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THERMAL TESTING OF THE SