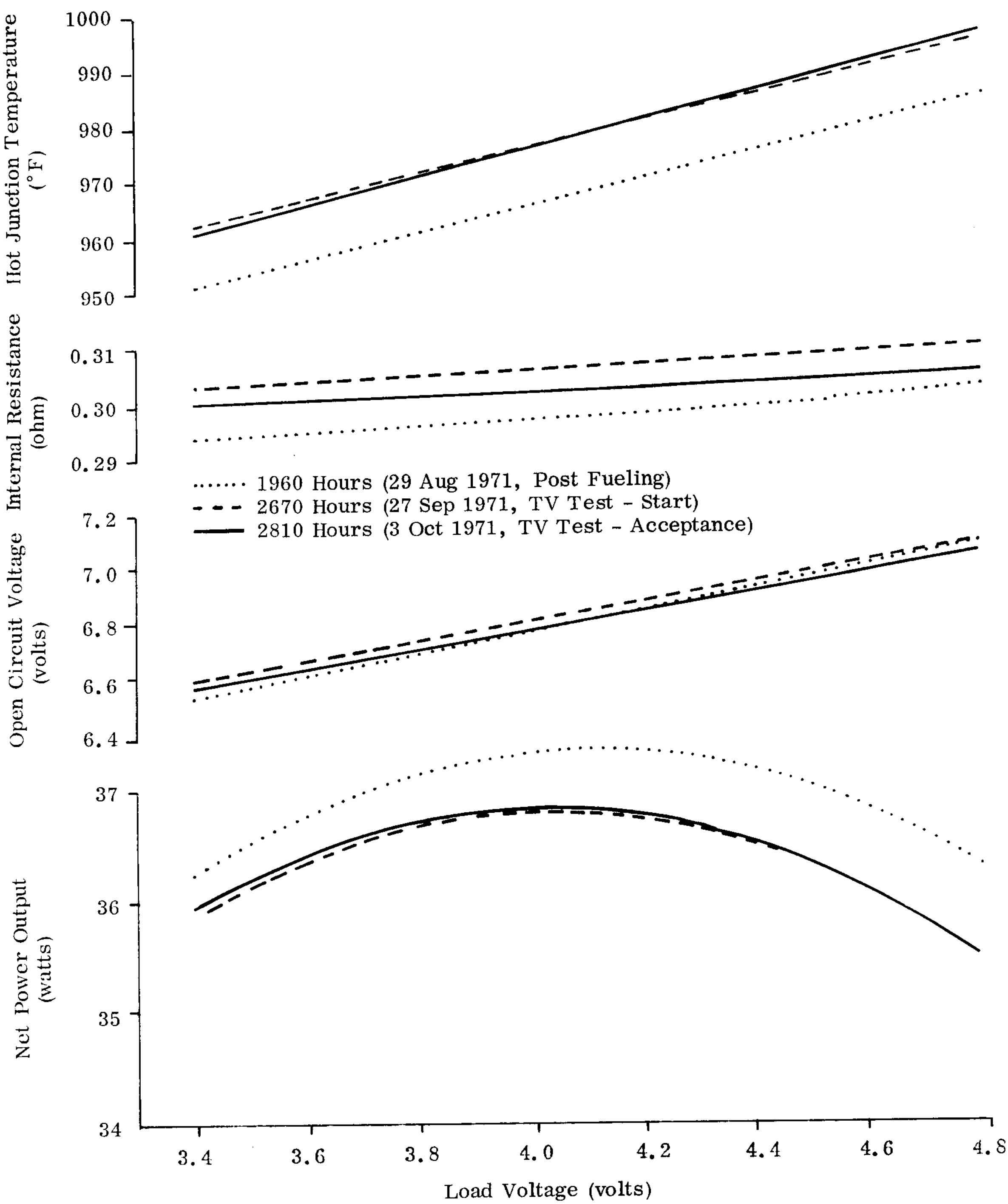


FIG. V-6. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 42
FIN ROOT TEMPERATURE: 330°F
645 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

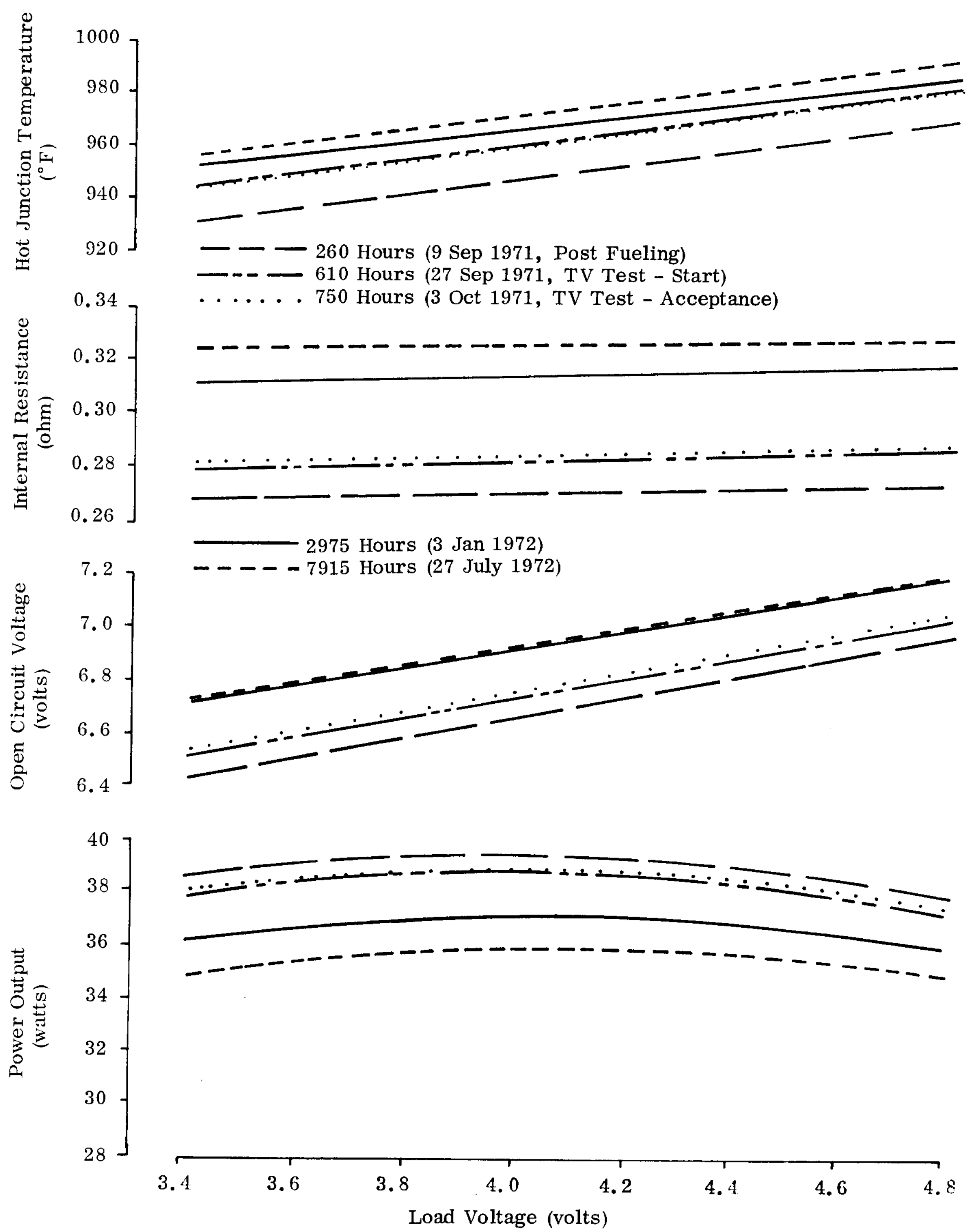


FIG. V-7. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 43
FIN ROOT TEMPERATURE: 330°F
648 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

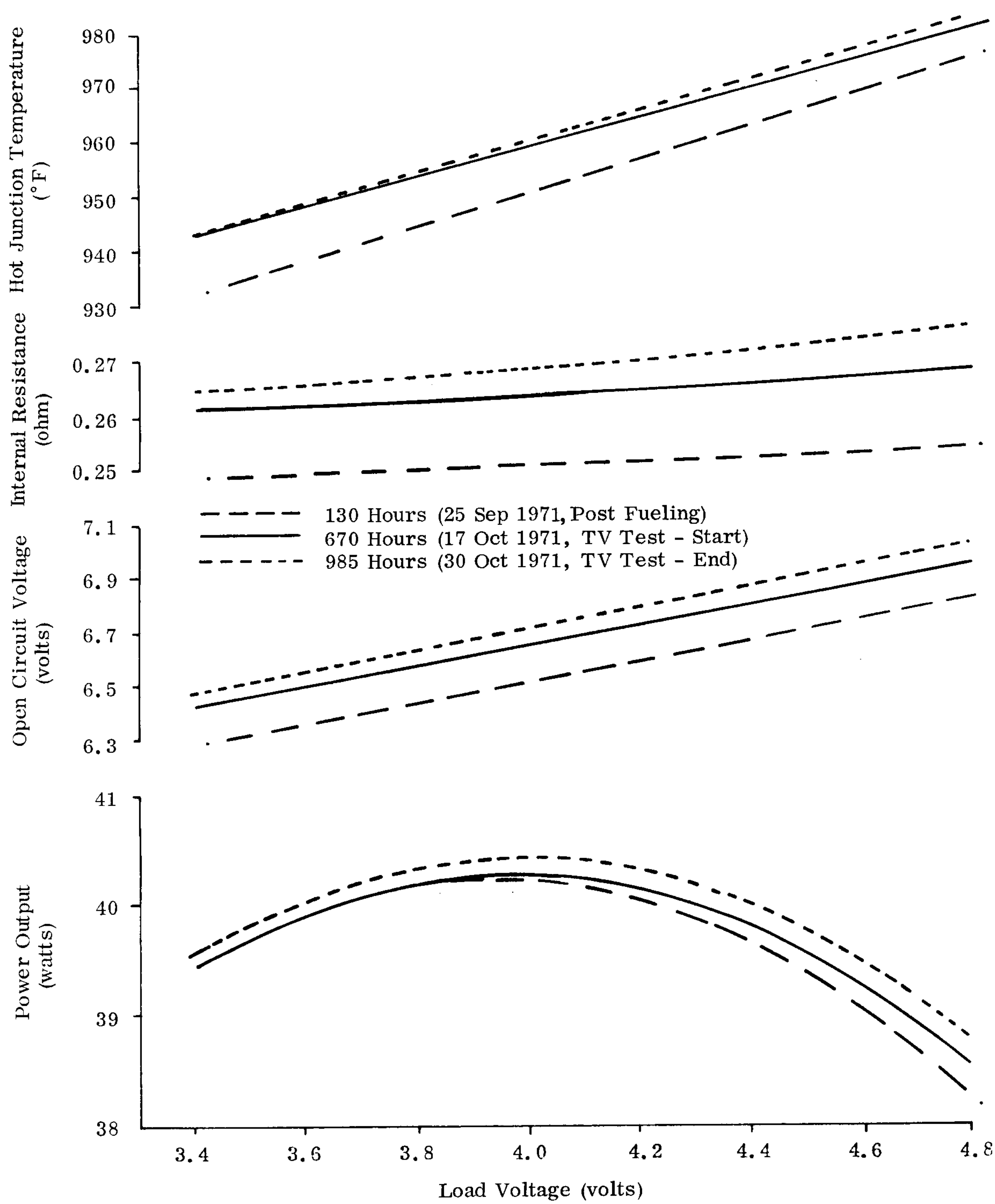


FIG. V-8. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 44
FIN ROOT TEMPERATURE: 330°F
649 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

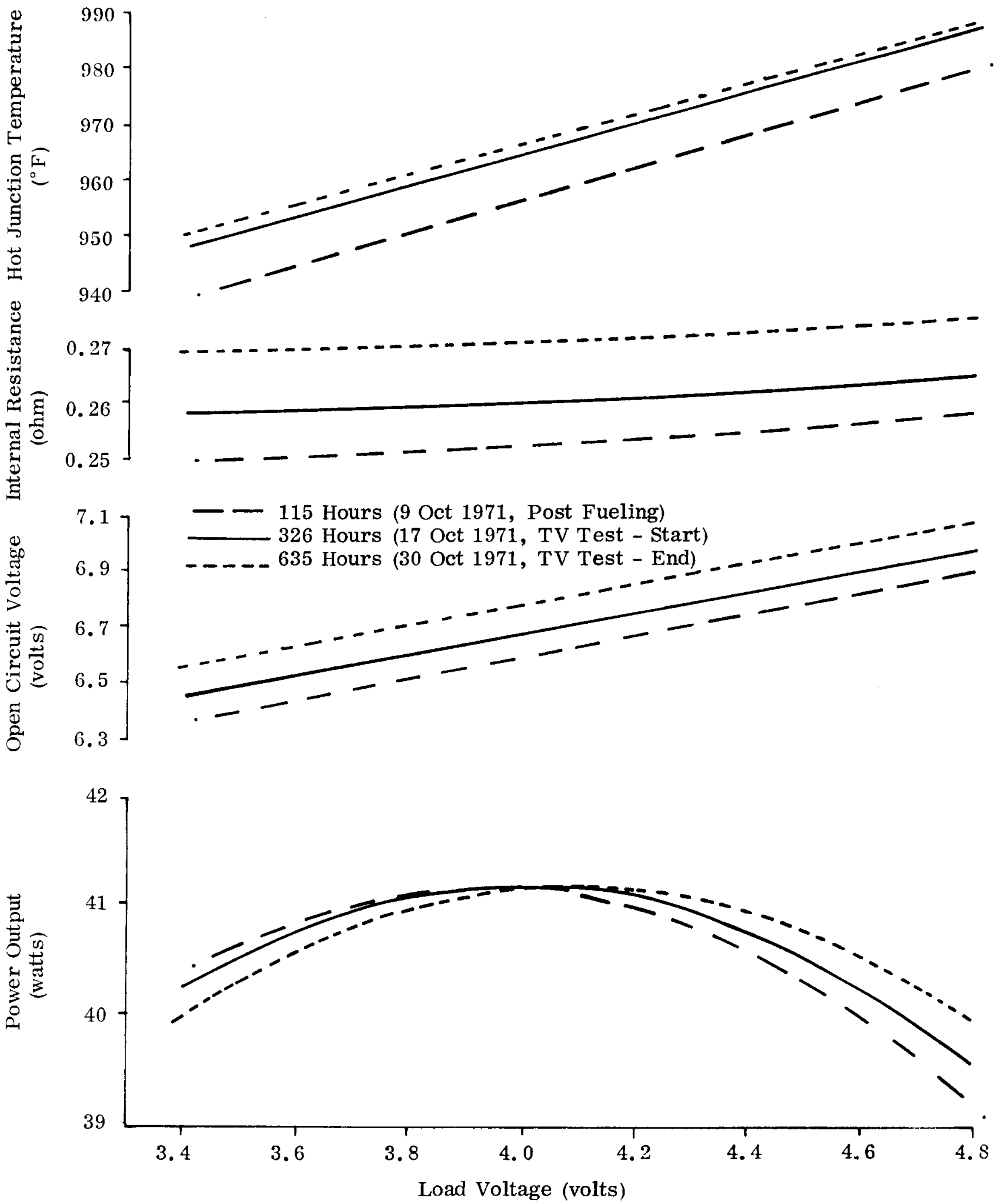


FIG. V-9. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 45
FIN ROOT TEMPERATURE: 330°F
646 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

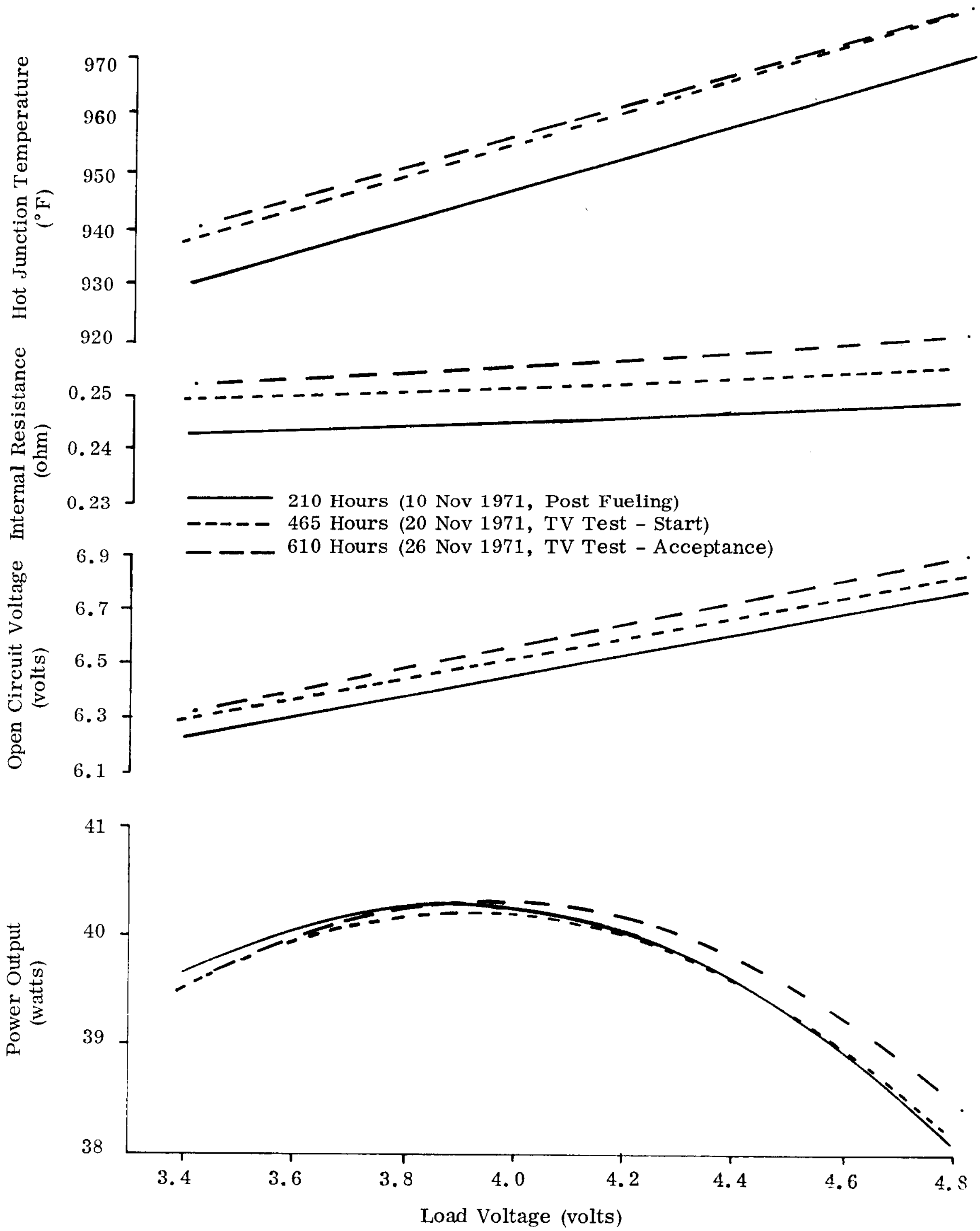


FIG. V-10. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 46
FIN ROOT TEMPERATURE: 330°F
647 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

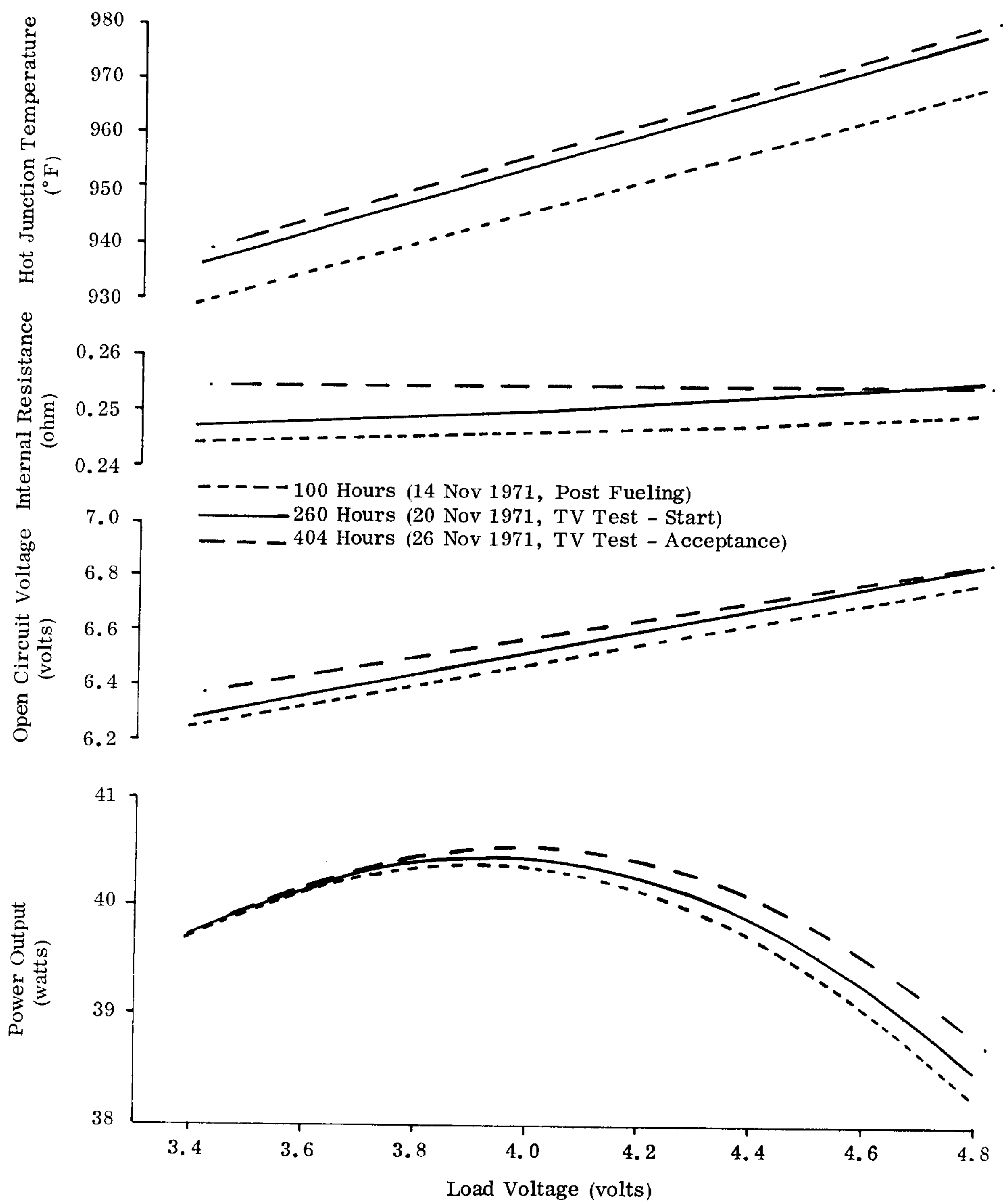


FIG. V-11. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 47
FIN ROOT TEMPERATURE: 330°F
647 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

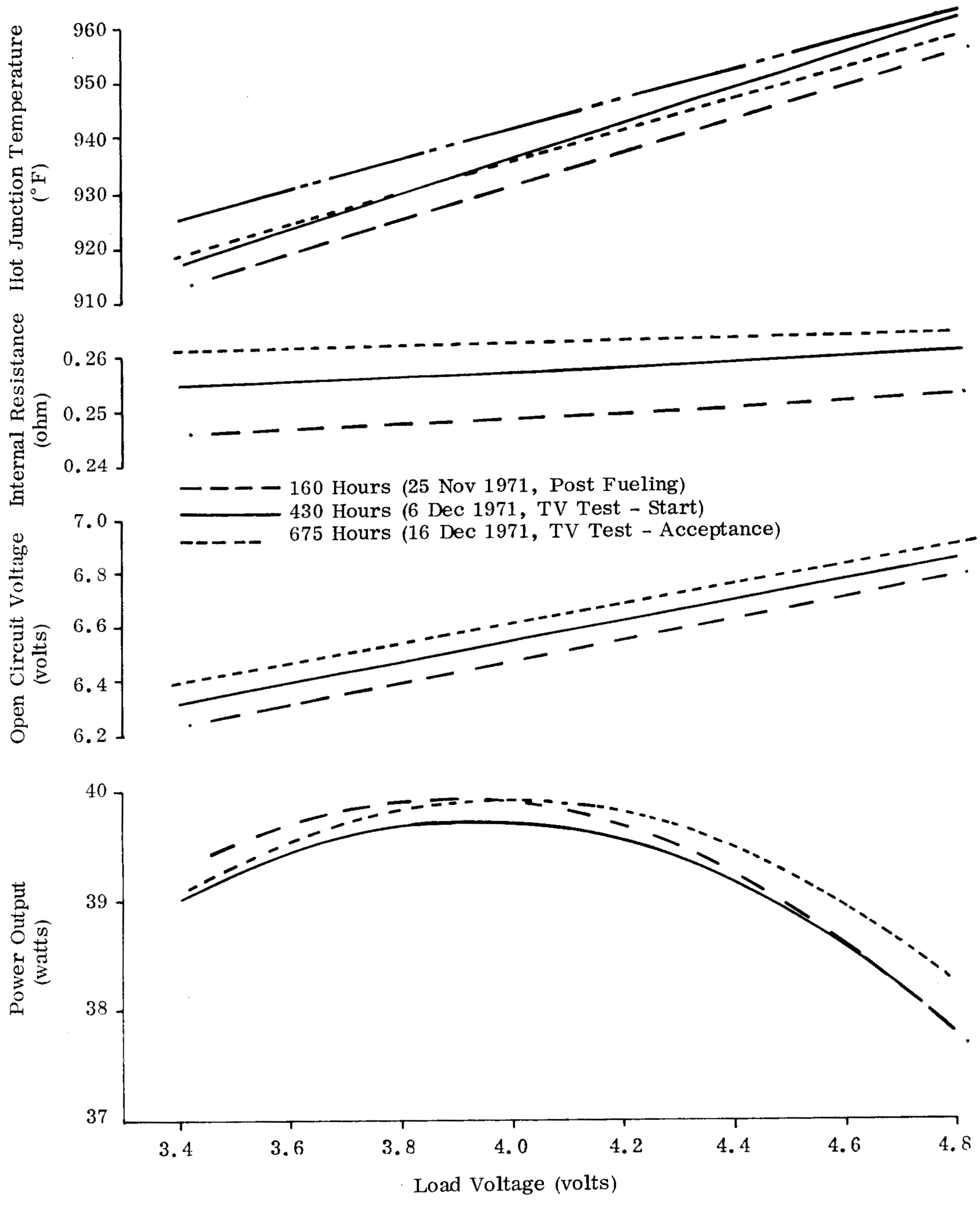


FIG. V-12. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 48
FIN ROOT TEMPERATURE: 330°F
649 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

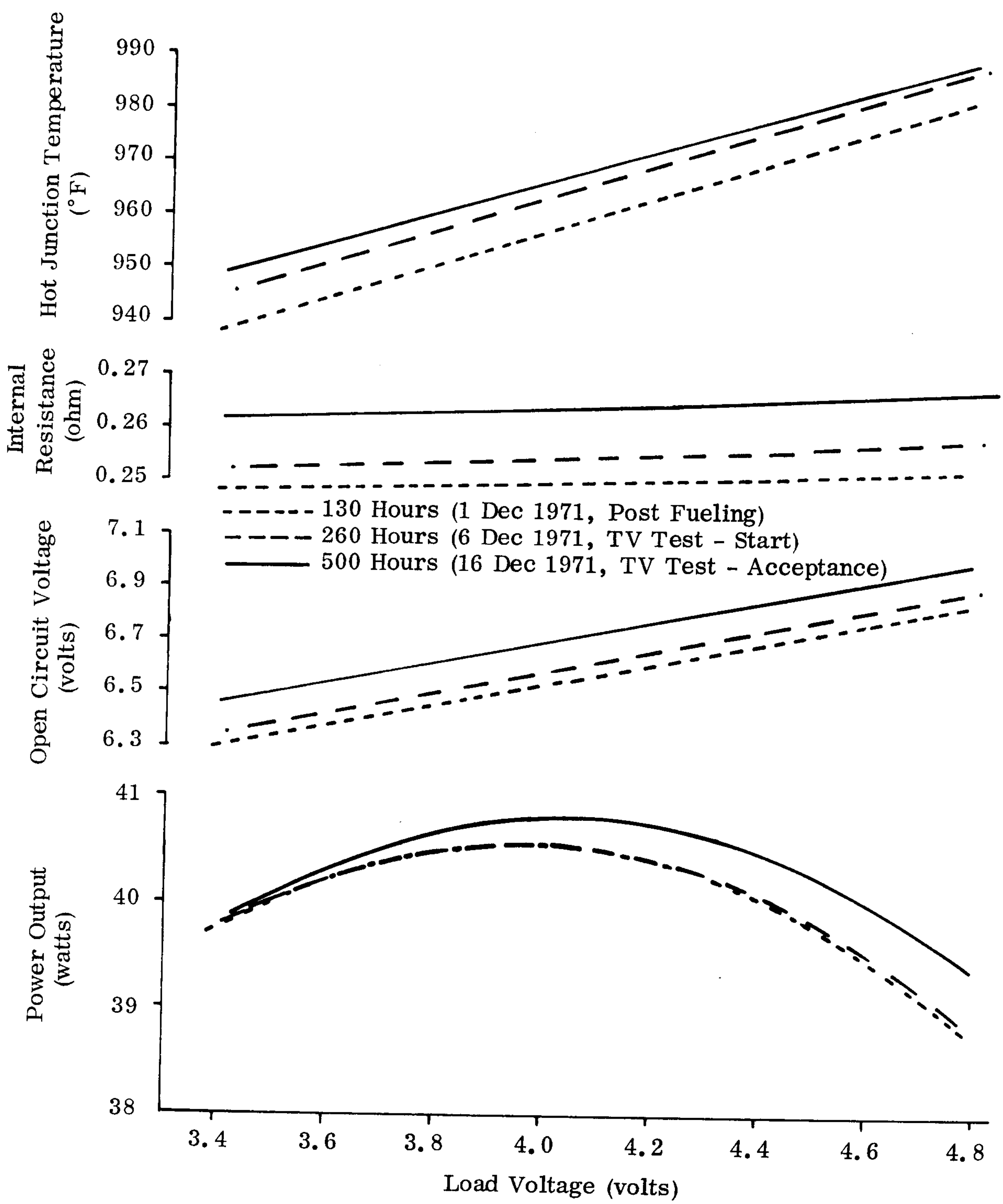


FIG. V-13. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 49
FIN ROOT TEMPERATURE: 330°F
649 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

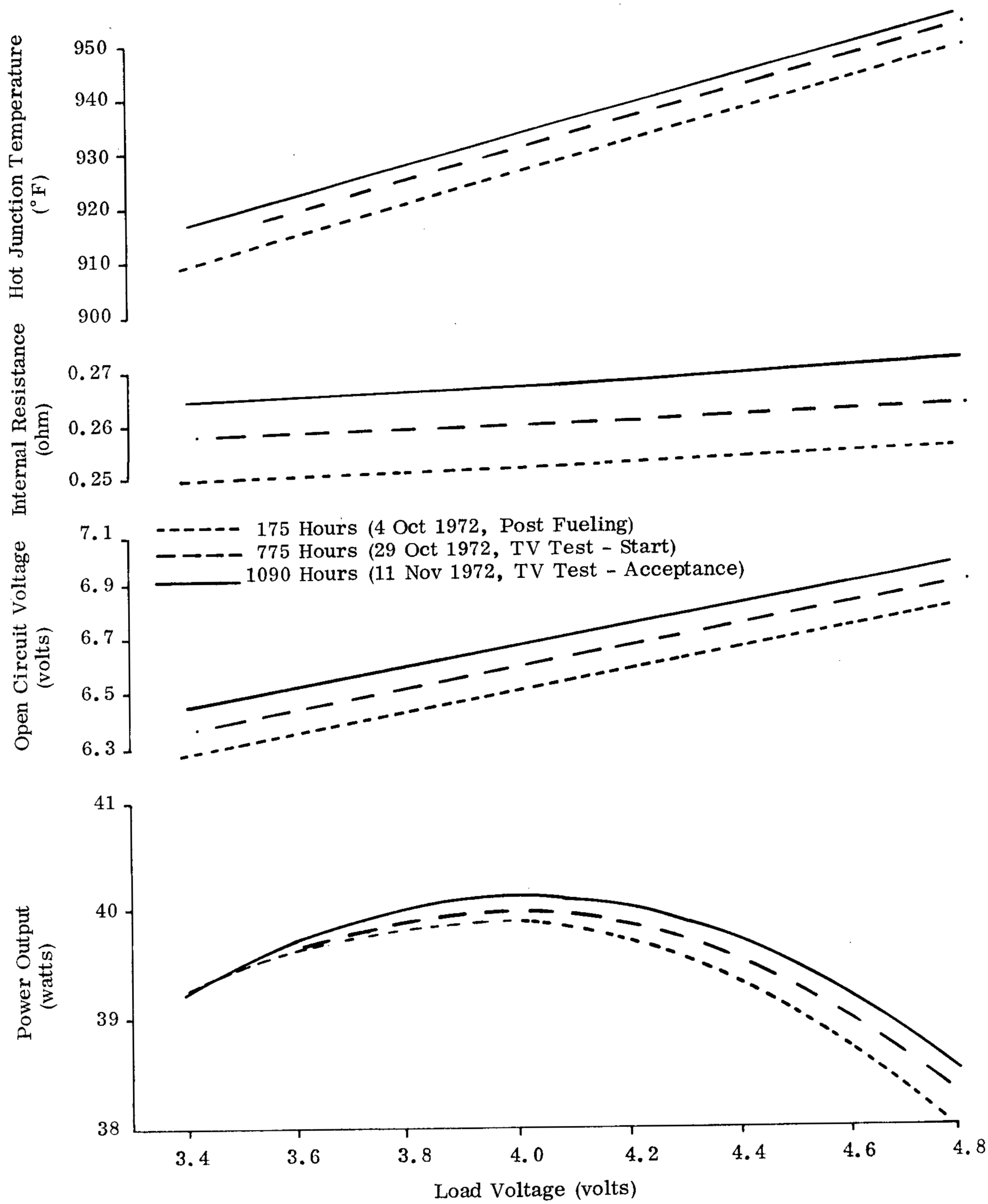


FIG. V-14. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 50
FIN ROOT TEMPERATURE: 330°F
643 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

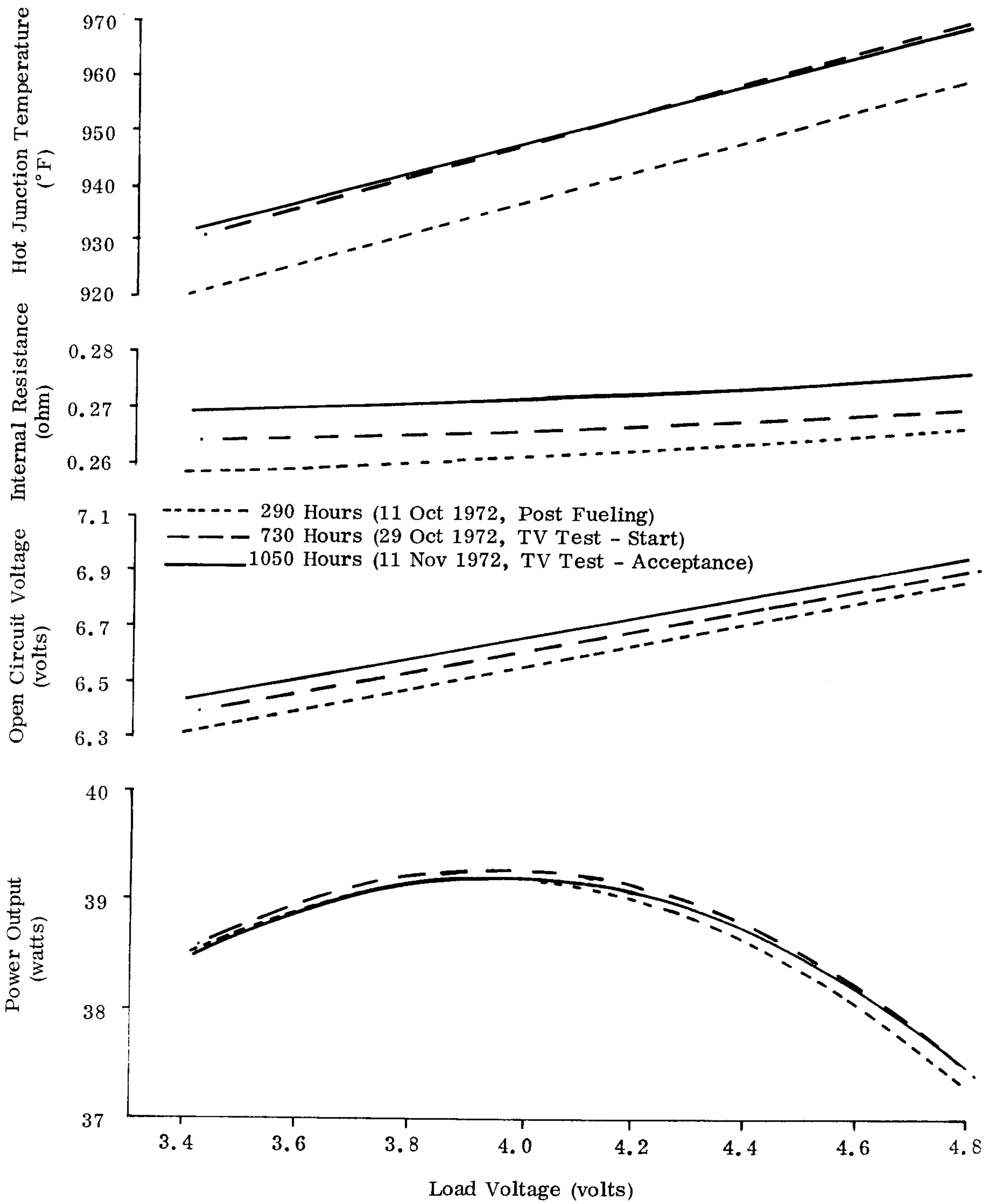


FIG. V-15. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 51
FIN ROOT TEMPERATURE: 330°F
650 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

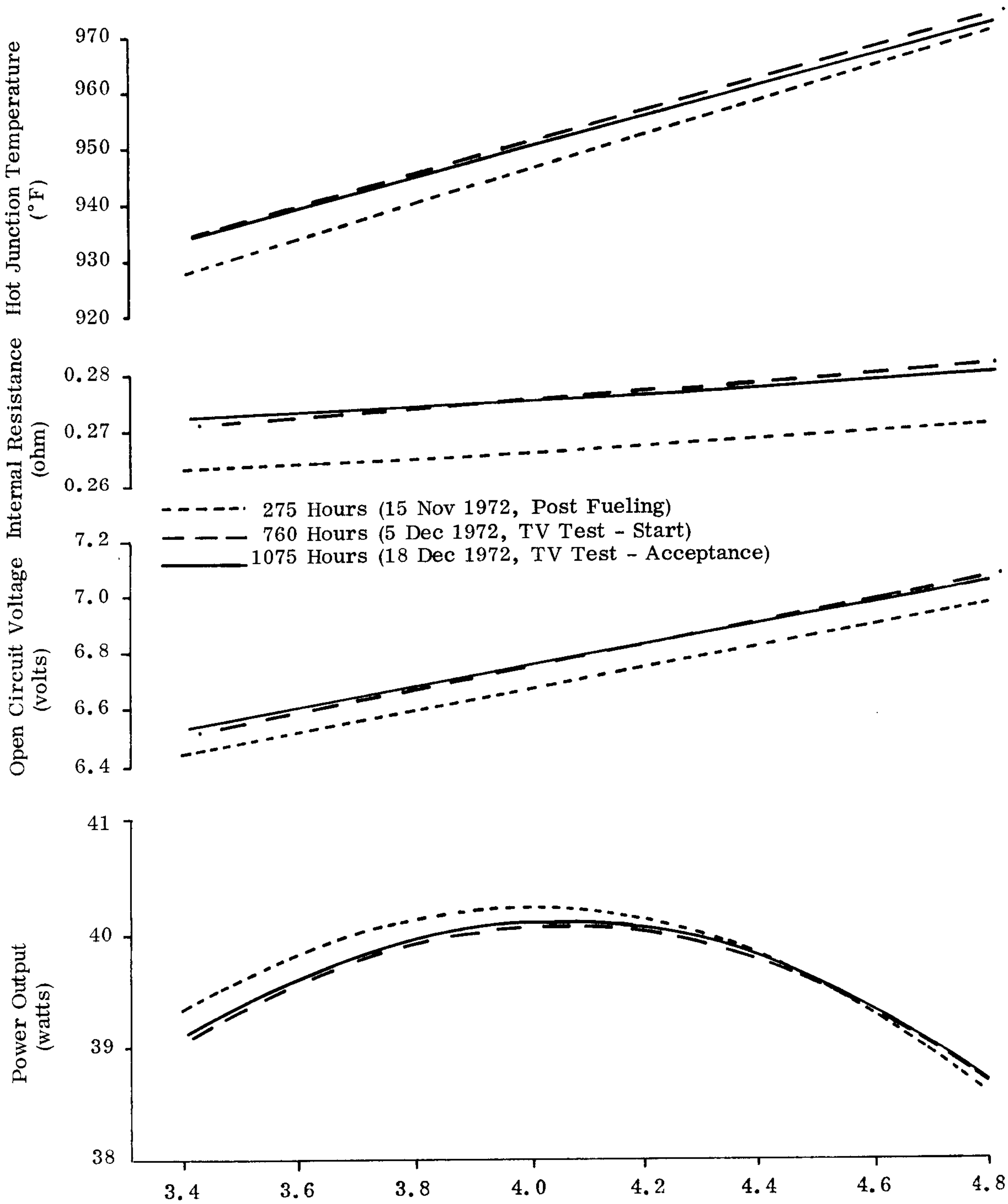


FIG. V-16. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 52
FIN ROOT TEMPERATURE: 330°F
649 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

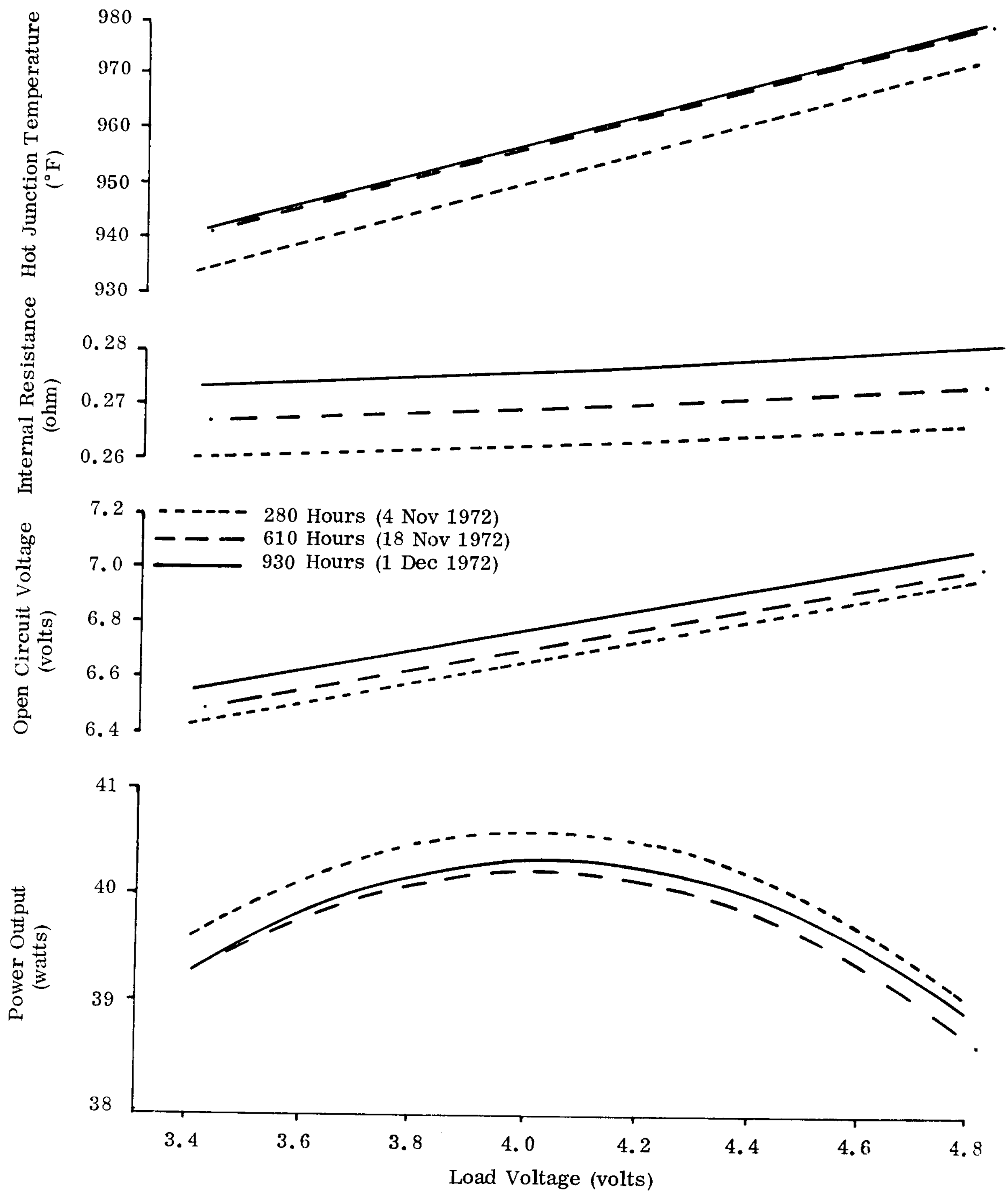


FIG. V-17. PARAMETRIC TEST RESULTS, SNAP 19 GENERATOR S/N 53
FIN ROOT TEMPERATURE: 330°F
649 WATTS (CAPSULE INVENTORY)
FILL GAS: 75% HELIUM/25% ARGON

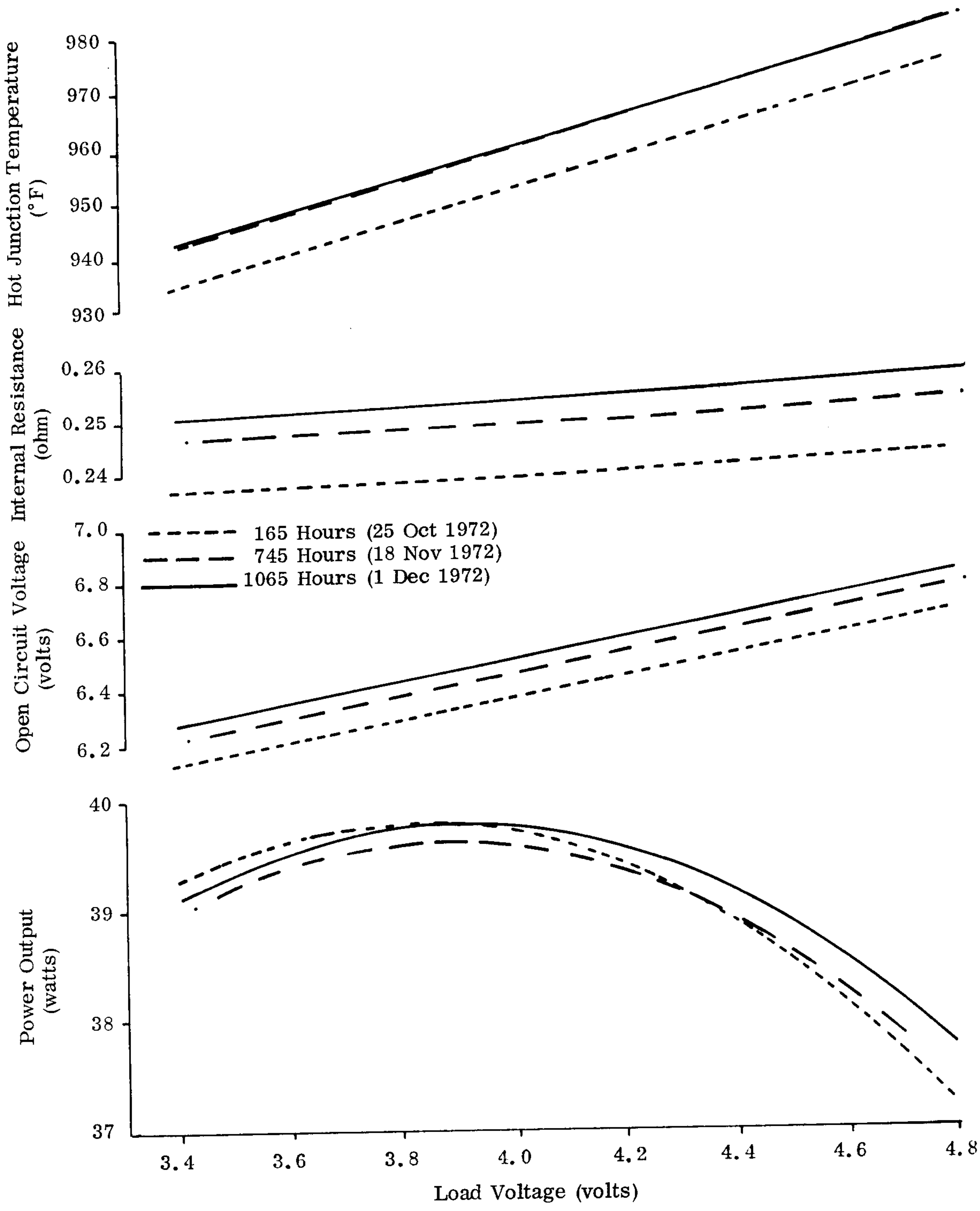
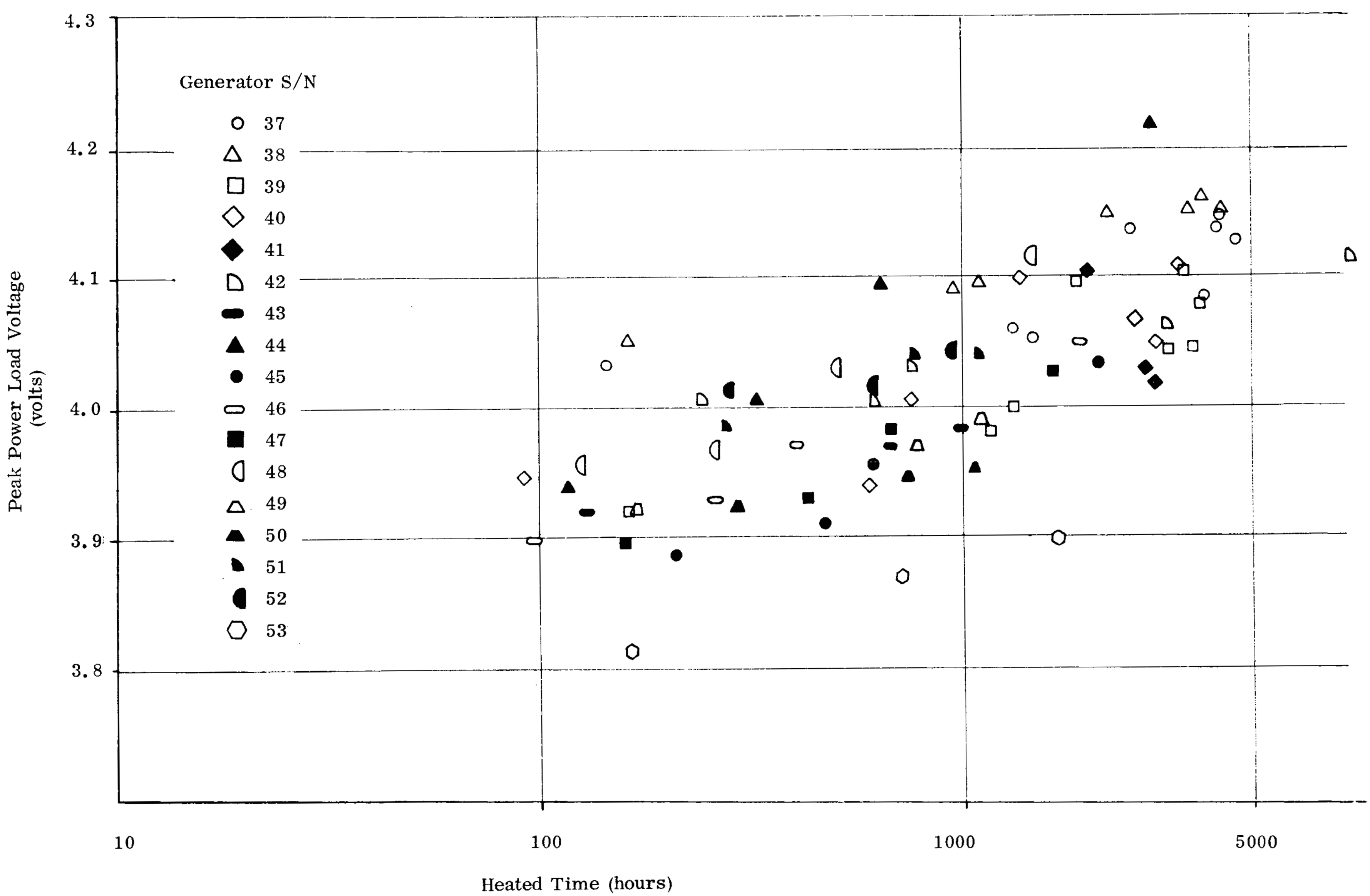


FIG. V-18. VARIATION OF PEAK POWER LOAD VOLTAGE WITH TIME



vibration leakage measurements are summarized in Table V-1. The test results obtained in thermal vacuum are discussed in Section 5.

The leakage observed from the Pioneer generator is entirely attributable to gaseous diffusion through the single Viton O-ring seal at the output power/instrumentation connector receptacle. Further, the variation in leakage observed is explainable by manufacturing tolerances which yield variable volumetric fill of the O-rings in the receptacle grooves. It is interesting to note that post fueling leakage data was collected before removal of a pressure gauge and associated fittings from the RTG and this is in accord with slightly higher measured leak rates than obtained following vibration. The leak rate measurements of RTG S/N 37 through 53 presented in Table V-1 are normally distributed with a mean of 2.31×10^{-5} scc/sec-atm and a standard deviation of 0.61×10^{-5}. The upper limit acceptance criterion on leak rate for flight generators is 4.3×10^{-5} scc/sec-atm which is seen to be about 3σ from the mean.

3. Radiation

The levels of radiation emitted from individual fuel capsules were measured in generator survey tests at Teledyne Isotopes and on individual fuel capsules at MRC. Results of these tests for each generator are presented in Figs. V-19 through V-35. The curves show total dose rates at distances up to about 10 feet from generator side and bottom surfaces.

A summary plot showing total side dose rates at 3 and 10 feet for generators S/N 37 through S/N 53 is presented in Fig. V-36. This figure illustrates the large decrease in dose rates which resulted in substitution of chlorine for the fluorine process in fuel cermet production. Procedures for generator level radiation measurements are identified in Reference 6.

4. Dynamic Tests

Generator response to dynamic loads expected during the launch vehicle ascent phases, including separation and RTG deployment was evaluated by exposure to vibration, acceleration and shock environments. Other dynamic loads, such as those created by handling and transportation are negligible. A record of the dynamic tests performed on generators S/N 36 through S/N 53 is presented in Table V-2.

a. Vibration

This section documents the successful vibration testing of Pioneer generators S/N 36 through S/N 53. The series of documented generators is begun with S/N 36 since it is the first generator employing welded end covers. Also, this and all subsequent generators used a

TABLE V-1

MEASURED LEAK RATES OF PIONEER RTG'S

Generator S/N	Rate of Helium Permeation in scc/sec* x 10^5 Post Fueling	Post Vibration
37	2.1	1.4
38	2.3	2.4
39	1.9	1.7
40	2.5	2.8
41	1.4	1.8
42	2.7	2.6
43	3.0	3.6
44	2.6	2.0
45	2.1	1.9
46	2.4	2.2
47	3.1	2.4
48	3.9	3.2
49	2.0	1.5
50	1.5	1.2
51	2.4	2.3
52	2.3	2.0
53	2.7	2.6

* At a seal temperature of 337°F and a helium pressure differential of one atmosphere across the seal.

TABLE V-2

RECORD OF DYNAMIC TESTS FOR

SNAP 19 PIONEER PROGRAM GENERATORS

Generator Serial Number	Vibration Acceptance	Vibration Qualification	Acceleration Qualification Level	Shock Qualification Level
36*	x	x		
37	x	x	x	x
38	x			
39	x			
40	x			
41	x	x		x
42	x	x		x
43	x			
44	x			
45	x			
46	x			
47	x			
48	x			
49	x			
50	x			
51	x			
52	x			
53	x			

* Electrically heated generator.

FIG. V-19. GENERATOR S/N 37 DOSE RATES
CAPSULE PF-1

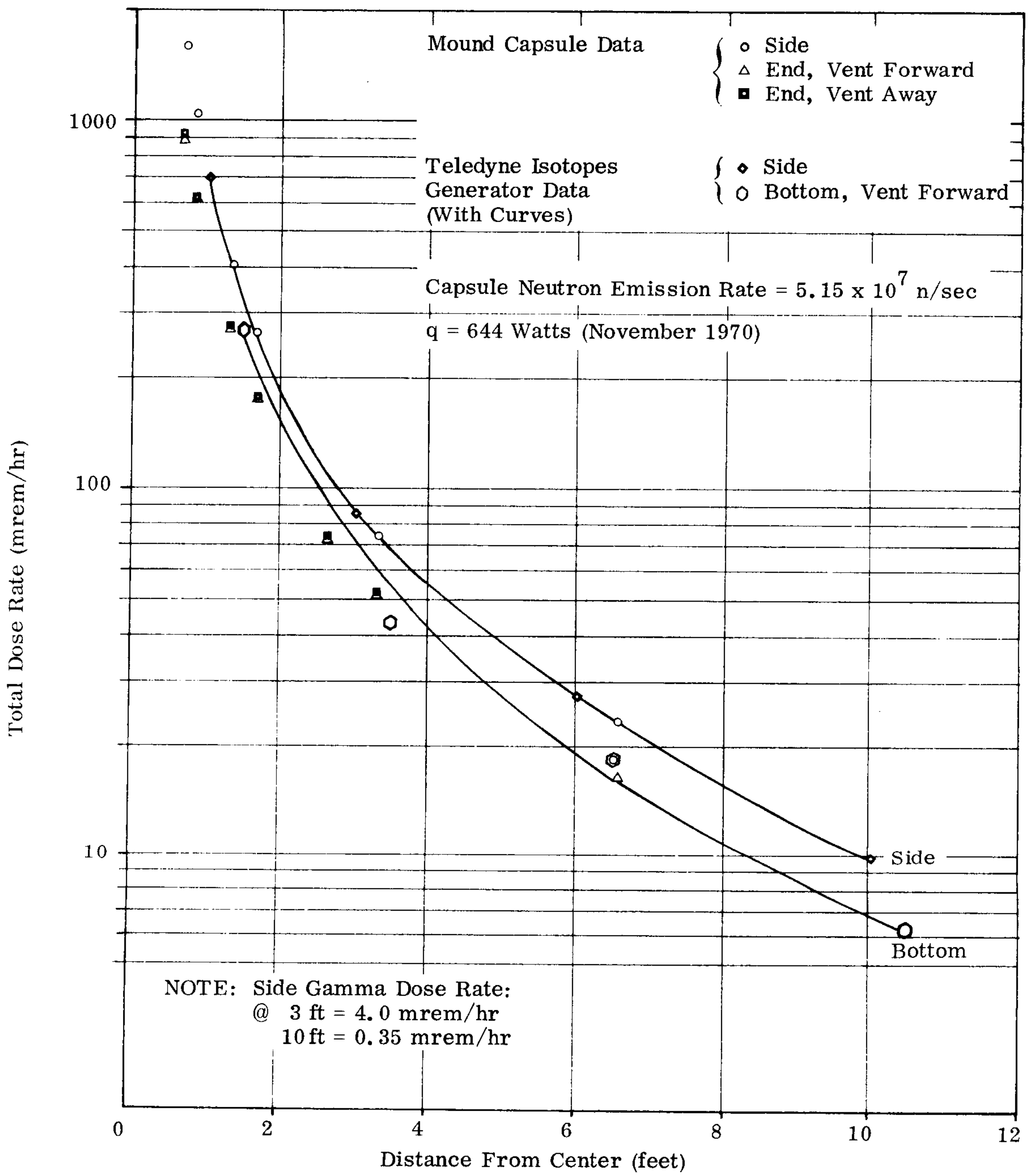


FIG. V-20. GENERATOR S/N 38 DOSE RATES
CAPSULE PF-2

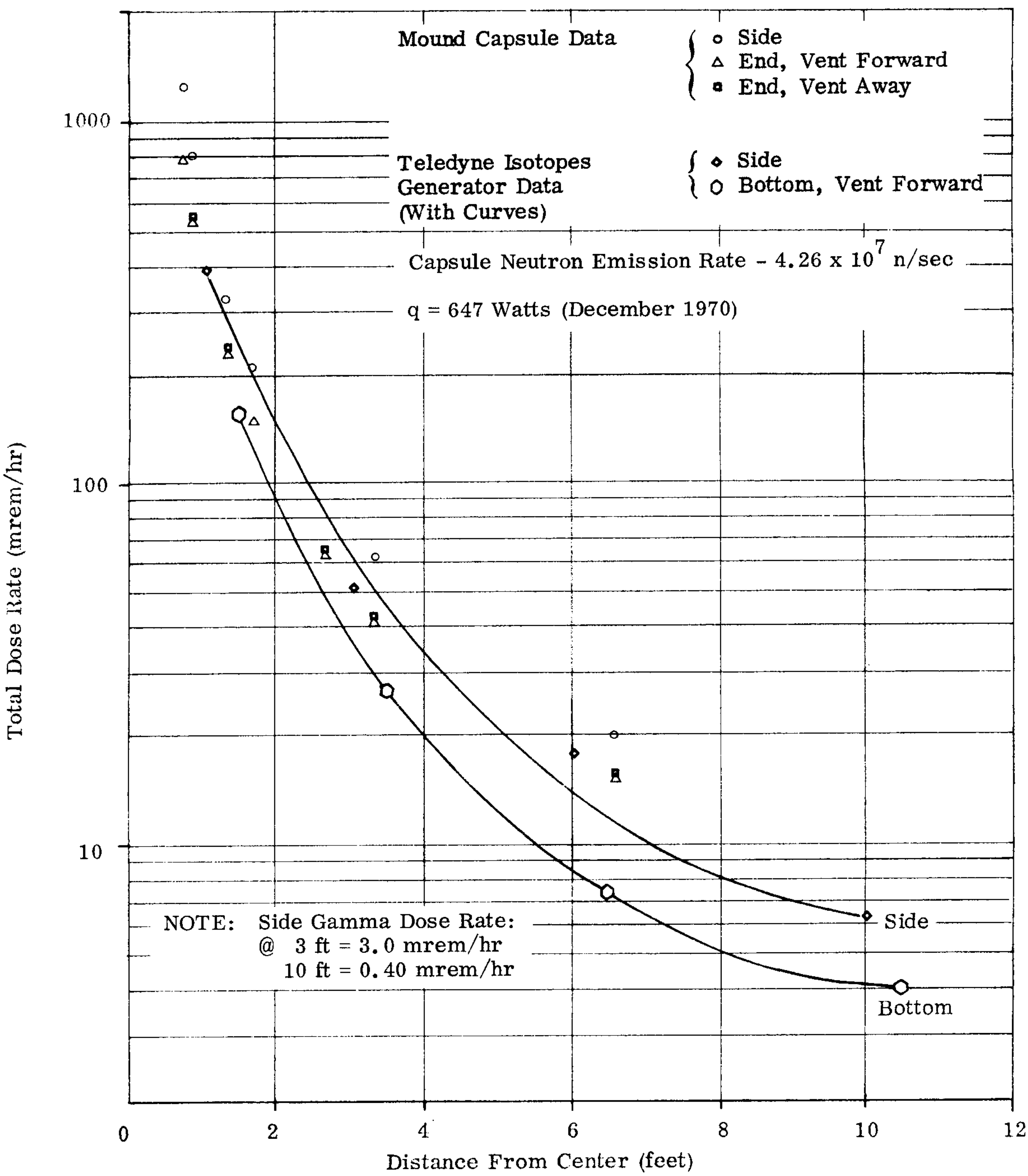


FIG. V-21. GENERATOR S/N 39 DOSE RATES
CAPSULE PF-3

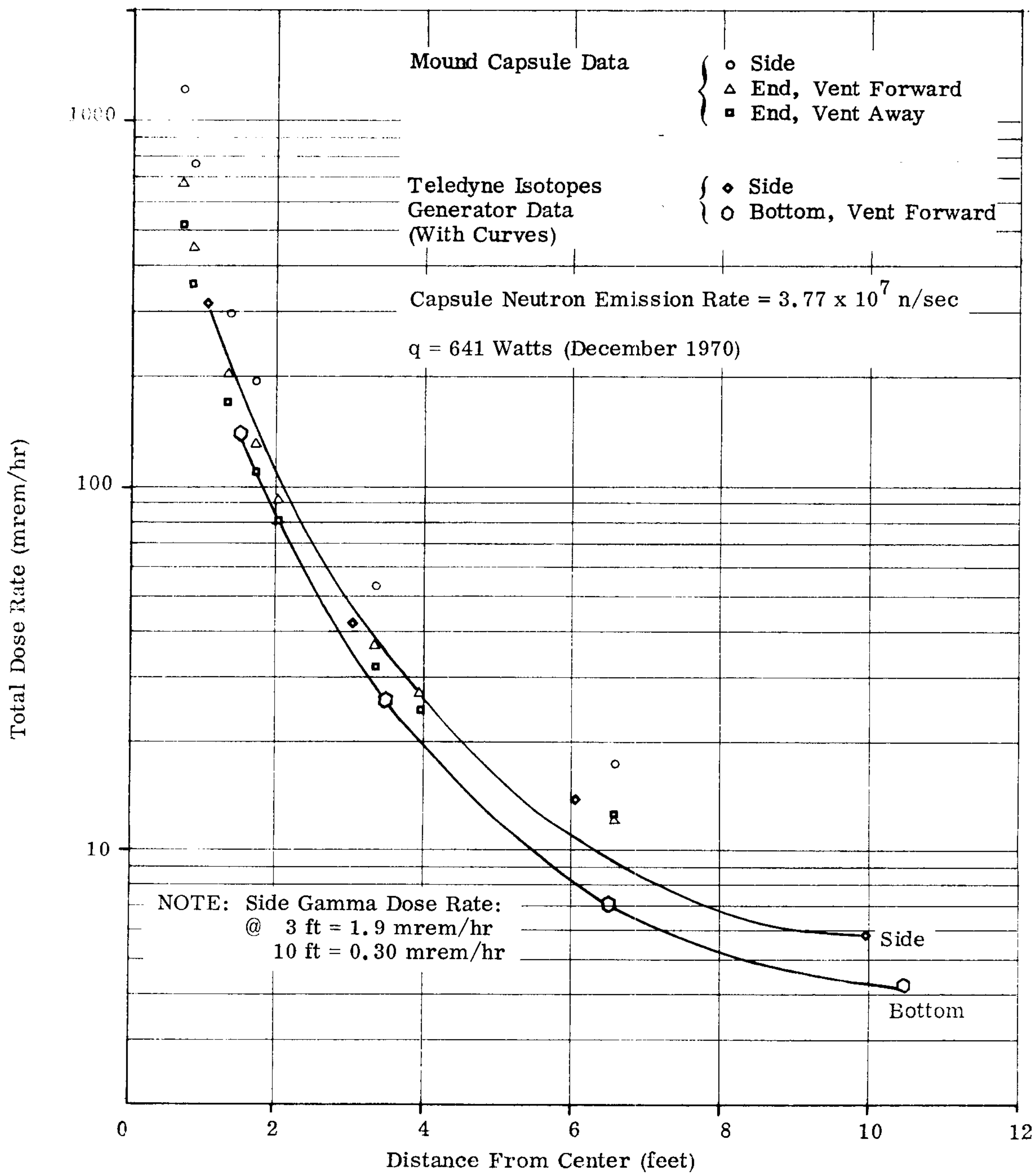


FIG. V-22. GENERATOR S/N 40 DOSE RATES
CAPSULE PF-4

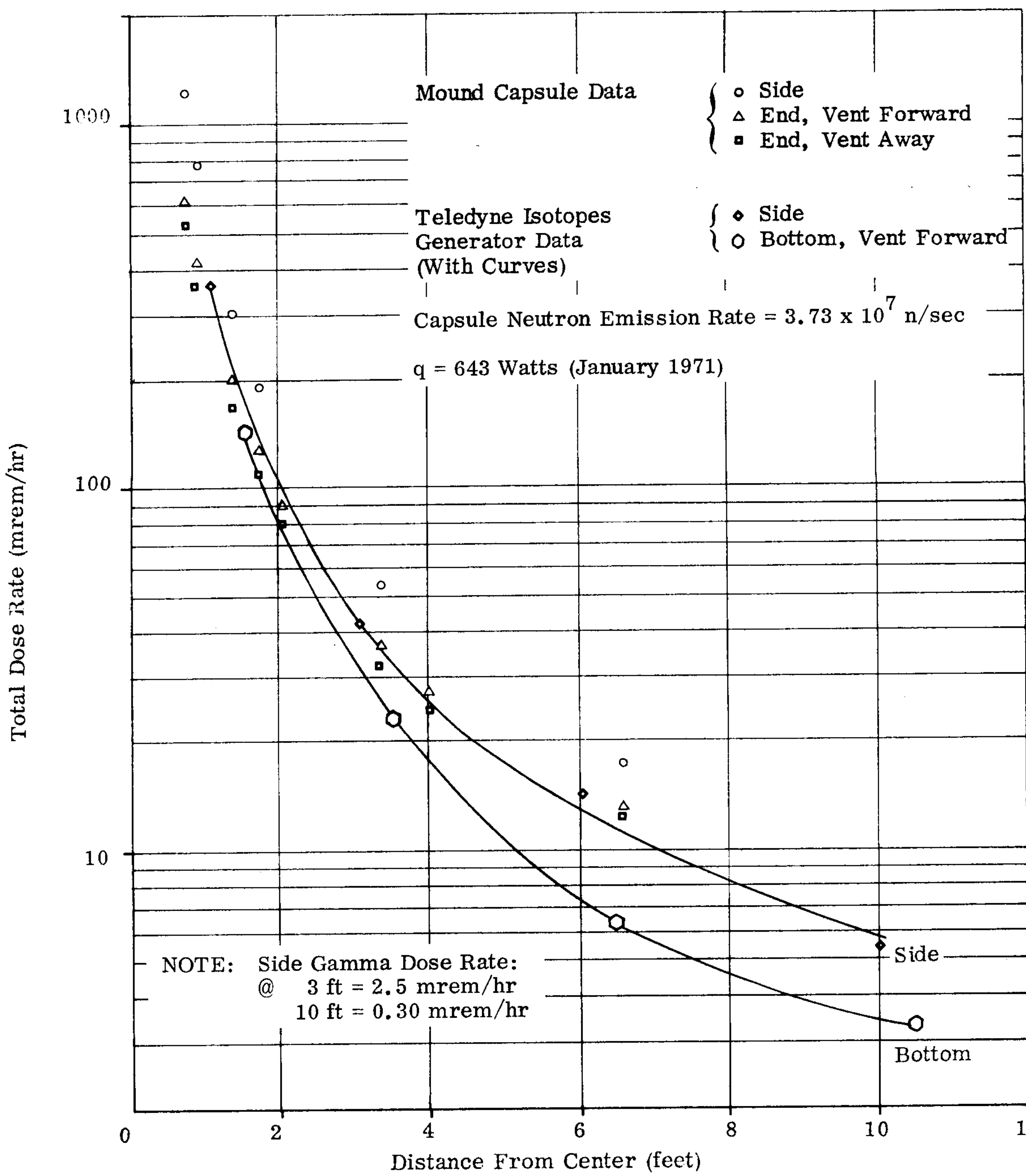


FIG. V-23. GENERATOR S/N 41 DOSE RATES
CAPSULE PF-7

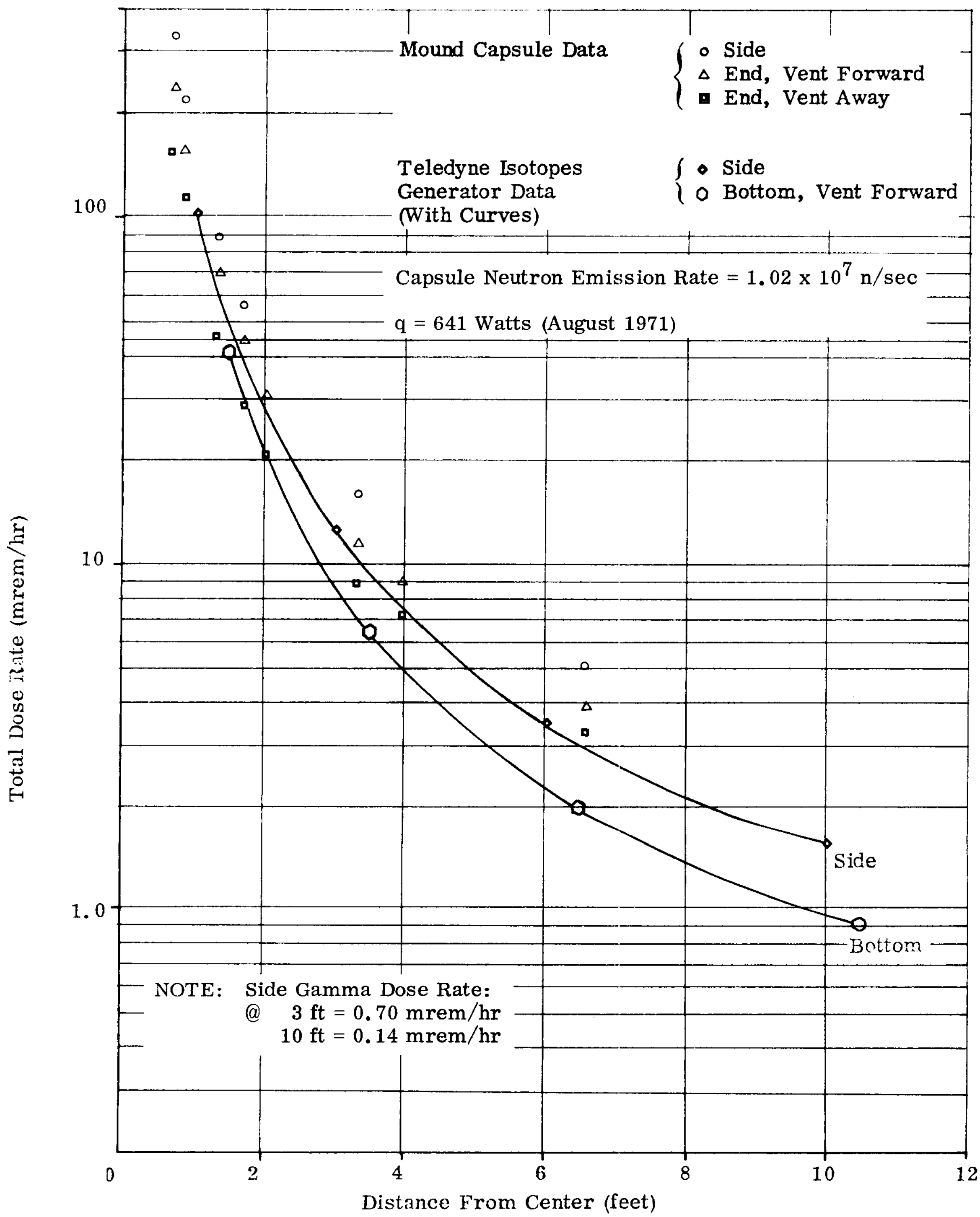


FIG. V-24. GENERATOR S/N 42 DOSE RATES
CAPSULE PF-8

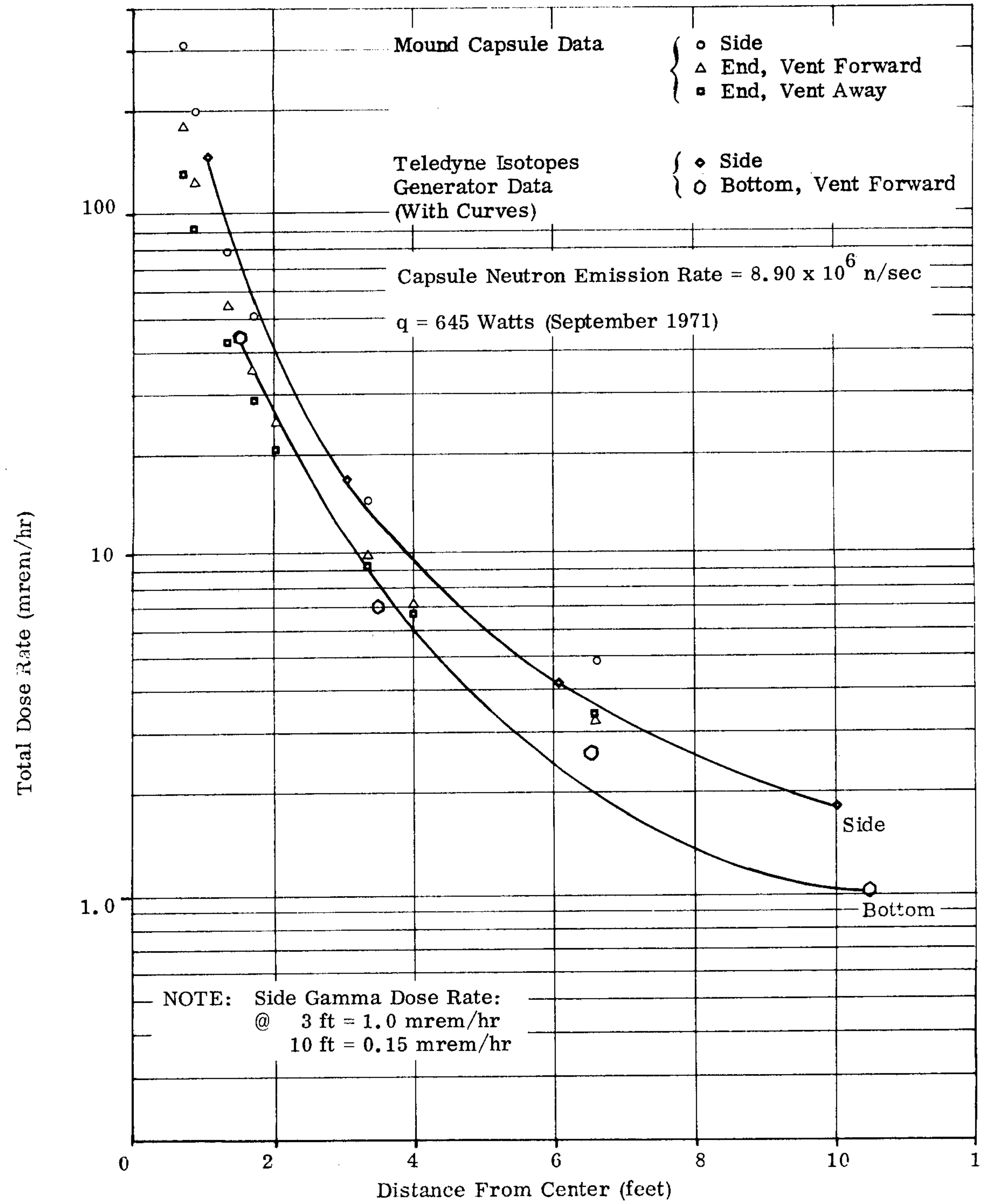


FIG. V-25. GENERATOR S/N 43 DOSE RATES
CAPSULE PF-9

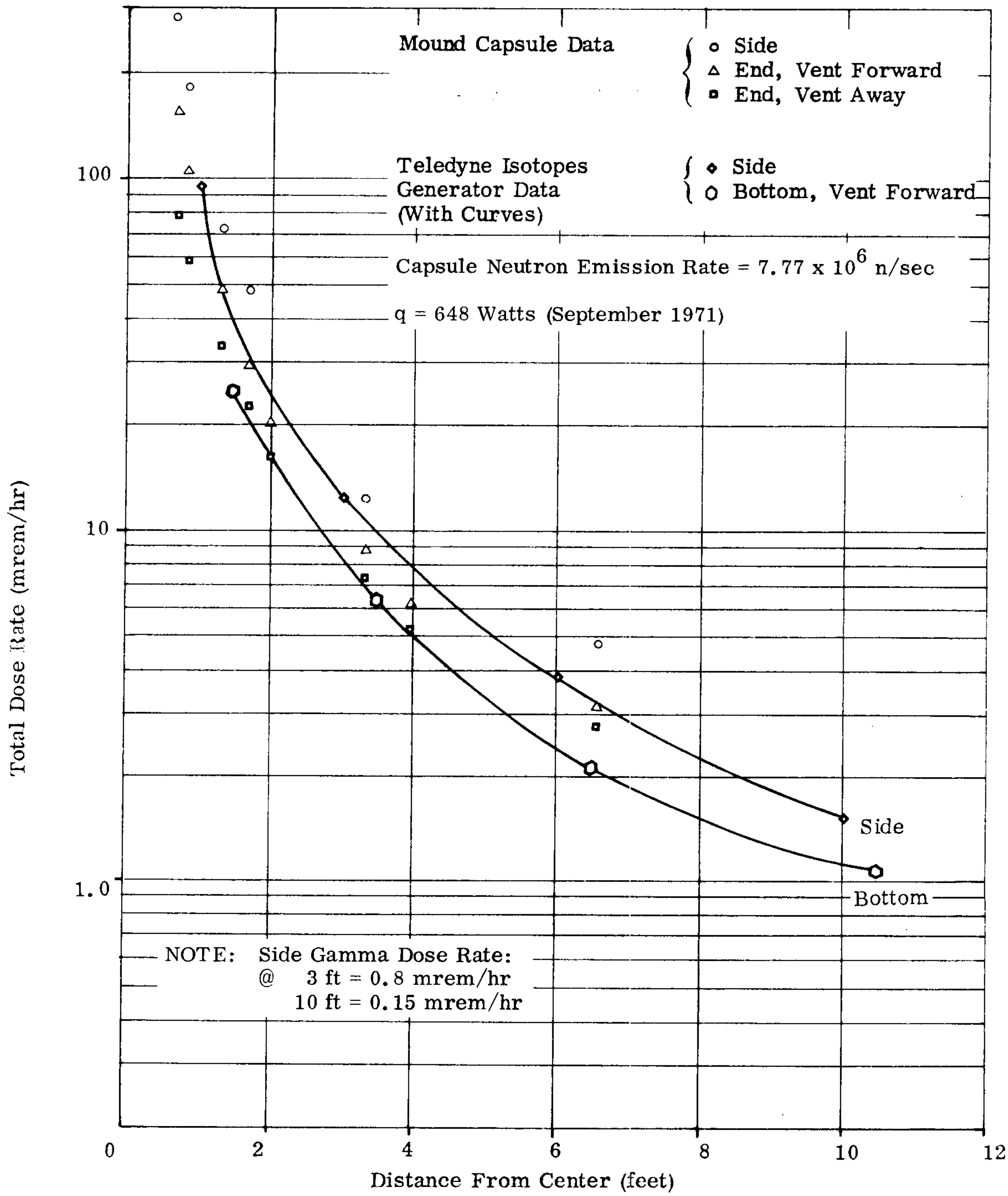


FIG. V-26. GENERATOR S/N 44 DOSE RATES
CAPSULE PF-10

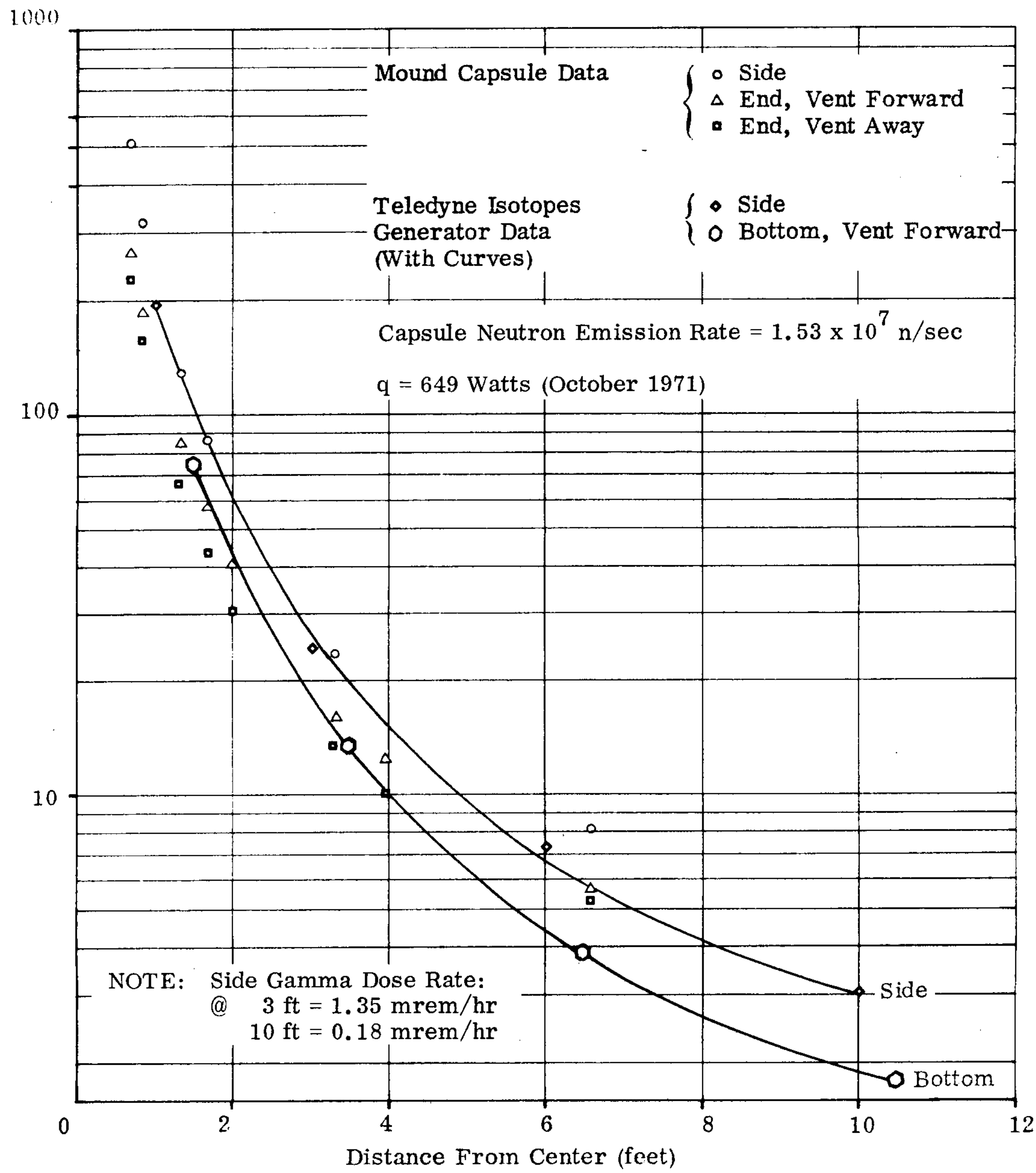


FIG. V-27. GENERATOR S/N 45 DOSE RATE
CAPSULE PF-12

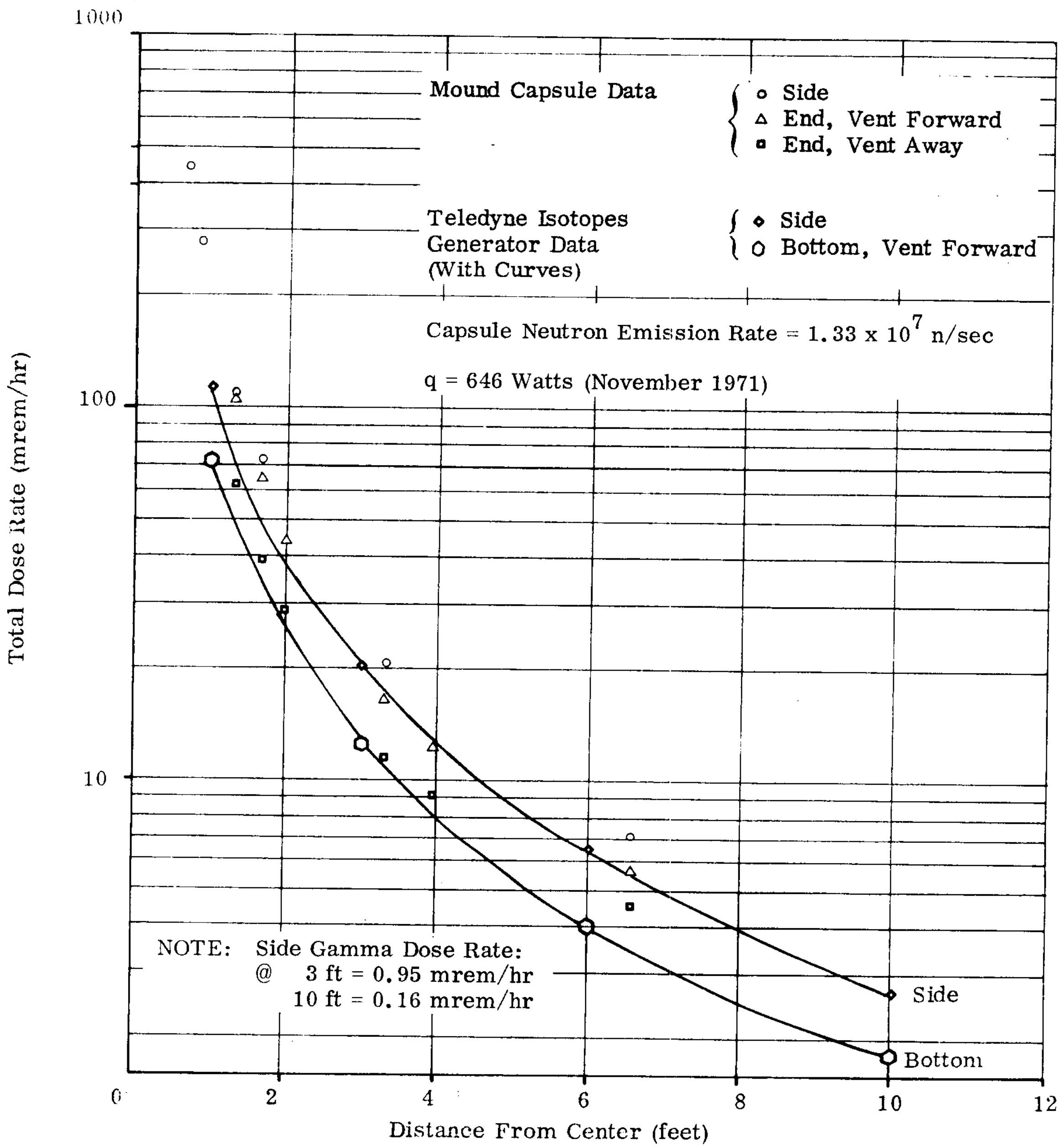


FIG. V-28. GENERATOR S/N 46 DOSE RATES
CAPSULE PF-11

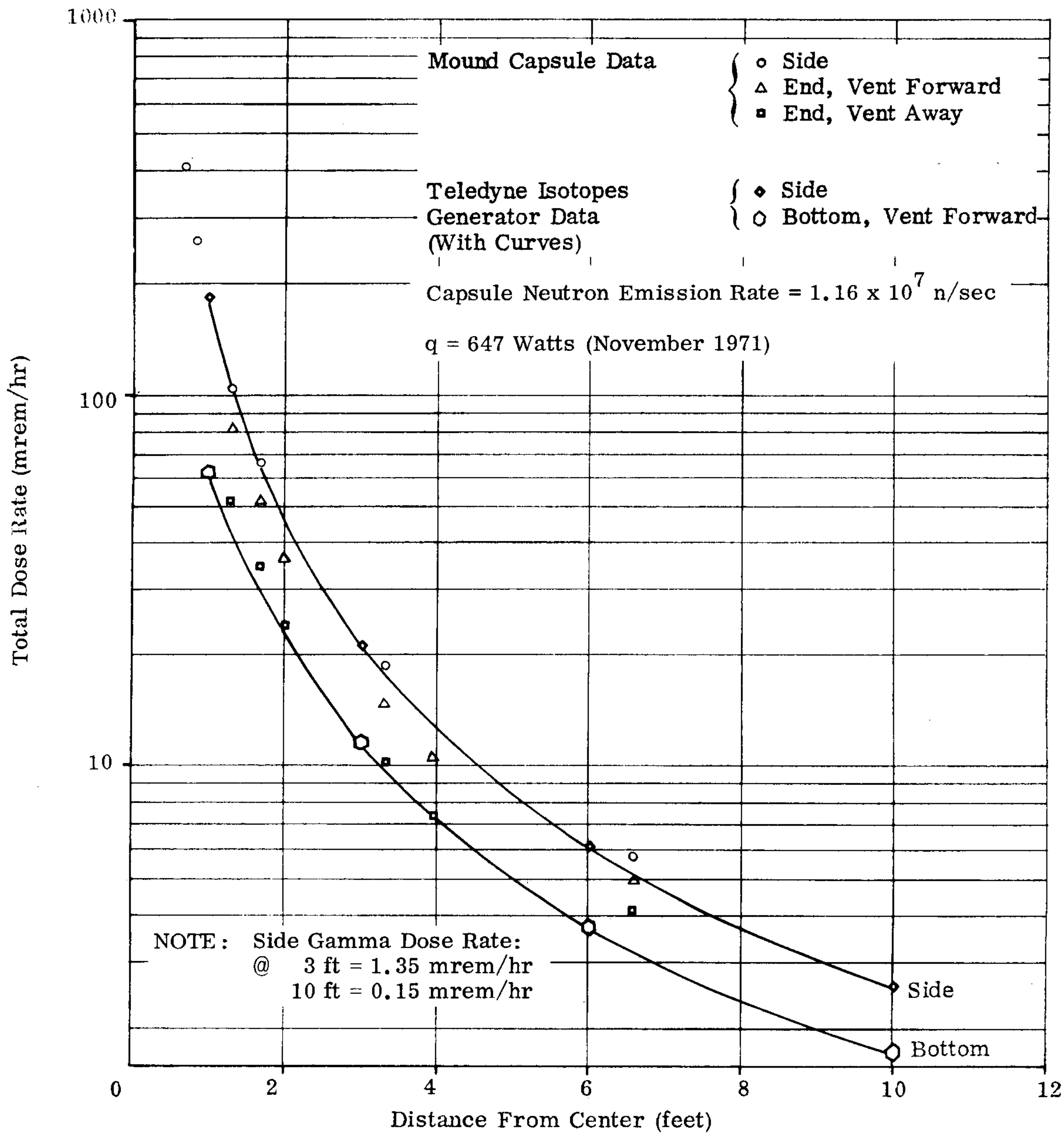


FIG. V-29. GENERATOR S/N 47 DOSE RATES
CAPSULE PF-13

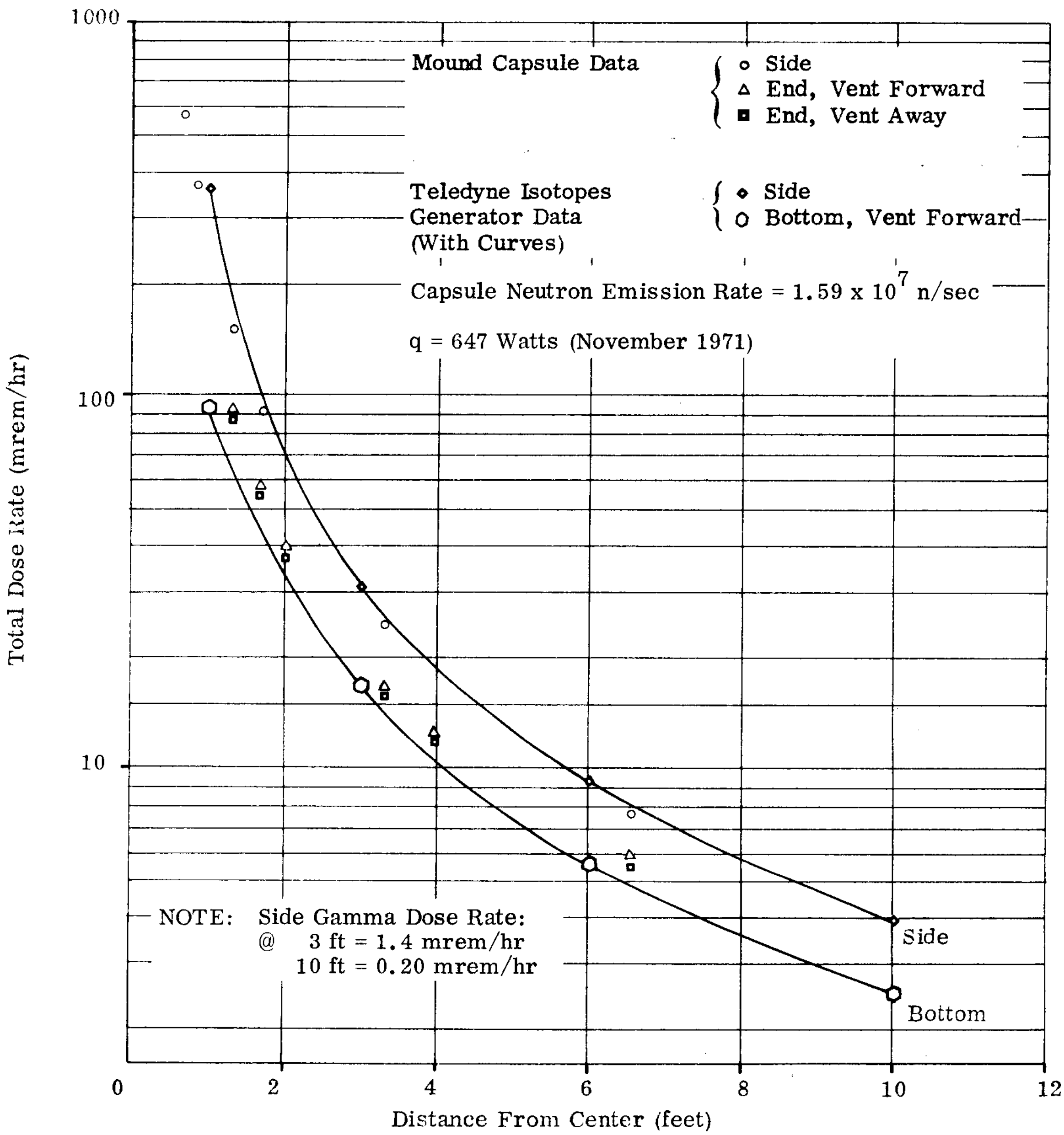


FIG. V-30. GENERATOR S/N 48 DOSE RATES
CAPSULE PF-14

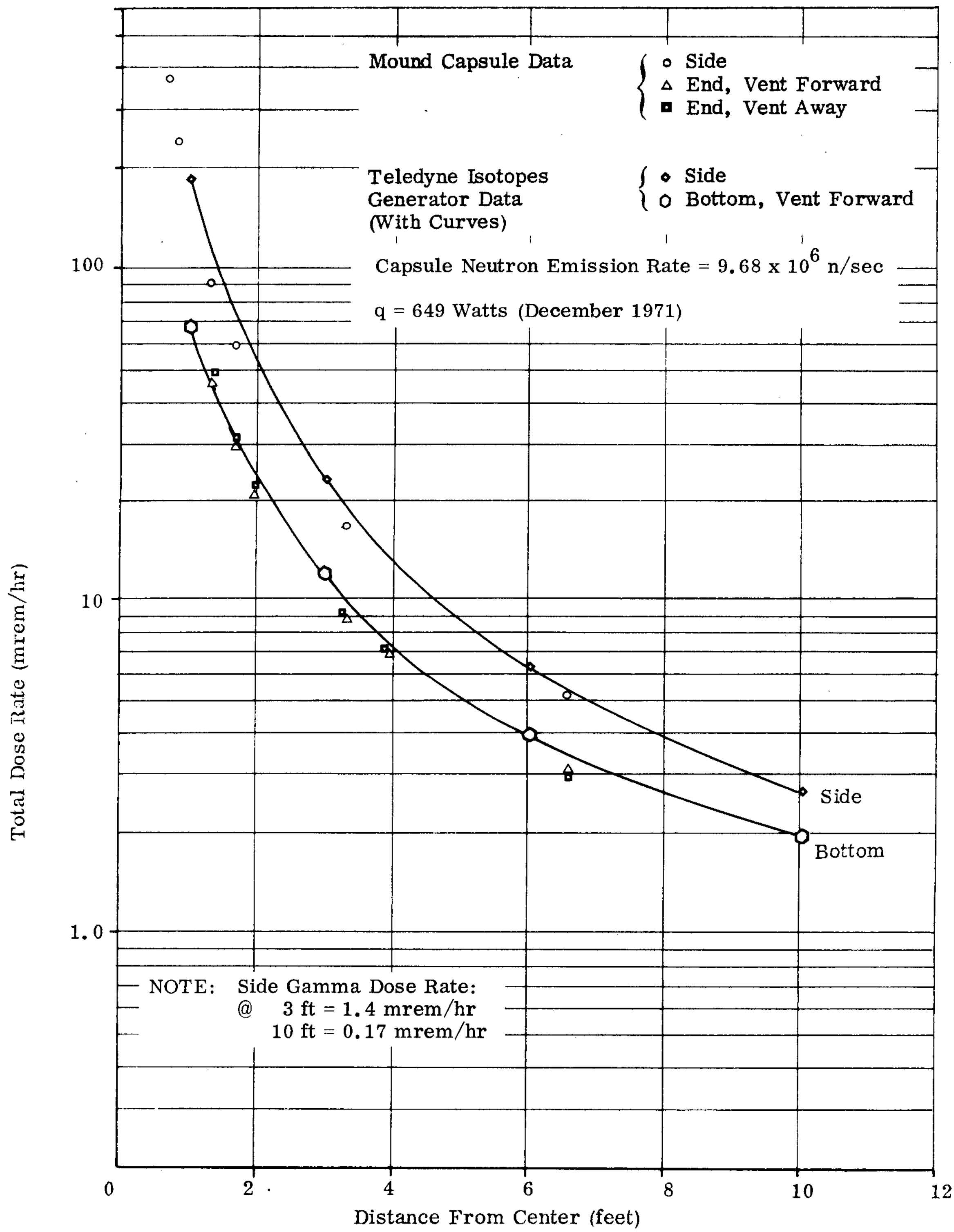


FIG. V-31. GENERATOR S/N 49 DOSE RATES
CAPSULE PF-17

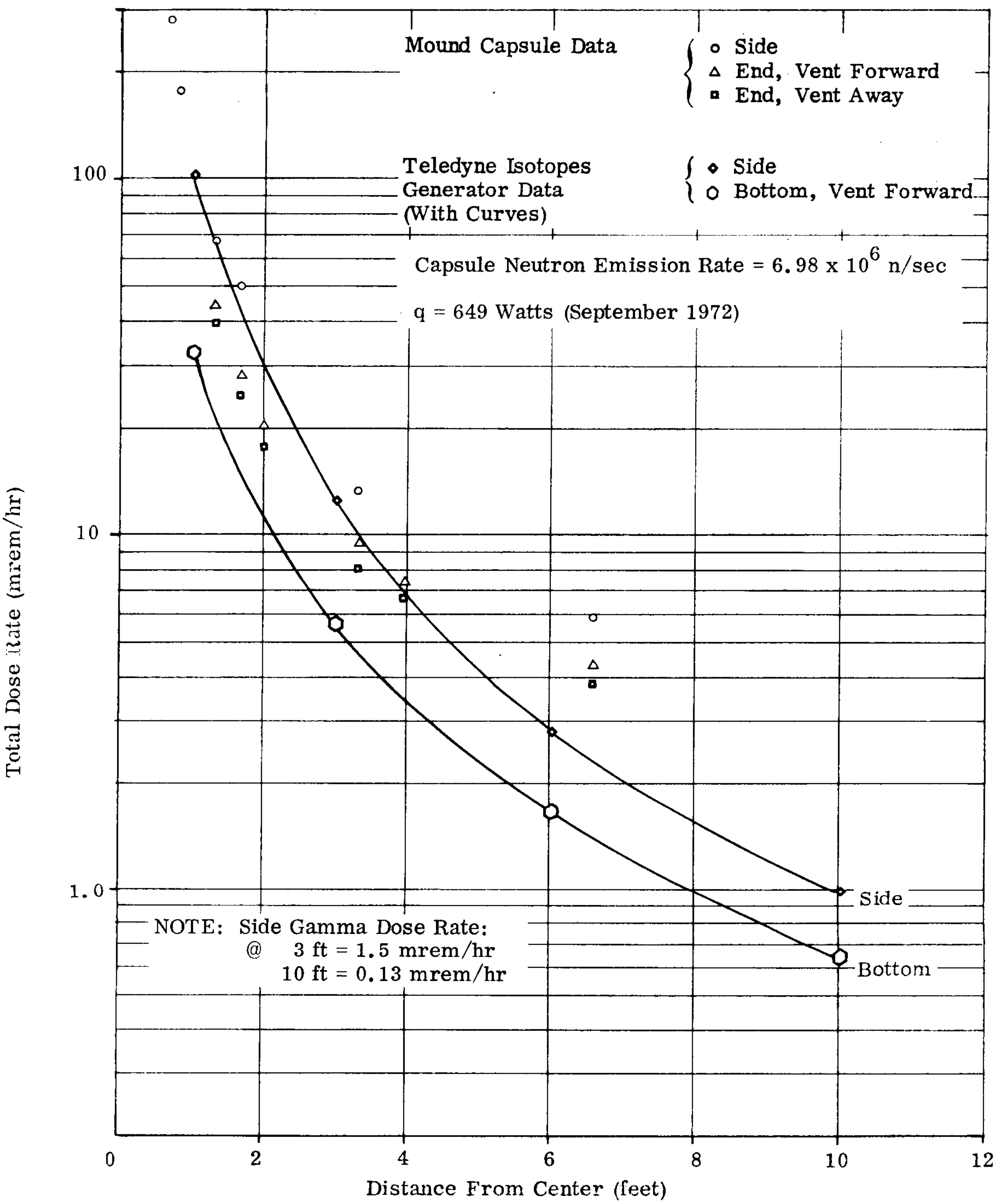


FIG. V-32. GENERATOR S/N 50 DOSE RATES
CAPSULE PF-16

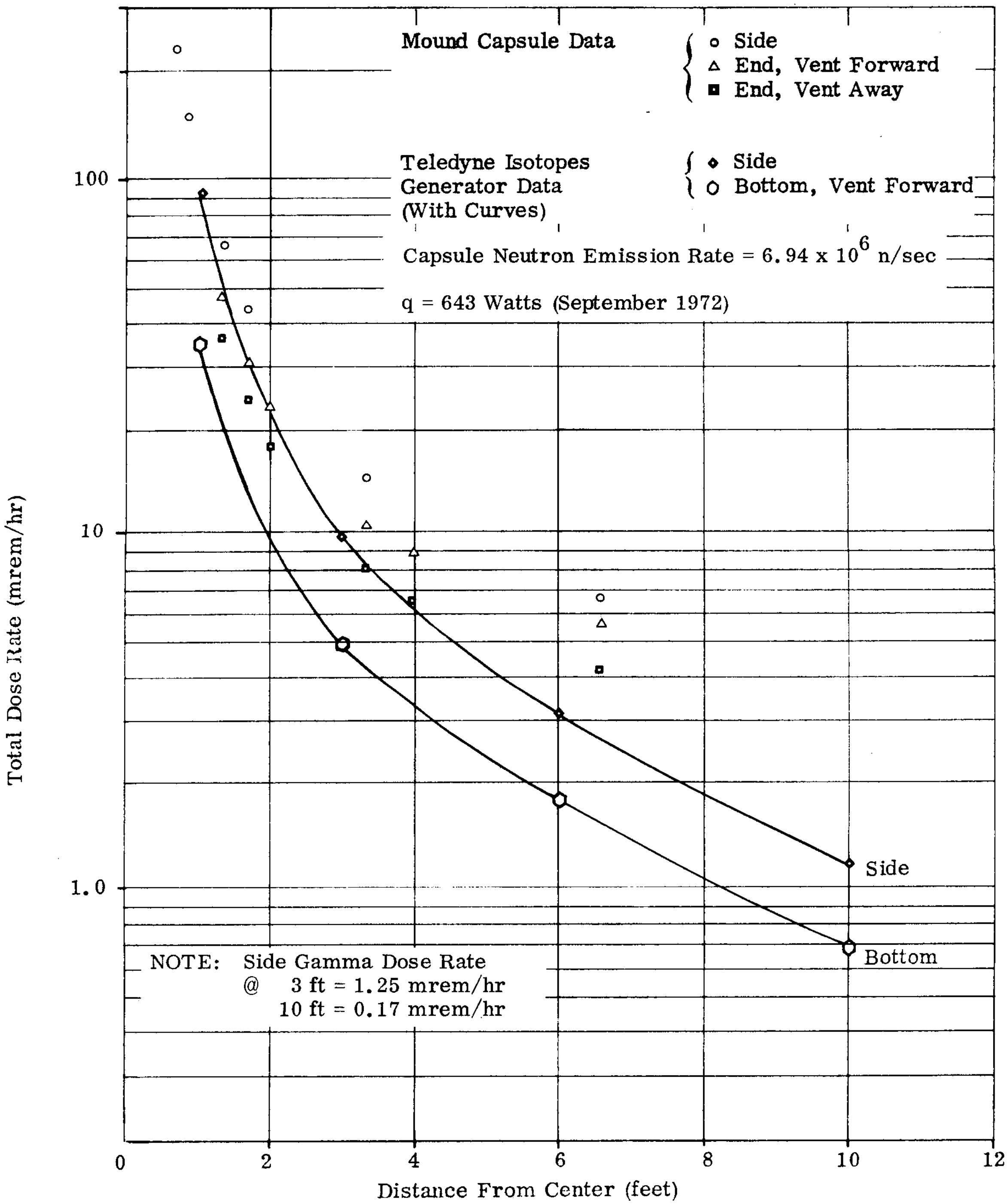


FIG. V-33. GENERATOR S/N 51 DOSE RATES
CAPSULE PF-20

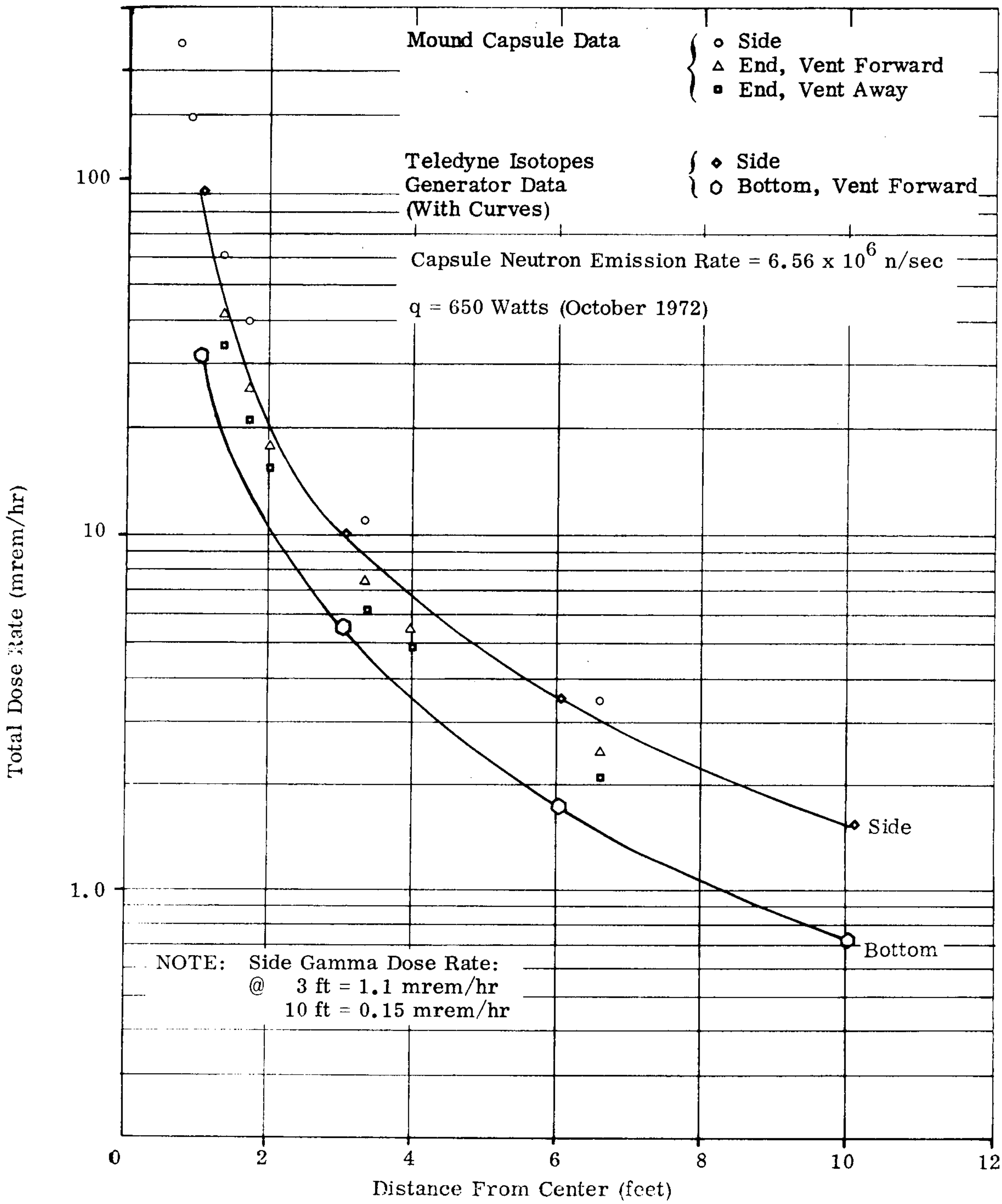


FIG. V-34. GENERATOR S/N 52 DOSE RATES
CAPSULE PF-19

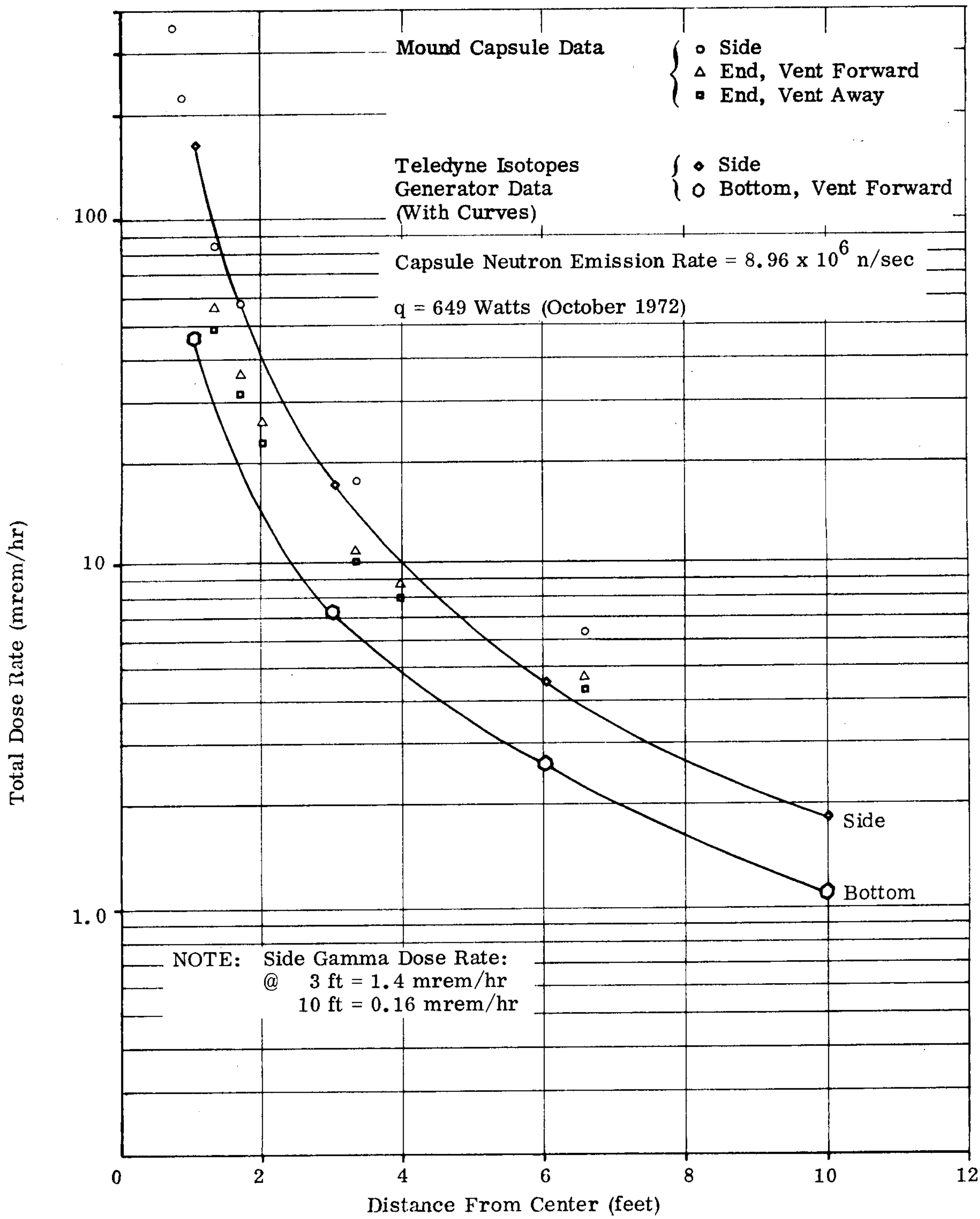


FIG. V-35. GENERATOR S/N 53 DOSE RATES
CAPSULE PF-18

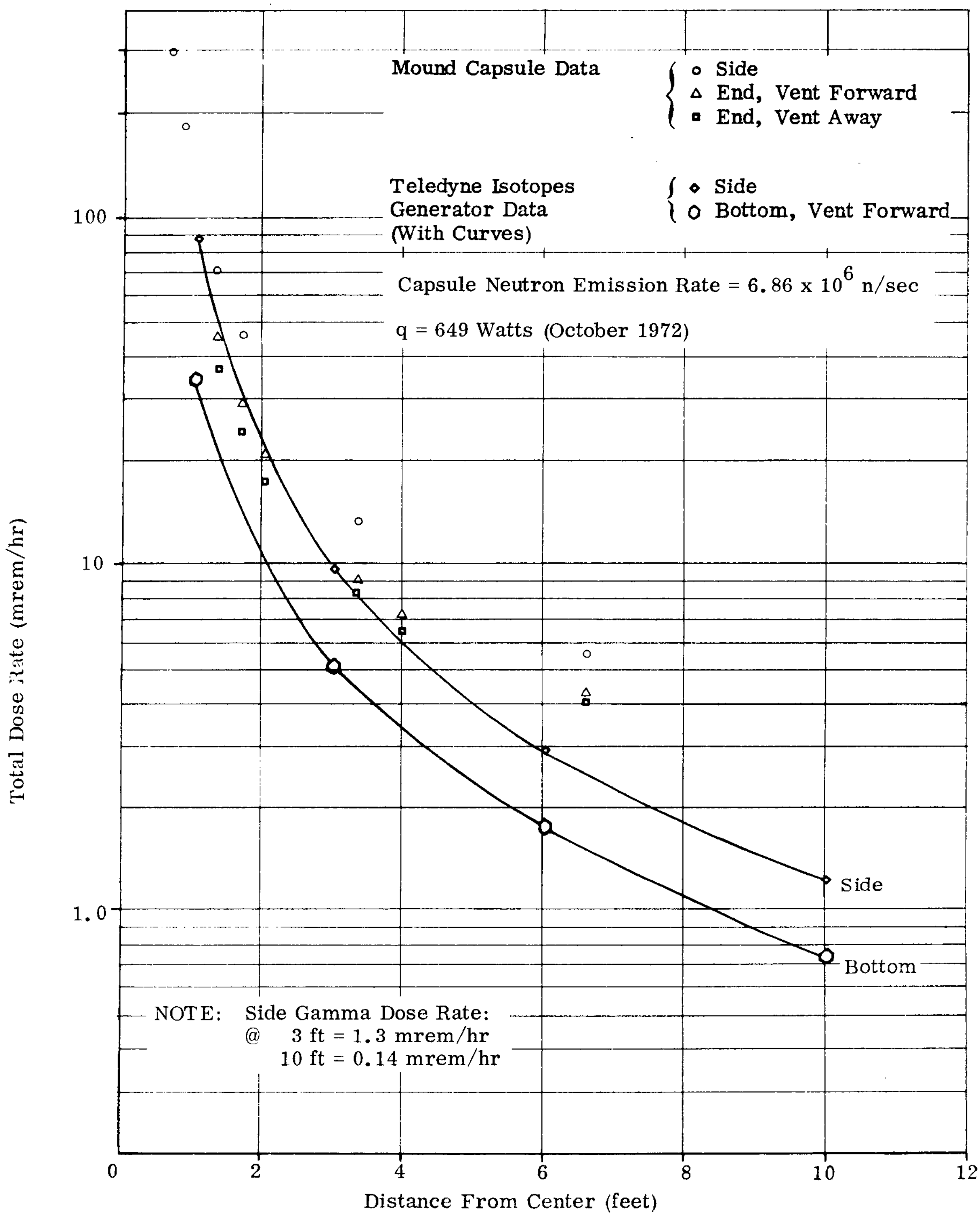
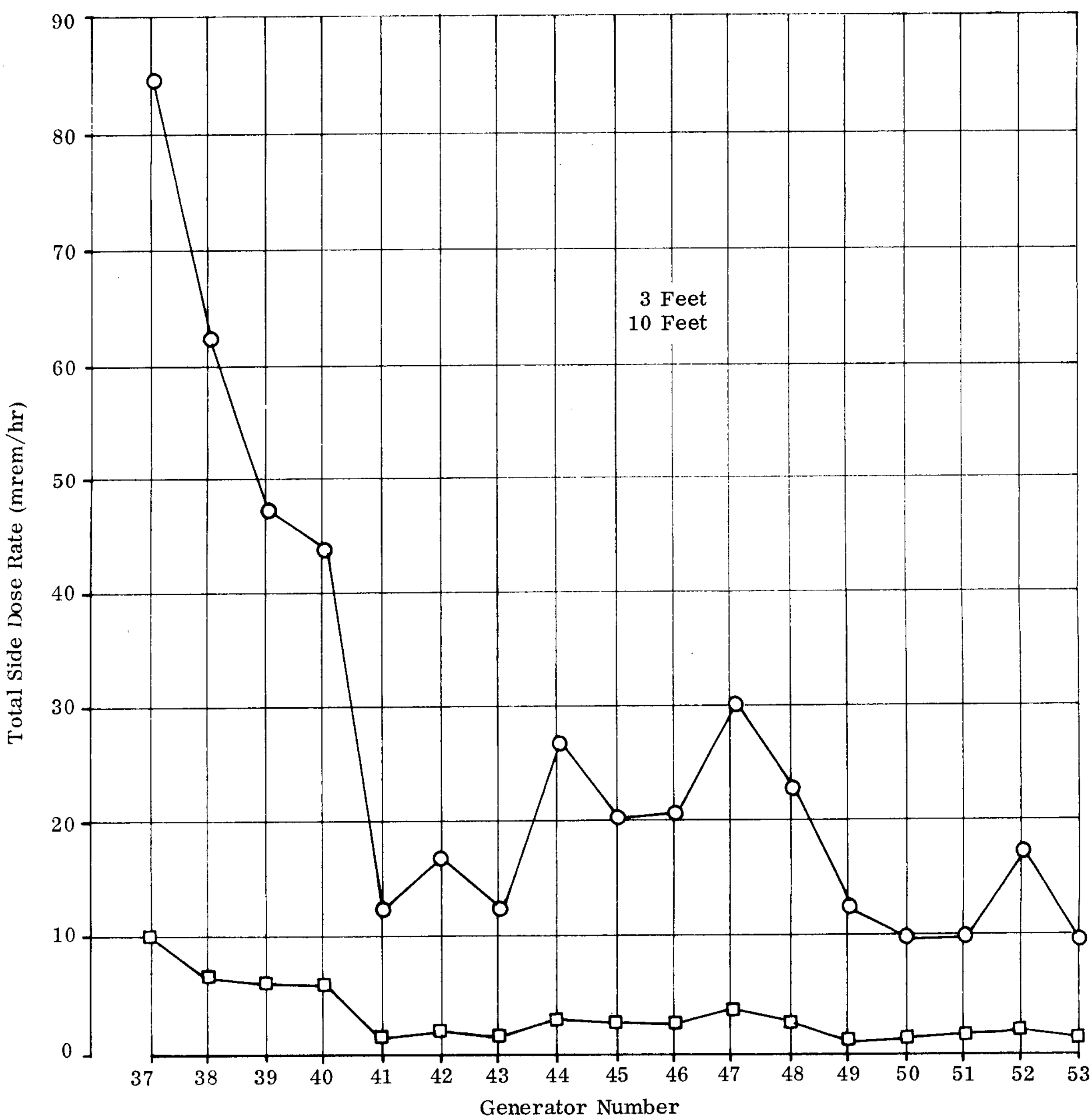


FIG. V-36. TOTAL DOSE RATE VERSUS GENERATOR



nominal gas fill of 75% helium/25% argon. S/N 36 differed from the subsequent generators in that it was an ETG and the rest were RTG's.

All tests were accomplished at the Space and Electronics Systems Division of Fairchild Industries in Germantown, Maryland.

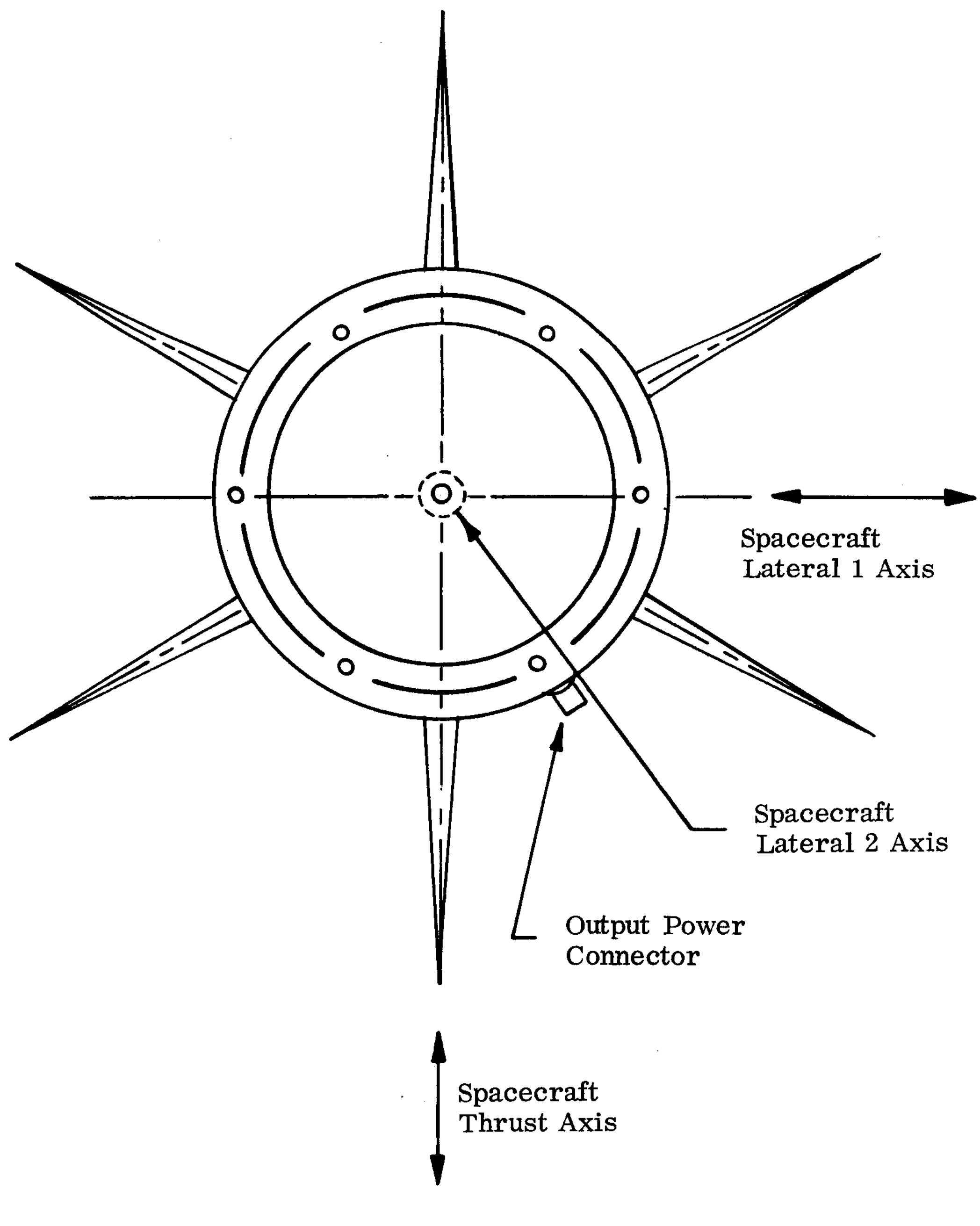
Vibration testing was accompoished on a Ling Model A300B shaker with input applied in each of three mutually perpendicular axes shown in Fig. V-37. Figure V-38 shows a typical generator mounted on the shaker to be vibrated in the lateral 1 axis (shaker horizontal) and in the lateral 2 axis (shaker vertical). Note that the photograph shows the "between fins" orientation of the lateral 1 axis. Vibration in the spacecraft thrust axis is achieved by rotating the generator 90° on the shaker table so that the input motion is "into" or parallel to a fin. During all tests the generator was uninsulated and the load was maintained at 4.2 volts.

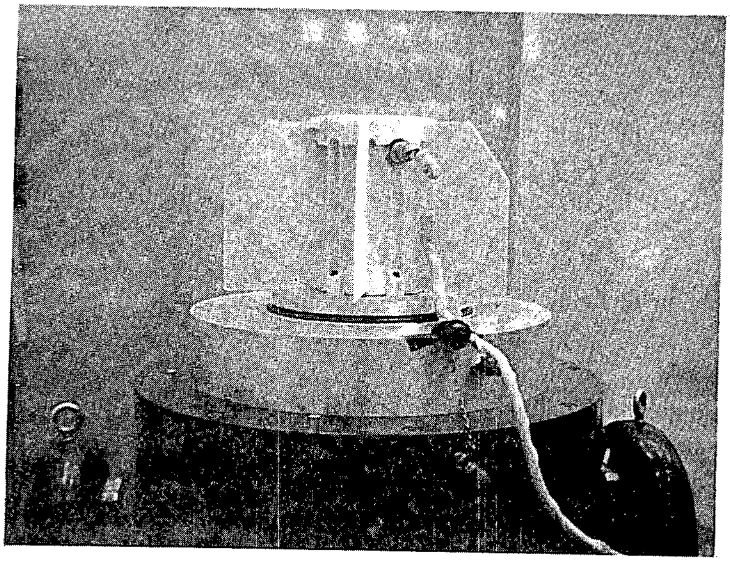
An accelerometer was located on the shaker table adjacent to the generator mounting flange. Vibration level and power input were recorded on an oscillograph. A Sanborn chart recorder was used to monitor and record generator output voltage and current. In addition, a parallel digital readout was used for generator output voltage and current measurement to provide increased accuracy and correlation with recorded data. Fig. V-39 shows the power instrumentation system schematically. Also, it shows the provision for hot junction (resistance temperature device--RTD) and fin root temperature (thermistor) measurement.

The vibration inputs consisted of levels and durations defined for the Pioneer mission as shown in Table V-3. Sinusoidal and random vibration was applied in each of three mutually orthogonal axes in the sequence of spacecraft lateral 2, lateral 1, and thrust. Sinusoidal vibration preceded random vibration for each axis. Detailed test procedures are given in References 7 and 8. References 9 through 18 give X-Y plots of the applied vibration versus frequency for generators S/N 36 through S/N 53 as well as detailed descriptions of the individual tests.

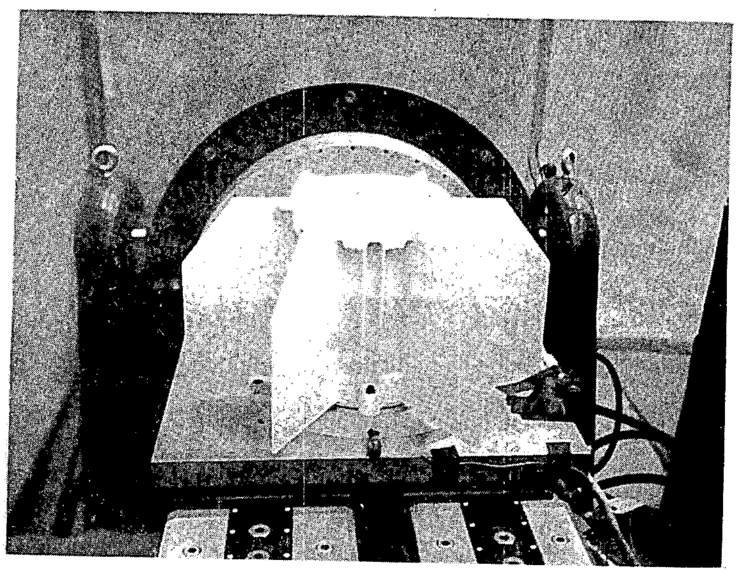
The performance parameters of all generators exhibited satisfactory behavior during tests. A comparison of stable generator performance data obtained before and after environmental testing is presented for each generator in Table V-4.

FIG. V-37. SNAP 19 AXES DESIGNATION FOR PIONEER APPLICATION





RTG S/N 52 WITH SHAKER VERTICAL (SPACECRAFT LATERAL 2 AXIS)



RTG S/N 53 WITH SHAKER HORIZONTAL (SPACECRAFT LATERAL 1 AXIS)

FIG. V-38. SHAKER ORIENTATION

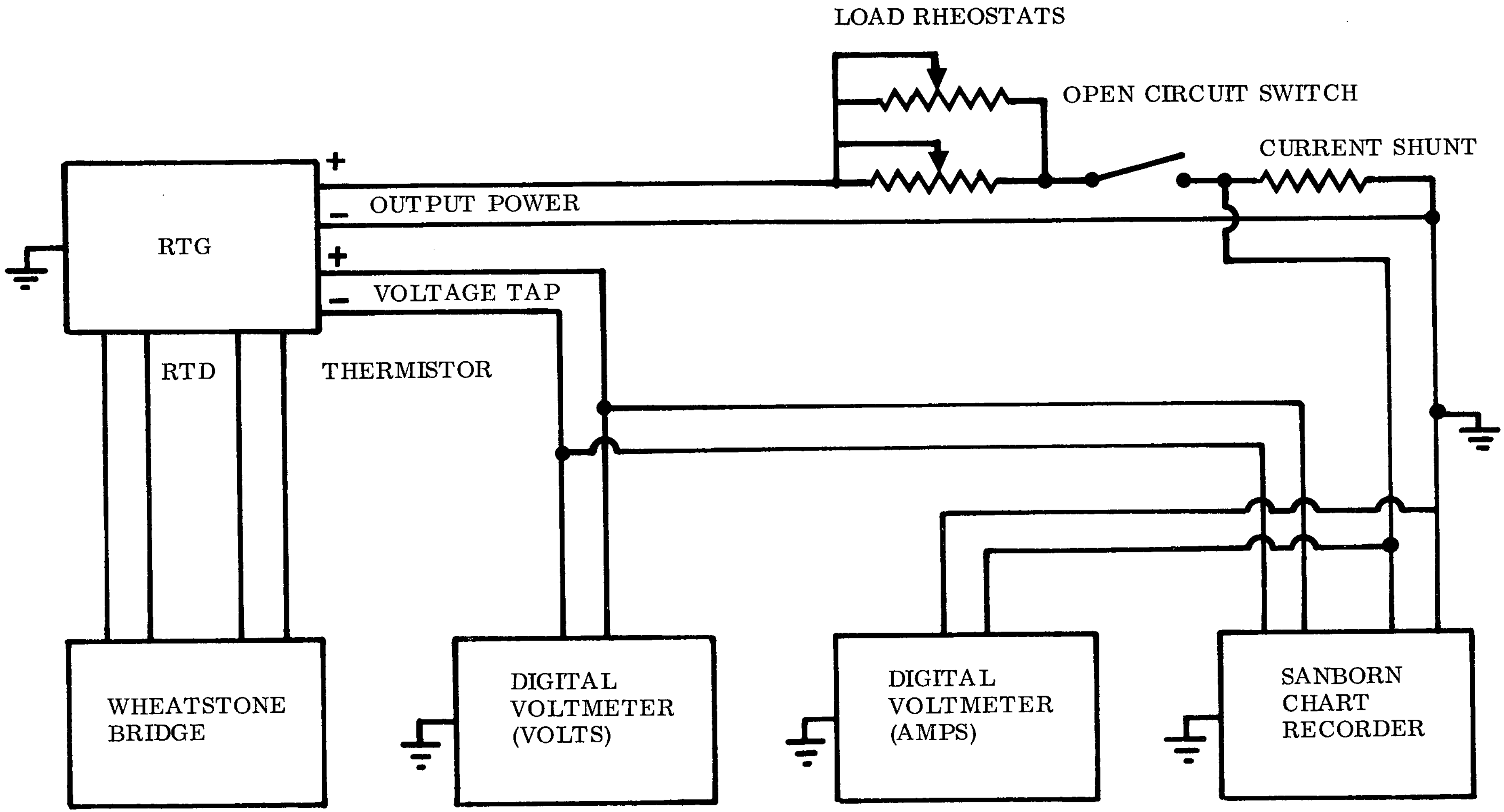


FIG. V-39. ENVIRONMENTAL TEST SCHEMATIC--INSTRUMENTATION SYSTEM

TABLE V-3

VIBRATION LEVELS FOR PIONEER APPLICATIONS

I. SINUSOIDAL VIBRATION LEVELS

Axis	Frequency Range (Hz)	Acceptance Acceleration (g's)	Qualification Acceleration (g's)
Normal to generator cylinder and parallel to fin (S/C thrust axis)	5 - 25	8.0*	12.0*
	25 - 50	18.0*	27.0*
	50 - 100	6.0	9.0
	100 - 200	1.5	2.3
Axes			
Normal to generator cylinder and normal to fin (S/C Lateral 1)	5 - 22	13.0*	20.0*
	22 - 100	12.0*	18.0*
	100 - 200	2.0	3.0
Axial, parallel to axis of generator (S/C Lateral 2)			
Sweep Rate (octave/min)		4	2

* or within 0.4 inch double amplitude displacement

II. RANDOM VIBRATION LEVELS

	Frequency Range (Hz)	PSD (g^2/Hz)	Acceleration g (rms)
Qualification level All three axes at 4.0 min/axis	20 - 50	0.40 at 50 Hz with 12 db/octave rolloff below 50 Hz	↑
	50 - 75	0.40	11.5
	75 - 200	Smooth rolloff (approx. 6 db/octave) from 0.4 at 75 Hz to 0.056 at 200 Hz	
	200 - 2000	0.056	↓
Acceptance level All three axes at 2.0 min/axis	20 - 50	0.179 at 50 Hz with 12 db/octave rolloff below 50 Hz	↑
	50 - 75	0.179	7.7
	75 - 200	Smooth rolloff (approx. 6 db/octave) from 0.179 at 75 Hz to 0.025 at 200 Hz	
	200 - 2000	0.025	↓

TABLE V-4

GENERATOR PERFORMANCE PARAMETERS

Normalized to a Fin Root Temperature of 330°F

	Prior to Environmental Testing				After Environmental Testing			
Generator S/N	Power (watts)	Load Voltage (volts)	E_{OC} (volts)	T_{HOT} (°F)	Power (watts)	Load Voltage (volts)	E_{OC} (volts)	T_{HOT} (°F)
36	41.1	4.23	6.70	987	41.1	4.22	6.74	988
37	41.2	4.27	6.85	981	40.1	4.30	6.87	984
38	40.3	4.27	6.84	980	40.2	4.31	6.86	981
39	39.2	4.27	6.80	946	39.2	4.26	6.80	947
40	39.6	4.28	6.71	965	39.6	4.28	6.71	966
41	37.0	4.32	6.92	976	36.5	4.30	6.92	976
42	39.0	4.26	6.80	957	39.0	4.26	6.82	966
43	40.3	4.28	6.75	960	40.3	4.27	6.75	962
44	41.2	4.28	6.77	967	41.3	4.28	6.78	968
45	39.8	4.34	6.65	960	39.7	4.33	6.66	963
46	40.1	4.30	6.60	957	39.8	4.31	6.65	957
47	39.7	4.20	6.62	941	39.4	4.20	6.62	941
48	39.8	4.20	6.63	961	40.3	4.20	6.64	963
49	40.1	4.20	6.73	935	39.8	4.20	6.70	930
50	39.1	4.20	6.72	946	39.0	4.20	6.72	943
51	40.3	4.20	6.84	957	40.2	4.20	6.85	955
52	40.5	4.20	6.81	958	40.3	4.20	6.80	956
53	39.7	4.20	6.56	962	39.7	4.20	6.57	955

b. Shock

Prototype RTG's were subjected to a shock spectrum as part of their environmental qualification tests. Shock testing was accomplished in the same setup as vibration at the Space and Electronics Systems Division of Fairchild Industries in Germantown, Maryland.

Generator S/N 37, the first fueled unit and qualification test specimen for the Pioneer program, was tested on December 19, 1970. Qualification of design changes led to tests of S/N 41 and S/N 42 on September 21, 1971.

Testing was accomplished on a Ling model A300B shaker. A mass model of the generator was initially used to adjust the synthesizer so as to provide the required shock spectrum.

Three shocks were applied in each of three mutually perpendicular axes. The arrangement of these axes is shown in Fig. V-37. A Sanborn recorder continuously displayed output voltage and current of the generator. Hot junction temperature (RTD) and fin root temperature (thermistor) were read periodically and the data recorded. Additional instrumentation included a wattmeter to provide a continuous check on generator output power and digital voltmeters to permit continuous visual monitoring of input and output power. An adjustable load maintained a 4.2 volt load voltage, and the generator fins were uninsulated. Fig. V-39 shows the instrumentation schematically.

Generator S/N 37 was tested with an MB Electronics Model N981 Synthesizer and Model N982 Analyzer. Technical difficulties with the analyzer allowed the shock spectrum to vary outside the desired tolerance envelope. However, it was sufficiently close that customer acceptance was granted. A typical shock spectrum, together with the tolerance envelope, is shown in Fig. V-40.

When testing of generators S/N 41 and S/N 42 began in September of 1971, better equipment was available for synthesis and analysis of the shock spectrum. A Ling Electronics Model ESD 13 Synthesizer Equalizer and Model SS1 Analyzer were used, and the actual shock spectrum produced was well within the tolerance envelope. Revisions in the predicted vehicle dynamics resulted in a change of the tolerance envelope from that used for S/N 37. The revised envelope, together with a typical shock spectrum, is shown in Fig. V-41.

FIG. V-40. SHOCK NO. 1 IN SPACECRAFT THRUST AXIS
RTG S/N 37

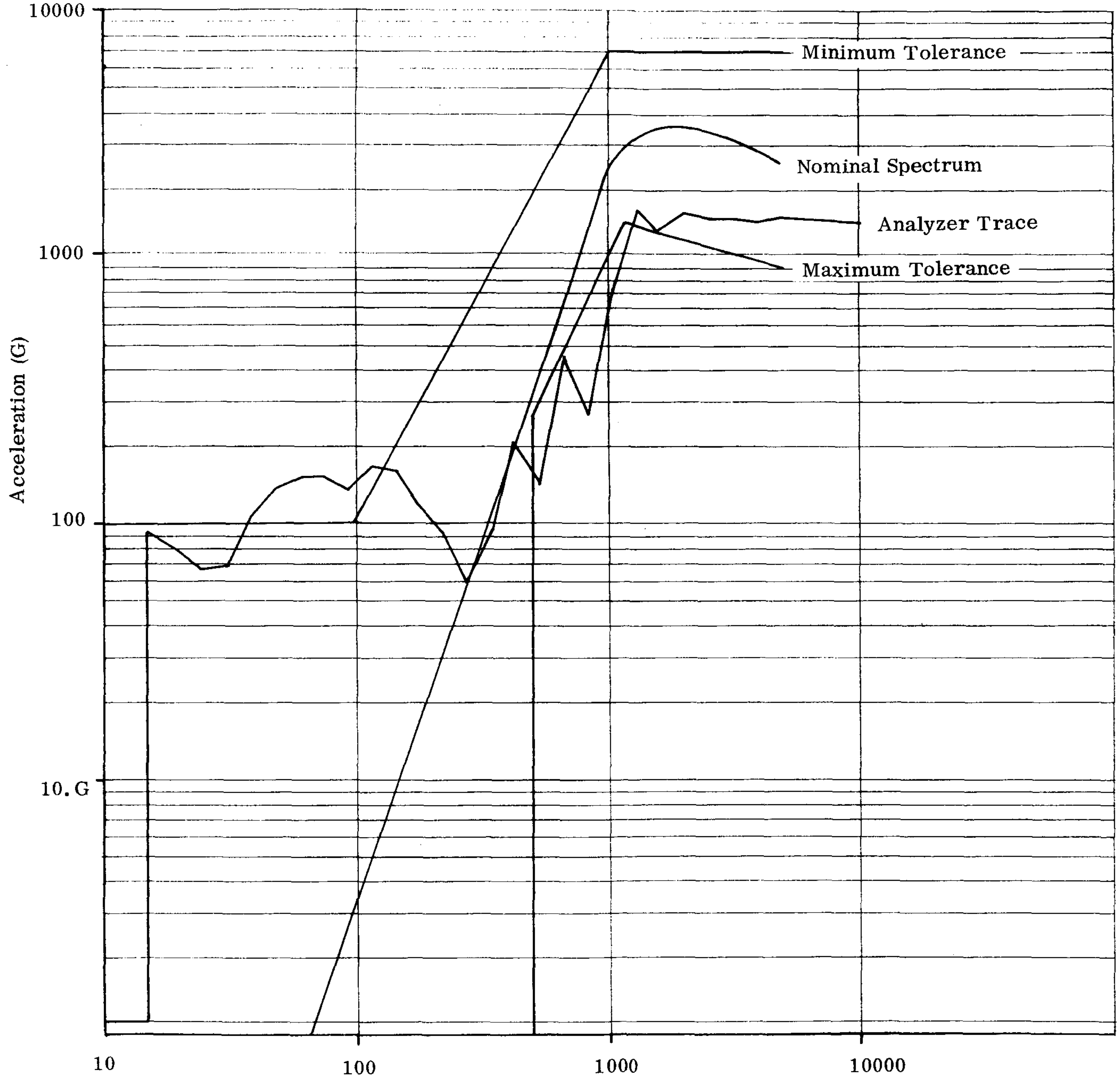
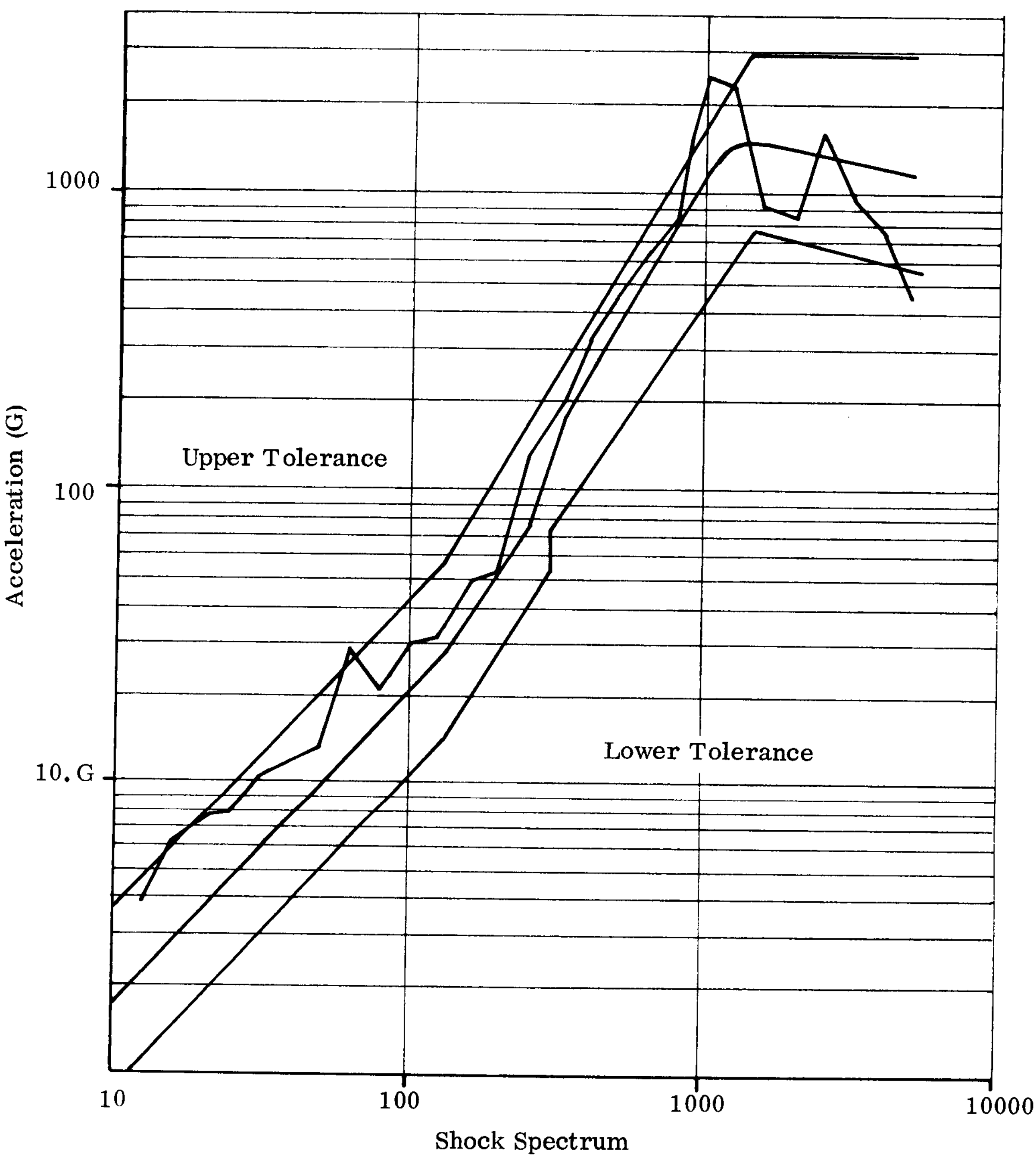


FIG. V-41. SHOCK NO. 1 IN SPACECRAFT THRUST AXIS
RTG S/N 41



Shock testing of generator S/N 37 is detailed in Reference 10 and the procedure for the test is given in Reference 20. The testing of generators S/N 41 and S/N 42 is presented in detail in Reference 12.

c. Acceleration

One prototype generator, S/N 37, was subjected to acceleration testing. This testing was accomplished during December 1970, at the Space and Electronics Systems Division of Fairchild Industries in Germantown, Maryland.

Testing was accomplished on an Achaevitz Model B-8-A rotary accelerator. The generator was mounted so that the acceleration load was applied in a direction equivalent to the vector sum of the vehicle thrust and spin accelerations. This direction lies in a plane formed by the thrust and lateral 2 axes (as shown in Fig. V-37). It passes through the center of the generator, and is inclined at an angle of 67.8° from the lateral 2 axis. All electrical connections to the generator are made through slip rings.

Acceptance acceleration of 24.3 g's was applied for three minutes. Acceleration loading was then increased to 36.5 g's for qualification testing, and held again for three minutes.

Actual rotational velocity of the rotary accelerator was measured by an electronic counter driven from an impulse transducer. Desired rotational velocity was determined from the necessary acceleration and the distance from the generator center to the acceleration boom rotation center. The desired rotational velocity was achieved in both acceptance and qualification tests.

Details of the acceleration test are presented in Reference 10, and the procedure used for testing is given by Reference 19.

The generator successfully passed both qualification and acceleration tests. Performance monitored before, during, and after testing showed no significant variation from anticipated values. Before and after test values of performance parameters are shown in Table V-4.

5. Thermal Vacuum

Generators S/N 37 through 53 were tested in vacuum for periods ranging from 7 to 14 days. The duration, fin root temperature, and completion dates of individual tests are identified in Table V-5. Test objectives were to achieve stable RTG performance in a simulated space environment without the effects of solar radiation and spacecraft mounting structures.

TABLE V-5

SUMMARY OF THERMAL VACUUM TESTS

Generator S/N	Configuration	Test Duration (Days)	Average Fin Root Temperature (°F)	Test Completion (Acceptance) Date
37 & 38	Tandem Mounted	7	327 & 328	1/15/71
39 & 40	Tandem Mounted	7	325 & 326	2/3/71
41 & 42	Tandem Mounted	7	333 & 316	10/4/71
43 & 44	Tandem Mounted	14	325 & 325	10/31/71
45 & 46	Tandem Mounted	7	329 & 333	11/27/71
47 & 48	Tandem Mounted	11	330 & 331	12/16/71
49 & 50	Tandem Mounted	14	327 & 326	11/12/72
51	Single, Upright	14	326	12/18/72
52 & 53	Tandem Mounted	14	326 & 326	12/2/72

Prior to the start of each test, stable performance and instrumentation parameters were recorded with the generator in ambient air and fins uninsulated. The vacuum test operations involved parametric tests in load voltage on the first and last days with a one to two week period of stable thermal and electrical behavior at a chamber pressure of less than 1×10^{-5} torr. To obtain and hold fin root temperatures of 325 ± 10°F during the tests, cold wall average temperatures near -50°F for tandem mounted generator pairs, and +20°F for a single generator (S/N 51) were required. Results and specific procedures of these tests are recorded in References 21 through 28.

Stable generator data, including parametric points from the S/N 49/50 thermal vacuum test are shown in Figs. V-42 and V-43. All parameters, i.e., output power, hot junction temperature, open circuit voltage and internal resistance are seen to increase during the period. The increases are attributed to thermoelectric property changes. The S/N 49/50 performance charts are typical of all generators during thermal vacuum. RTG performance at "acceptance" (last parametric test before delivery) is summarized in Table V-6.

6. Mass Properties

Mass properties of all SNAP 19 generators were determined by laboratory testing. Weight, center of gravity, and moments of inertia with respect to three mutually perpendicular axes were measured for all RTG's. In addition, generators S/N 37 and S/N 38 were subjected to measurement both before and after environmental testing to determine constancy of the center of gravity. Because no change was detected, subsequent generators had mass property measurements made only after environmental testing.

Properties for nominal generators were predicted with a computer code. This code accepted as input the basic mass properties of all components used in a generator. Agreement between predicted and measured parameters was satisfactory.

a. Test Chronology

Mass properties testing of RTG S/N 37 through 42 was conducted at the Space and Electronics System Division of Fairchild Industries, Germantown, Maryland. Center of gravity and moment of inertia testing was performed on RTG S/N 37 and S/N 38 on

FIG. V-42. GENERATORS S/N 49 AND S/N 50 PERFORMANCE DURING THERMAL VACUUM TEST

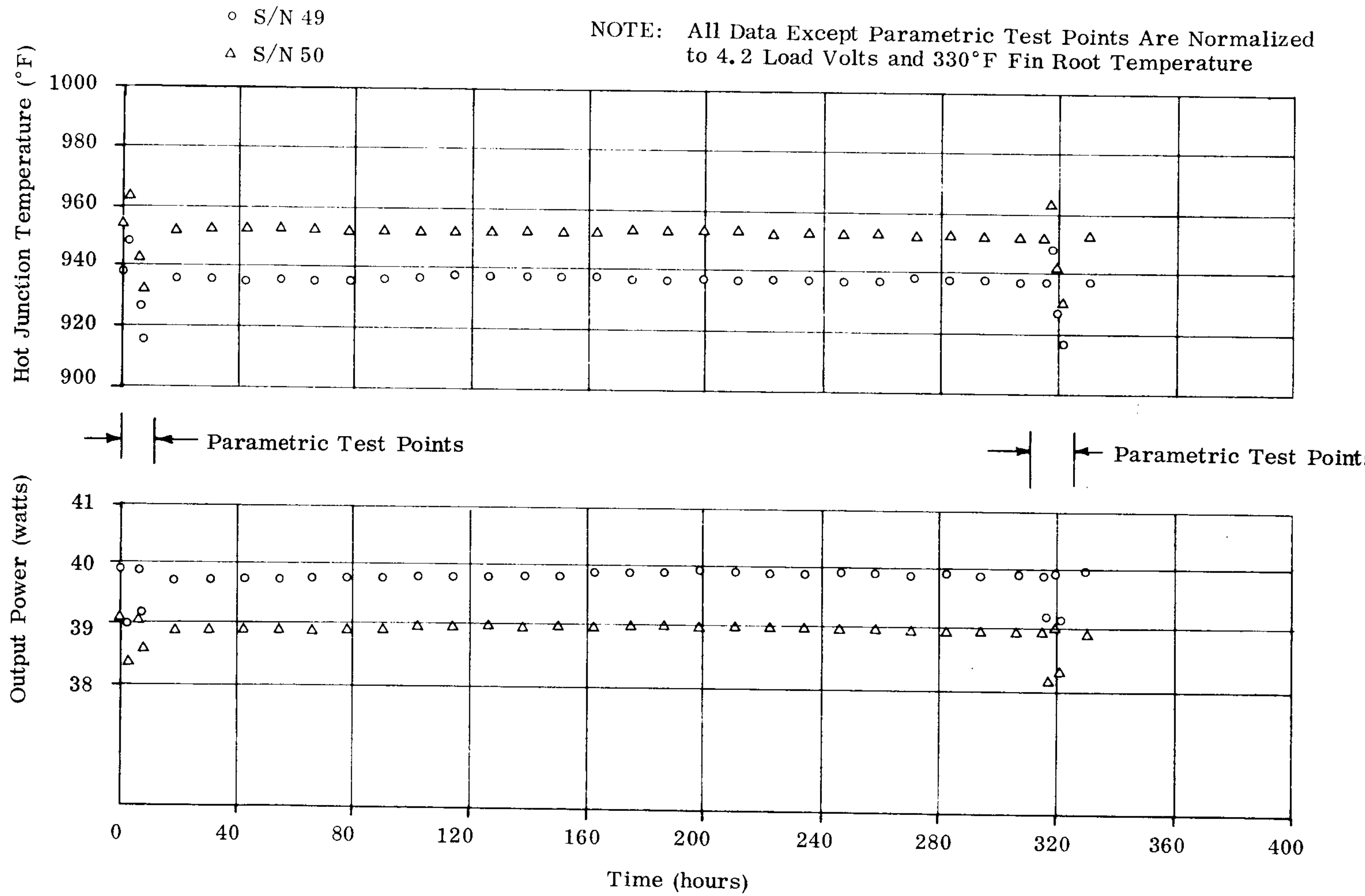


FIG. V-43. GENERATORS S/N 49 AND S/N 50 PERFORMANCE DURING THERMAL VACUUM TEST

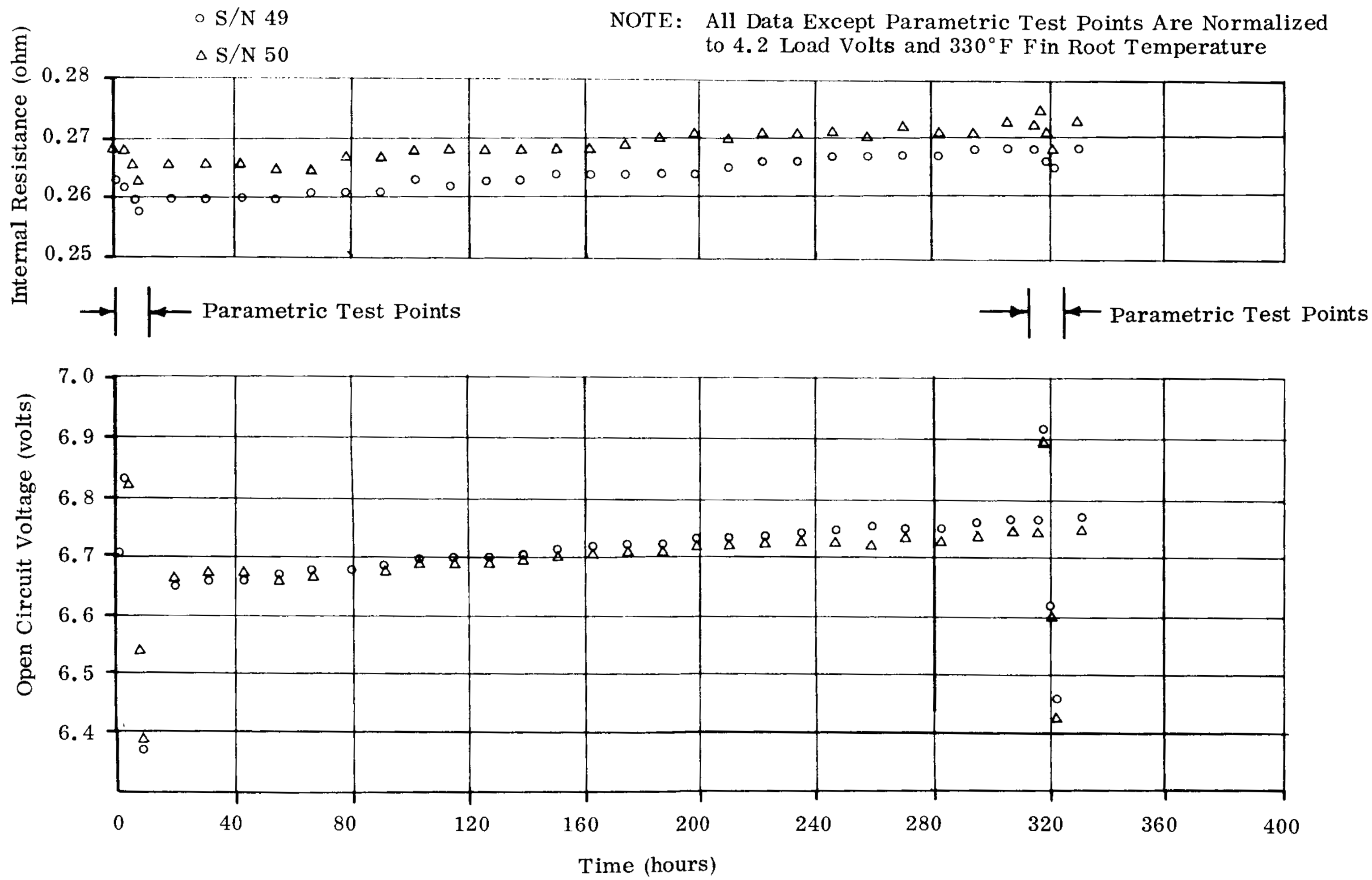


TABLE V-6

RTG PERFORMANCE AT ACCEPTANCE

(at 4.2 Load Volts, 330°F on Fin Root)

RTG S/N	Power Output (watts)	Hot Junction Temperature (°F)	Heated Hours
37	39.7	996	1440
38	40.3	987	1080
39	38.6	952	1300
40	39.2	970	750
41	36.8	982	2810
42	38.9	967	750
43	40.3	967	985
44	41.1	973	6635
45	40.2	964	610
46	40.4	963	404
47	39.8	942	675
48	40.7	972	500
49	40.0	939	1090
50	39.1	954	1050
51	40.1	956	1075
52	40.3	964	1030
53	39.6	965	1065

December 17, 1970. The tests were repeated on December 21, 1970 after RTG S/N 37 received acceptance and qualification vibration, shock and acceleration environmental tests. RTG S/N 38 was subjected to acceptance vibration testing, after which testing for mass properties was repeated. RTG's S/N 39 and S/N 40 were subjected to acceptance vibration testing prior to the mass properties testing performed on January 15, 1971. RTG S/N 41 and S/N 42 were tested in September 1971.

Testing of RTG's S/N 40 and 43 through 53 was conducted at TRW Systems Group in Redondo Beach, California. Mass properties testing of S/N 43 and S/N 44 was accomplished in November 1971, and S/N 45 through S/N 50 in December 1971. Generator S/N 51 was tested in January 1973, and Generators S/N 52 and 53 in December of 1972

b. Test Description

(1) Measurement technique at Fairchild Industries

Mass properties were measured with a Miller Dynamic Balancing (Airdyne) Machine Facility, Model 299.

The center of gravity is determined with this machine by measuring the static force on a load sensitive device at the periphery of a table supported by a nearly frictionless gas bearing.

Moment of inertia determination is obtained by measuring the period of oscillation of a torsional pendulum which supports the specimen and mounting platform. The period determination for moment of inertia is made by measuring between alternate interruptions of a light beam. A photoelectric detector system and a wand attached to the table are utilized in conjunction with an electronic timer.

Weight measurement of the RTG and its shorting connector was performed on a HOMS beam balance scale model 105 TWX utilizing NBS master weights register No. 6.6/15 6007. The weight of the RTG shorting plug was obtained by a separate measurement of the plug. The technique of measurement is to balance the scale with the test specimen in place, remove the test specimen, and obtain the same balance with NBS weight-standards.

(2) Measurement technique at TRW

The TRW Mass Properties Measurement System, Model 100/10000 enables determination of center of gravity by rotating the specimen about a vertical axis and detecting the resulting oscillatory torque about some horizontal axis. In practice, balancing weights are added to null the oscillatory torque at two different angular spin rates.

Moments of inertia are measured in a manner similar to that of the Fairchild-Hiller machine. The period of oscillation of the mounting fixture and specimen about a vertical axis enable the determination from known characteristics of a rectilinear spring torsional pendulum.

RTG weight was measured with an Ohaus 20 kilogram beam balance. Calibration covered a range of 28 to 34 pounds with a set of Class C calibration weights.

(3) Results of measurements

Results of the mass properties tests are summarized in Table V-7. The center of gravity and moment of inertia values are the result of statistical analysis of several test runs performed in each axis.

The data are referenced to the mounting plane of the generator and do not include the effects of the shorting plug. Generators S/N 37 to S/N 40 were tested both before and after vibration, but the values in Table V-7 are post-vibration only, since the results were indistinguishable.

Detailed explanation of testing procedure and raw test data is available in References 1 to 3.

7. Generator Test Chronologies

The sequence and dates of tests on 2N-TAGS 85 generators S/N 26 through S/N 53 (including refurbished generators S/N 33R and S/N 35R) are presented in Tables V-8 through V-10. All significant tests and activities between the completion of initial outgassing and delivery/disposition, where applicable, are shown. For cases where generator acceptance (by the customer) was contingent on satisfactory results of mass property measurements performed after delivery, the dates of such measurements have been shown. In-field testing by user agencies or Teledyne Isotopes facility tests following initial delivery to a customer designated facility have been omitted.

TABLE V-7

MASS PROPERTIES DATA SUMMARY

RTG S/N	Center of Gravity $\overline{X}$ inches	$\overline{Y}$ inches	$\overline{Z}$ inches	Moments of Inertia I_{xx} lb-in^2	I_{yy} lb-in^2	I_{zz} lb-in^2	W lbs
37	+0.013 ± 0.004	+0.039 ± 0.004	5.606 ± 0.008	*	*	*	28.925 ± 0.002
38	+0.012 ± 0.005	+0.036 ± 0.003	5.647 ± 0.005	*	*	*	28.865 ± 0.002
39	+0.003 ± 0.005	+0.043 ± 0.005	5.650 ± 0.010	1190.60 ± 0.9	1208.40 ± 0.7	197.60 ± 0.8	28.925 ± 0.002
40	+0.007 ± 0.009	+0.049 ± 0.007	5.607 ± 0.016	1184.90 ± 0.2	1230.10 ± 1.0	205.70 ± 0.7	28.915 ± 0.002
41	-0.007 ± 0.003	-0.008 ± 0.001	5.606 ± 0.003	1218.60 ± 0.5	1224.00 ± 0.6	218.40 ± 0.6	29.355 ± 0.007
42	+0.001 ± 0.004	-0.008 ± 0.003	5.557 ± 0.003	1217.20 ± 0.6	1237.30 ± 0.5	257.50 + 0.7	29.355 ± 0.007
43	+0.004 ± 0.0012	0.0 ± 0.0031	5.613 ± 0.0012	1277.10 ± 0.212	1277.49 ± 0.198	251.80 ± 0.266	30.083 ± 0.004
44	+0.016 ± 0.0017	-0.009 ± 0.0042	5.626 ± 0.0021	1277.82 ± 0.252	1280.71 ± 0.196	252.72 ± 0.286	29.944 ± 0.004
45	+0.016 ± 0.0016	-0.006 ± 0.0027	5.625 ± 0.0014	1284.02 ± 0.244	1285.95 ± 0.288	256.21 ± 0.340	30.058 ± 0.004
46	+0.032 ± 0.0013	0.0 ± 0.0022	5.661 ± 0.0013	1296.11 ± 0.199	1295.78 ± 0.305	249.47 ± 0.391	30.004 ± 0.004
47	+0.018 ± 0.0012	-0.002 ± 0.0019	5.640 ± 0.0010	1291.21 ± 0.269	1293.10 ± 0.328	252.43 ± 0.536	30.096 ± 0.004
48	+0.010 ± 0.0015	+0.005 ± 0.0018	5.634 ± 0.0014	1293.52 ± 0.246	1296.51 ± 0.200	257.14 ± 0.276	30.182 ± 0.004
49	+0.017 ± 0.0005	-0.003 ± 0.0032	5.630 ± 0.0017	1293.89 ± 0.292	1293.68 ± 0.541	258.92 ± 0.429	30.170 ± 0.004
50	+0.016 ± 0.0005	+0.003 ± 0.0022	5.627 ± 0.0009	1287.23 ± 0.389	1289.76 ± 0.524	257.84 ± 0.399	30.110 ± 0.004
51	+0.022 ± 0.0014	+0.005 ± 0.0033	5.641 ± 0.0013	1298.03 ± 0.222	1301.03 ± 0.601	259.74 ± 0.540	30.200 ± 0.004
52	+0.026 ± 0.0009	+0.007 ± 0.0018	5.649 ± 0.0014	1285.23 ± 0.435	1285.42 ± 0.401	251.16 ± 0.325	29.910 ± 0.004
53	+0.017 ± 0.0005	+0.006 ± 0.0022	5.631 ± 0.0017	1292.01 ± 0.409	1293.14 ± 0.565	256.60 ± 0.633	30.140 ± 0.004

* Raw data not reduced, mass properties machine not functioning properly.

TABLE V-8

GENERATOR TEST CHRONOLOGIES S/N 26 THROUGH S/N 34

Activity	S/N 26	S/N 27	S/N 28	S/N 29	S/N 30	S/N 31	S/N 32	S/N 33	S/N 33R	S/N 34
Complete outgassing	5/8/69	5/29/69	5/29/69	8/11/69	10/23/69	10/23/69	12/10/69	12/13/69	2/11/70	1/20/70
Manufacturing power check	5/8/69	5/29/69	5/29/69	8/11/69	11/14/69	10/23/69	12/10/69	12/13/69	2/11/70	1/20/70
Cool down		5/29/69	5/29/69	8/12/69	11/14/69	10/24/69	12/10/69	12/13/69	2/11/70	1/20/70
Heat up		6/5/69	6/5/69	8/18/69	11/18/69	10/27/69	12/11/69	12/15/69	2/17/70	1/22/70
Initial parametric	5/21/69	6/7/69	6/5/69	8/19/69	11/21/69	10/28/69	12/12/69	12/15/69	2/18/70	1/23/70
Hot argon leak test		6/9/69	6/7/69	8/21/69	11/19/69	10/29/69	12/13/69	12/15/69	2/21/70	1/29/70
Start burn in									2/22/70	1/31/70
Complete burn in									3/24/70	3/1/70
Cool down		6/9/69	6/9/69	8/21/69	11/21/69	11/8/69	12/14/69	12/16/69	3/24/70	
Heat up		6/11/69	6/10/69	8/25/69			12/15/69	12/16/69		
Start vibration		6/12/69	6/11/69	8/25/69			12/16/69	12/17/69		
Complete vibration		6/14/69	6/14/69	8/26/69			12/18/69	12/18/69		
Cool down		6/14/69	6/14/69				12/19/69	12/18/69		
Heat up		6/25/69	6/25/69				1/12/70			
Parametric test	7/24/69	6/29/69	6/27/69	8/27/69			1/12/70			
Reduced power input parametric							1/15/70			3/18/70
Hot argon leak test		6/27/69	6/26/69				1/16/70			
Cool down		7/1/69	7/1/69	8/29/69			1/17/70			
Heat up		10/8/69	11/19/69	9/25/69						
Parametric test	9/24/69		11/20/69							
Start gas fill tests				9/29/69						
Complete gas fill tests				11/21/69						
Load transient tests				1/26/70						
Start fin root sweep	10/30/69	10/14/69		1/28/70						3/2/70
Complete fin root sweep test	11/7/69	10/28/69		2/10/70						3/13/70
Load switching tests										4/3/70
Parametric test	12/2/69									
Hot argon leak test			11/24/69	2/27/70						
Cool down		10/29/69	11/26/69							6/10/70
Load transient tests	1/7/70									
Start endurance test	4/20/70			4/3/70						
Gas fill and pressure tests	3/23/71									
Diagnostic disassembly								ESD 1/70		
Delivery/disposition	on test at Teledyne Isotopes	Langley 5/70	Langley 5/70	on test at Teledyne Isotopes	Goddard 12/69	JPL 12/69	Ames 1/70		Ames 5/70	Ames 6/70

TABLE V-9

GENERATOR TEST CHRONOLOGIES S/N 35 THROUGH S/N 43

Activity	S/N 35	S/N 35R	S/N 36	S/N 37	S/N 38	S/N 39	S/N 40	S/N 41	S/N 42	S/N 43
Complete outgassing	3/18/70	7/1/70	9/17/70	11/15/70	11/25/70	12/11/70	12/21/70	1/24/71	9/3/71	9/21/71
Manufacturing power check	3/18/70	7/1/70	9/17/70	11/15/70	11/25/70	12/11/70	12/21/70	1/24/71	9/4/71	9/21/71
Cool down	3/19/70	7/2/70			11/26/70		12/22/70	1/26/71		
Heat up	3/24/70							6/2/71		
Gas exchange		7/3/70		11/17/70	11/30/70	12/14/70	12/30/70	6/4/71	9/8/71	9/22/71
Heat up		7/3/70			12/1/70		1/4/71			
Gas fill and pressure tests								6/18/71		
Cool down in vacuum								8/18/71		
Getter installation and outgassing								8/26/71		
Bottom stack weld								8/28/71	9/9/71	9/23/71
Fueling				11/19/70	12/3/70	12/16/70	1/5/71	8/28/71	9/11/71	9/24/71
Hot gas leakage tests	3/27/70	7/4/70	9/18/70	11/20/70	12/6/70	12/17/70	1/6/71	8/30/71	9/12/71	9/26/71
Parametric	3/25/70		9/18/70	11/21/70	12/7/70	12/17/70	1/7/71	8/29/71	9/11/71	9/25/71
Radiation survey				11/23/70	12/8/70	12/23/70	1/11/71	8/31/71	9/13/71	10/10/71
Final weld			9/17/70	11/24/70	12/10/70	12/21/70	1/8/71	8/31/71	9/13/71	9/28/71
Mass properties				12/17/70	12/17/70			9/5/71	9/15/71	
Vibration - acceptance	5/5/70		9/24/70	12/18/70	12/20/70	1/13/71	1/14/71	9/7/71	9/19/71	10/12/71
Cool down	4/30/70	7/4/70	9/25/70							
Heat up	5/4/70	7/8/70	9/28/70							
Vibration - qualification			9/28/70	12/18/70				9/15/71	9/20/71	
Cool down	5/5/70	7/9/70	9/29/70							
Heat up			9/30/70							
Shock				12/19/70				9/18/71	9/22/71	
Acceleration				12/19/70						
Mass properties				12/21/70	12/21/70	1/15/71	1/15/71	9/19/71	9/23/71	
Radiography of capsule								9/20/71	9/24/71	
Hot gas leakage			10/1/70	12/23/70	12/23/70	1/26/71	1/26/71	9/23/71	9/25/71	10/15/71
Parametric test			10/2/70							
Thermal vacuum - start				1/7/71	1/7/71	1/27/71	1/27/71	9/27/71	9/27/71	10/17/71
Thermal vacuum (acceptance)				1/15/71	1/15/71	2/3/71	2/3/71	10/4/71	10/4/71	10/31/71
Start endurance test									10/12/71	
Parametric test									1/3/72	
Parametric test									7/27/72	
Power checks									9/27/72	
Short circuit operation									9/28/72	
Cool down			10/2/70							
Mass properties test at TRW										11/16/71
Diagnostic disassembly	ESD 5/70									
Delivery/disposition		Ames 7/70	Ames 10/9/70	Ames 1/29/71	Ames 1/29/71	Ames 2/19/71	Ames 2/19/71	defueled MRL 10/7/71	MRL/JPL 10/2/72	Ames 11/4/71

TABLE V-10

FLIGHT GENERATOR TEST CHRONOLOGIES S/N 44 THROUGH S/N 53

Activity	S/N 44	S/N 45	S/N 46	S/N 47	S/N 48	S/N 49	S/N 50	S/N 51	S/N 52	S/N 53
Complete outgassing	10/4/71	11/2/71	11/10/71	11/19/71	11/25/71	7/28/72	1/14/72	8/24/72	9/21/72	10/19/72
Manufacturing power check	10/5/71	11/3/71	11/10/71	11/20/71	11/25/71	7/28/72	1/14/72	8/24/72	9/21/72	10/19/72
Gas exchange							1/16/72			
Cool down						7/30/72	1/17/72	8/26/72	9/23/72	
Heat up							7/15/72			
Complete second outgassing							7/28/72	10/19/72		
Manufacturing power check							7/28/72	10/19/72		
Cool down							7/30/72	10/21/72		
Gas exchange	10/6/71	11/4/71	11/11/71	11/21/71	11/26/71	9/28/72	10/4/72	11/8/72	10/25/72	10/20/72
Heat up						9/29/72	10/5/72	11/9/72	10/25/72	
Fueling	10/7/71	11/9/71	11/13/71	11/24/71	11/30/71	10/3/72	10/10/72	11/14/72	11/3/72	10/24/72
Parametric test	10/9/71	11/10/71	11/14/71	11/25/71	12/1/71	10/4/72	10/11/72	11/15/72	11/4/72	10/25/72
Hot gas leakage test	10/9/71	11/10/71	11/14/71	11/25/71	12/1/71	10/4/72	10/11/72	11/15/72	11/4/72	10/25/72
Radiation survey	10/10/71	11/11/71	11/16/71	11/29/71	12/2/71	10/6/72	10/13/72	11/19/72	11/8/72	10/29/72
Final weld	10/10/71	11/11/71	11/15/71	11/28/71	12/2/71					
Vibration - acceptance	10/14/71	11/16/71	11/18/71	12/1/71	12/3/71	10/24/72	10/25/72	11/30/72	11/14/72	11/15/72
Hot gas leakage test	10/16/71	11/18/71	11/19/71	12/2/71	12/5/71	10/27/72	10/28/72	12/1/72	11/16/72	11/17/72
Thermal vacuum - start	10/17/71	11/20/71	11/20/71	12/6/71	12/6/71	10/29/72	10/29/72	12/5/72	11/10/72	11/18/72
Thermal vacuum (acceptance)	10/31/71	11/27/71	11/27/71	12/16/71	12/16/71	11/12/72	11/12/72	12/18/72	12/2/72	12/2/72
Mass properties test at TRW	11/16/71	12/8/71	12/8/71	12/29/71	12/29/71	12/14/72	12/14/72	1/16/73	12/29/72	12/29/72
Delivery/disposition	Ames 11/4/71	Ames 11/28/71	Ames 11/28/71	Ames 11/18/71 Defueled	Ames 12/18/71	Ames 12/1/72	Ames 12/1/72	TRW/ Ames 1/6/73	Ames 12/15/72	Ames 12/15/72

S/N 36 is identical to S/N 35R except that it contains TZM compliant cups between the compliant pad and the graphite end plugs.

Prior to the diagnostic disassembly of RTG S/N 37, a gas tap was performed on ETG S/N 36. Upon completion of the gas sampling, S/N 36R was filled with the RTG type gas mixture of 75% helium and 25% argon.

VI. GENERATOR TECHNOLOGY PROGRESS

In addition to the incorporation of TAGS thermoelectric material and a modified heat source, several evolutionary type changes were implemented in the SNAP 19 RTG to increase confidence in its ability to satisfy the objectives of the Pioneer program. The most significant of these may be grouped into design modifications affecting inert cover gas management, reduction of active gaseous contaminants, and fuel capsule mechanical constraint. The following paragraphs describe the rationale leading to the final design selection in an effort to exemplify the maze of situations created by seemingly minor alterations.

A. INERT COVER GAS MANAGEMENT

The initial need for inert cover gas in the SNAP 19 RTG concerned reduction of sublimation of the TAGS and 2N thermoelectric materials. The SNAP 19 NIMBUS generators had employed an initial fill of about 15 psi argon and, because of relatively large viton O-ring seal area, a leak rate in excess of 10^{-4} scc/sec atm He yielded a very low gas pressure after two years in space despite the continuous replenishment of gas (He) from the decaying plutonium fuel. Thus, initial efforts were directed towards reduction of the leak rate by employing double O-ring seals at the housing to cover interfaces at both ends of the generator. However, the approach was not sufficient because of uncertainty of the helium release rate from the fuel, potential necessity for reducing heat source temperatures by filling initially with helium instead of argon, and uncertainty of the long term characteristics of the large Viton seals. Additionally, the resulting gas pressure of less than 5 psi at 39 months (the maximum specified time interval) was not believed to provide ample barrier to sublimation.

In order to enable retention of higher gas pressure in the RTG, the welded end closure design was developed and the Viton O-ring at the connector receptacle to housing interface was the significant remaining gas leak path. The small Viton area at the point yielded helium leak rates of nearly one order magnitude less (about 2×10^{-5} scc/sec atm) and thereby enabled assurance of cover gas pressure in excess of 5 psi for all ranges of helium release rate (down to <u>zero</u>). Of course, this result depended on the Viton seal maintaining constant leak rate characteristics through the 39 month period and, subsequently, test data were effective in obtaining adequate assurance of this constancy.

With regard to the Viton seal suitability, it should be noted that the 77-545 Viton formulation used in NIMBUS was applied to the Pioneer F flight generators, but for the Pioneer G mission a new formulation 747-75 Viton was used. The latter formulation demonstrated superior resistance to deterioration from elevated temperature and temperature cycling exposure and was deemed to provide greater margin of safety against low gas pressure.

In the same vein, the connector receptacle shell material was changed to 20CB3 stainless steel for the Pioneer G generator, where 321 stainless steel was applied for the Pioneer F RTG's. Again, manufacturers' tests and tests by Teledyne Isotopes showed superior margin for the 20CB3 configuration and it was adopted successfully.

B. REDUCTION OF GASEOUS CONTAMINANTS

The insidious nature of gaseous contaminants was experienced in the development activities leading to the final SNAP 19/Pioneer RTG design. An initial underestimation of the capacity of Min-K to retain water together with ignorance of the sensitivity of generator components to oxygen and hydrogen caused the adoption of conservative design and processing features. The following paragraphs present a brief summary of the events which occurred.

When the welded end closure design was effected, the leak rate of air into the RTG housing was reduced to a negligible amount. This fact, together with difficulties encountered with disintegrating getters in ETG tests prompted omission of the oxygen and water getter (zirconium) from initial ETG and RTG prototypes. It was not until observations of anomalous behavior in RTG S/N 37 that investigation of the gas composition of SNAP 19/Pioneer generators was initiated. Investigation of suspect power-time performance of S/N 37 (later shown to be caused by large helium release from the fuel) revealed the presence of a small amount of hydrogen (about two percent) and, more important, deterioration of the fuel containment members. In addition, measurements of gas content in ETG's showed continuous production of H_2O after extended periods of operation. Because of pressing schedule commitments, it was decided to reduce the likelihood of gaseous contaminants (primarily H_2O) and make changes in the heat source configuration to reduce its sensitivity to potential degradation mechanisms without quantitative evaluation of the original conditions or the effects of remedies.

To this end, corroborating evidence of water entrapment in the Min-K insulation of electrically heated generators and the experimentally determined affinity of Min-K for adsorbing moisture from ambient air were used to develop revised processing techniques for Min-K preparation, final generator assembly and pre-fueling outgassing of the generator. The new procedures specify that after initial bakeout and vacuum outgassing at elevated temperature ($\sim 1000°F$) Min-K insulation details are not allowed exposure to ambient air. The low water content atmosphere is maintained through the use of a glove box line for final generator assembly operations. In addition to this precaution, a more thorough outgassing procedure was instituted during initial heatup of the generator prior to fueling. The new method employs vacuum outgassing up to 600°F hot junction temperature and a continuous purge of inert gas up to normal operating temperature ranges until a <25 ppm water vapor measurement is satisfied. The necessity for such a procedure in view of the careful Min-K handling has not been established, but removal of additional water is observed and thereby a "purer" gas environment is obtained.

In order to provide further reduction of the potential for deleterious amounts of water and oxygen accumulating during RTG operation, a zirconium getter with a re-designed inert container of palladium was added to the generator. For conservatism, the getter capacity is sufficient for removal of water and oxygen even if the generator were exposed to air during assembly and outgassing operations were ineffective.

Since other mechanisms in addition to contaminated gas were potential causes of deterioration to the fuel containment members, modifications were made to the fuel (puck size) and capsule interface materials (Mo-Re foil between fuel and primary encapsulant). These changes were instituted to reduce the rates of solid state oxygen diffusion and/or gaseous oxygen transport within the heat source.

Table VI-1 illustrates the reduction of oxygen contamination effected by the modified RTG configuration. These data, obtained from R. Mulford of Los Alamos Laboratories, show that the oxygen content of the capsule strength member is greatly reduced in modified heat sources operated in generators employing a getter and improved outgassing procedures.

Thus, the diagnostic disassembly of additional prototype RTG's S/N 41 through 43 verified that elimination of the degrading mechanisms was achieved as a result of instituting all of the corrective actions. However, because of time and cost limitations, the effect of any one change was never evaluated. Indeed, two of the original prototype RTG's, S/N 38 and S/N 40, while they did not contain getters nor receive special outgassing preparation, continue to exhibit power performance quite similar to the Pioneer 10 flight system. Thus, although these generators were not usable because of deteriorated heat sources (verified by x-ray studies) unusual thermoelectric degradation was not observed. This last observation may be significant in the future if conditions occur which preclude glove box assembly of SNAP 19/Pioneer type generators. One would conclude that pre-fueling outgassing and the use of getters is sufficient to prevent unusual thermoelectric degradation and most probably would provide conditions for maintaining integrity of the fuel capsule.

TABLE VI-1

OXYGEN CONTAMINATION OF T-111 STRENGTH MEMBER

	RTG/ Capsule No.		Time at Temperature Greater than 800°C (hrs.)	Oxygen Content Max/Avg (ppm)
Original Capsule/ Converter Configuration	S/N 37	PF 1	2470	1900/1000
	S/N 39	PF 3	2400	600/500
		PF 5*	950	4500/3000
Modified Capsule/ Converter Configuration	S/N 41	PF 7	600	160/121
	S/N 43	PF 9	400	200/120
	S/N 47	PF 13	1000	140/106

*Not operated in an RTG, but surrounded by Min-K which was not outgassed thoroughly.

C. HEAT SOURCE MECHANICAL CONSTRAINT

It became evident during vibration testing of the engineering ETG's S/N 32, 33 and 34 that the method of constraining the fuel capsule within the heat shield applied to the SNAP 19/ NIMBUS program was inadequate for the Pioneer program. Not only was the solid electrical heat source poorly fixed by the compressed tantalum felt pads and tantalum cups, but the multilayered radioisotope capsule with loose fitting fuel pucks promised to impose additional loads which threatened the integrity of the thermoelectric modules. After many design iterations and a series of room temperature vibration tests of generators containing simulated fuel capsules (thorium oxide pucks in the three layer containment) a hard mount design was adopted.

The selected design possesses the feature of constraining the outermost containment layer (Pt-Rh) tightly, but allowing for unusual thermal expansion (as during reentry) by a shearable ring machined into each graphite heat shield end plug. The ends of the fuel capsule are not allowed to bear directly against the graphite end plugs because the low thermal resistance path yields excessive heating during reentry, and zirconium oxide rings are used as load transmitting thermal barriers at each end.

Additional thermal protection of the fuel capsule is afforded by a pyrolytic graphite ring located in an annulus between the fuel capsule and integral Poco graphite heat shield. The pyrolytic graphite, a thermally anisotropic material, is formed to yield high thermal resistance in the radial direction (towards the capsule) but much lower resistance in the axial direction to facilitate heat transport to the thermoelectric modules.

VII. AEROSPACE NUCLEAR SAFETY SYNOPSIS

The safety evaluation effort for the Pioneer mission commenced during September of 1969 and was terminated with the launch of Pioneer F (10). Significant innovations were introduced in the course of the program which permitted more qualitative estimates of the risk of releasing radioactive fuel to the environment. Among these were a transition matrix approach which was applied to launch pad accidents to consider quantitatively the sequence of environments and the variety of potential states of the nuclear system, a method for determining the probability density for initial reentry conditions (V-gamma maps), incorporation of radiative heating contributions during reentry, development work with regard to the net effect of reentry oxidation and sublimation of the graphitic heat shield, practical application of meteorological statistics to determine exposure risks and a contribution to the understanding of oxygen transport from fuel to the T-111 alloy fuel capsule.

A safety test program comprising reentry simulations, impact response at terminal speed, and simulation of severe launch pad accident environments was begun in Jaunuary of 1970 and terminated during June of 1971. Supporting experimental and analytical data in areas of fuel properties, fuel/capsule compatibility, fuel release modules and biological exposures were provided by other AEC contractors including Los Alamos Scientific Laboratory, Oak Ridge National Laboratory, Monsanto Research Corporation-Mound Laboratories, and the NUS Corporation.

Results of the test programs were utilized to confirm predictive techniques in the cases of reentry temperatures ablative recession and heating distributions, provide estimates of reentry motion, in the case of aerodynamic force and moment measurements, and to infer failure conditions for various elements of the nuclear system.

Safety evaluation effort culminated with the completion of the Safety Analysis Report in July of 1971. Review meetings for the benefit of the Interagency Safety Review Panel included the Nuclear Power Systems Safety Group meeting at the Cape Kennedy Air Force Station, November 8, 1971, and the World-Wide Safety Review meeting also during November of that year. A series of Notes were prepared and submitted to the AEC in answer to questions raised during the reviews. These constitute supplements to the Safety Analysis Report.

An annotated bibliography of some of the literature pertinent to the Pioneer Safety Evaluation is presented below.

BIBLIOGRAPHY

Reference	Significant Contents
Safety Analysis Report	
(a) INSD-2873-42-1, Vol. I, Reference Design Document 6/71	Describes Pioneer mission objectives and profile. Launch vehicle and spacecraft are described summarily and nuclear system is presented in greater detail.
(b) INSD-2873-42-2, Vol. II, Accident Model Document 6/71	Presents method of analysis to determine fuel release probability. Summarizes relevant vehicle failure modes, effects and reliabilities. Describes accident environments, initial conditions and response of the nuclear system, for launch pad and in-flight accidents. (Error analysis techniques were applied consistently for the first time in nuclear safety evaluation to estimate failure probabilities for the radioactive fuel containment devices.) Transition matrix and fault-tree combinatorial models are described.
(c) INSD-2873-42-3, Vol. III, Safety Analysis Document 6/71	Presents models for source terms, i.e., quantity of fuel released in the event of fuel capsule rupture for each potential release condition. Describes estimation of activity transport after release and the number of potential exposures at a given level.
(d) INSD-2873-42-4, Vol. IV, Risk Assessment Document (CRD)	Presents composite risk estimate, combining fuel release and exposure probabilistics for net risk assessment.

Safety Analysis Report - Supplemental Notes Prepared in Support of Safety Evaluation

II-1 Variation of African Impact Probability with T_{REL} (launch window limits)

II-2 Response to Comments on Volume II

II-3 Response to Reviews of Pioneer F Safety Reentry Thermal Analysis

II-4 SNAP 19/Pioneer Error Analysis-Graphite Sublimation

II-5 Post-Impact Oxidation vs. Temperature

II-6 Burial Probabilities

III-1 Response to Comments in ESD-71-719

III-2 Effect of Separated versus Lumped Sources

IV-1 Response to Comments on Volume IV, Risk Analysis Document - Pioneer F Safety Analysis Report

BIBLIOGRAPHY (CONTINUED)

Reference	Significant Contents
Pioneer F Safety Test Reports	
INSD-2873-67 Heat Source Vibration	
INSD-2873-72 Graphite Oxidation	
INSD-2873-73 Blast Overpressure	
INSD-2873-74 Fragment Impact	
INSD-2873-75 Liquid Fire	
INSD-2873-76 Solid Fire	
INSD-2873-77 Capsule Impact on Granite	
INSD-2873-78 Drop Tests	
INSD-2873-79 Plasma Arc (Reentry Heating)	
INSD-2873-80 Heat Transfer Measurements	
INSD-2873-81 Force and Moments Measurements	
GDC-BTD70-010 Pioneer F AEC Safety Study Phase I (GD/Convair) 3/8/71	A detailed description of the launch vehicle, launch complex facility and nominal launch trajectories is provided.
GDC-BTD70-015 Pioneer F AEC Safety Study Phase II (GD/Convair) 3/8/71	Launch pad accident environments, launch vehicle failure modes and associated reliability data are presented. This report constitutes the basic input to accident initiation and initial environments for the nuclear system. A portion of the document was contributed by TRW and describes the effect of spacecraft breakup on the initial states of the nuclear system.
ESD-2873-138 A Predictive Model for Oxygen Transport in the Alloy T-111 7/72	A phenomenological model is proposed to explain observed oxygen transport in T-111. A combination of diffusive and capture mechanisms are responsible, in this model, for the "frozen" oxygen density distribution in spite of a relatively large diffusivity. Empirical values of the transport parameters are deduced and used to infer the time dependence of oxygen doping.
NUS-738 P. M. Altomare, "Meteorological Data Summary and Atmospheric Transport at Kennedy Space Center," February 1971	Near ground atmospheric transport of radioactive particles and downwind exposure. Supplemented by two ad hoc graphs showing hot line concentrations + isopleth area, for aged PMC. Since updated as SNS-NUS-827, 9/71.

BIBLIOGRAPHY (CONTINUED)

Reference	Significant Contents
MLM-1706 J.E. Selle, et al, "Compatibility of $^{238}PuO_2$ with Various Refractory Metals and Alloys: Interim Report (Draft)" July 9, 1970	Very limited information on T-111 (3 pages)
"Abstracts of Briefings, PMC Fuel-Ta Heat Source Compatibility Meeting Oct. 16, 1970	Notes in detail on meeting at AEC/HQ.
CMB-5-C-76 L. B. Lundberg, "Effect of Oxygen Content on Impact Behavior of Tantalum-Based Alloy T-111 at 2400°F, " April 19, 1971	Interim Report on Magnaform tests at GE-Valley Forge.
CMB-5-C-101 "PMC Fuel Manual"(LASL)	Compilation of data on response analyses.
CMB Series Monthly reports on Pu-238 Fuel Development Program and Advanced Safety Technology Program	Primarily test data, with some analytical study results.
MLM-1691 "Plutonium-238 Isotopic Fuel form Data Sheets"*	More emphasis on isotopic data than in LASL manual.
"Data on Plutonium Molybdenum Cermet Fuel Form and Fuel Capsule Assembly," Appendix A of Pioneer F Range Safety/Procedures Manual	Brief summary with wider scope than above references.
LA-4914-MS S.E. Bronisz, "Source Term Calculations for Pioneer Radioisotopic Thermoelectric Generators," issued May 1972 but draft portions were available for Pioneer.	Argumentative on minor points but unique source of certain test results.

*Similar LASL report, LA-4976-MS, was unavailable at time of Pioneer analysis.

VIII. AGE

The ground support equipment provided for the SNAP 19/Pioneer program is grouped into two categories, (1) electrical and (2) mechanical. The electrical AGE consists of equipment used to monitor performance of the RTG's during transient handling as well as power supplies for the ETG's. The mechanical AGE consists of shipping containers, generator handling adapter and generator fin insulator pads.

A. ELECTRICAL AGE

1. Portable Monitor Package

The purpose of the portable monitor package (PMP) is to provide a complete instrumentation unit for functional checkout, calibration and performance monitoring of both ETG's and RTG's.

The PMP is used to check generator current, voltage, temperatures and pressure. The monitor can be powered by either an external 115 volt, 60 cycle sourc or by its internal batteries. The AC-OFF-DC switch selects the source. External power is connected to receptacle J5 on the front of the unit. External power should be used whenever feasible in order to conserve the internal battery supply. The portable monitor will operate approximately 240 hours on its battery supply.

The complete PMP consists of a front panel assembly, a carrying case and interconnecting cables. The PMP can be operated in either a horizontal or a vertical (upright) position.

The functions which the unit is cable of monitoring are:

a. Hot junction temperatures (RTD type, two).

b. Pressure measurements (two, ETG's S/N 32-34 only).

c. Fin root temperature (thermistor type, two).

d. Hot and cold junction and fin root temperature (thermocouple type, 32).

e. Load circuits for two generators.

f. Load circuit voltage as well as momentary open circuit voltage from two generators.

g. Load current from two generators. Generator power output can be obtained from (f) and (g).

h. Miscellaneous binding posts and associated switches to facilitate the connections of external meters, recorders, digital voltmeters.

i. Front panel terminals to check periodically the status of the internal battery power supply.

2. ETG Power Supply

The ETG power supply provides a convenient and fail-safe method of supplying programmed DC power to the heaters of an electrically heated generator. An ETG power supply is capable of delivering regulated power to two separate ETG's.

The caster-mounted console contains the following units:

Heater power supply control panel assembly

Two DC power supply panel assemblies

Console retractable table assembly

Console main power control panel assembly

Dummy panel

Rear connector panel assembly

The heater power supply control panel has two independent control systems for managing the DC outputs of the regulated power supply units which provide separate power directly to heater circuits of the ETG's. This panel also has two separate alarm systems which are independently activated when the temperature of either of the ETG's should reach a prohibitive level. This event then activates an alarm control function which consists of a red warning light and a loud buzzer. In case of a possible overtemperature, the alarm control function effects an automatic reduction of heater power to a manually pre-set and acceptable level for the respective ETG. After the automatic alarm function is executed, the visual and audible alarm, however, will continue until the alarm indication is acknowledged by the operator by pressing an alarm switch indicator. It should be noted that the operation of the second ETG will not be affected in case of an alarm condition of the first ETG and vice-versa.

The DC power supply assembly is a solid-state regulated power supply which also has positive features to prevent any detrimental effects to the electrical heaters and/or the generators in case of a malfunction of the DC power supply proper. If for example, there would be a thermal overload in the DC supply, a thermostat and a thermal overload indicator lamp, located on the front panel, are energized and the supply switches itself off automatically. After this trouble is corrected, the thermal overload alarm device can be reset by pressing a thermal overload reset button on this unit.

3. ETG Power Supply Load Test Unit

The purpose of the load test unit is to provide a convenient and accurate method of checking out the ETG power supply console after shipment and to calibrate the console periodically. In addition to simulating the heater loads of two ETG's, the load test unit provides a checkout of the high temperature alarm circuitry.

Four heavy-duty Ohmite resistors capable of dissipating one kilowatt each are housed in a perforated metal case. An enclosed terminal strip on the rear of the case permits access to the resistor interconnection. Thermocouple connector sockets are provided to give continuity to the generator alarm thermocouple system.

The load test unit is used by connecting thermocouple, power and ground leads to the ETG power supply console. A fan or blower should be provided to cool the test unit during operation due to the high power dissipation. Power is gradually applied to the load unit from the power supply console, and the voltage is monitored with a digital voltmeter. Adjustments to the console controls are made to achieve the appropriate power level at each console power setting, if necessary.

Response to an alarm circuit loop break is measured with the load test unit. The time between removal of the thermocouple jack and initiation of a buzzer/light indicator warning is measured and adjusted to 180 seconds or less.

4. Connector Saver Cables

The purpose of the connector saver cables is to minimize wear and tear on the generator receptacles. The cables also provide an easy means for short-circuiting the generator through the use of a shorting plug attached to one leg. Shaped like a "Y", one leg is kept attached to the generator receptacle. Of the other two legs, one is used for attachment to the load and the other is used for short circuiting the generator when no load is applied. Each generator, both ETG and RTG is supplied with a connector saver cable.

5. AGE Interface Cables

The PMP unit is furnished with one set of interface cables consisting of three cable assemblies. One cable is used for 115 VAC facility power connection. The other two polarized cables are used for generator No. 1 and generator No. 2 interface. The AC facility power interface cable is 15 feet long and each of the generator interface cables is 20 feet long.

The ETG power supply console is furnished with one set of interface cables consisting of four cable assemblies. Two polarized cables are used for 115 VAC facility power connections. The other two polarized cables are used for No. 1 ETG and No. 2 ETG interface. The AC facility power interface cables are 25 feet long and the ETG interface cables are 20 feet long. Each cable includes an adapter so that seven or 26 pin connectors may be accommodated. This allows the use of any set of cables on any delivered ETG.

B. MECHANICAL AGE

1. RTG Handling Adapter

An RTG handling adapter is provided which can be mounted to the generator upper end. It attaches to three lugs located on the generator housing and provides an attachment interface for mounting the required handling tools. Thus, the need to repeatedly attach and detach handling tools directly to the generator is eliminated.

The adapter is designed so as to avoid any interference with the generator interface cable and/or interface cable of the PMP unit. It is constructed from 6061-T651 aluminum machined into the form of a ring with two flanges forming the top and bottom faces of the ring.

2. ETG Shipping Container

The ETG shipping container holds a single generator. It is approximately 33 inches square by 19 inches high, and is constructed of plywood. Heavy wooden cleats are attached to the bottom to permit handling by a forklift truck.

The bottom of the shipping container serves as a base for four Dow-Elco shock mounts.

A 0.50 inch thick magnesium plate (or 0.38 inch thick aluminum plate) is bolted to the top of the shock mounts. This mounting plate supports the generator and effectively isolates it from shocks of transportation.

When in transit, the ETG is mounted on a shipping adapter, a large flanged aluminum ring. The adapter is first bolted to the mounting plate of the shipping container, then the generator mounting lugs are bolted to the shipping adapter.

3. RTG Shipping Container

The SNAP 19/Pioneer RTG shipping container supports and protects two generators mounted vertically end-to-end. Aluminum structural framing covered with heavy gauge screening provides an open but rugged protective cage around the RTG's. Air may circulate freely around the generator fins allowing adequate convective cooling. Large mounting feet on the bottom provide adequate clearnce for forklift handling.

Instrumentation provisions are made for short circuiting the RTG during transit. Access doors in the container permit plug-in of the AGE interface cabling. Thus, the generators can readily be connected to the portable monitor package, permitting performance evaluation prior to, during and after transporting the generators without removing them from the container. Generator mounting points are isolated from the shocks of handling by Dow-Elco shock mounts. Appropriate hazard and caution markings are applied.

4. Generator Fin Insulation Pad Set

When generators are operated in air, convection supplements radiative cooling resulting in a considerable decrease of fin root temperature. To thermally simulate space operation, insulating pads are slipped over the fins of a generator. These pads are supplied as a set of six thermally matched units, each constructed of Fiberfrax ceramic blanket filler covered with Berton Plastics heat-cleaned cloth sewed with fiberglas thread. Metal snap fasteners attach to adjacent pads to positively hold them in place.

By manually adjusting the pads inward or outward on the fins, the heat loss from the fins can be accurately controlled. Thus, a given high operating temperature can be maintained regardless of the steady state room ambient temperature.

IX. REFERENCES

1. SNAP 19/Pioneer Mass Properties Status Report No. 1, INSD-2873-51, February 1971.
2. SNAP 19/Pioneer Mass Properties Test Report, RTG's S/N 41 and 42, INSD-2873-91, January 1972.
3. Mass Properties Measurements of SNAP 19 RTG's for Pioneer F/G, TRW Systems Group Report No. 21449-6002-RO-00, December 1971.
4. Parametric Tests in Load Voltage, Proc. Drawing 452B5100409.
5. Fueled Generator Gas Leakage Tests, Proc. Drawing 452B5100408.
6. Radiation Survey, SNAP 19 Pioneer Generator Drawing 452B5100401.
7. SNAP 19 Generator Vibration Test Procedure for Electrically Heated Generators, Drawing 452A4000413.
8. SNAP 19 Fueled Generator Vibration Test Procedure, Drawing 452B5100413.
9. Vibration Test Report for ETG S/N 36, INSD-2873-43.
10. Environmental Qualification Test Report for RTG S/N 37, INSD-2873-48.
11. Acceptance Vibration Test Report for RTG S/N 38 through S/N 40, INSD-2873-57.
12. Environmental Qualification Test Report for RTG's S/N 41 and 42, INSD-2873-92.
13. Acceptance Vibration Test Report for RTG's S/N 43 and 44, INSD-2873-100.
14. Acceptance Vibration Test Report for RTG's S/N 45 and 46, INSD-2873-108.
15. Acceptance Vibration Test Report for RTG's S/N 47 and 48, INSD-2873-110.
16. Acceptance Vibration Test Report for RTG's S/N 49 and 50, ESD-2873-146.
17. Acceptance Vibration Test Report for RTG S/N 51, ESD-2873-148.
18. Acceptance Vibration Test Report for RTG's S/N 52 and 53, ESD-2873-147.
19. Fueled Generator Acceleration Test Procedure, Drawing 452B5100414.
20. Fueled Generator Shock Test Procedure, Teledyne Isotopes Drawing 452B5100404.
21. RTG Thermal Vacuum Tests, Proc. Drawing 452B5100402.
22. Generator S/N 37-40 Thermal Vacuum Tests, INSD-2873-111, January 1972.
23. Generator S/N 41 and 42 Thermal Vacuum Test, INSD-2873-93, November 1971.
24. Generator S/N 43 and 44 Thermal Vacuum Test, INSD-2873-104, December 1971.
25. Generator S/N 45 and 46 Thermal Vacuum Test, INSD-2873-116, January 1972.
26. Generator S/N 47 and 48 Thermal Vacuum Test, INSD-2873-119, February 1972.
27. Generator S/N 49-53 Thermal Vacuum Test, ESD-2873-152, February 1973.
28. Generator Performance Acceptance Criteria, Dwg. 452B5100500.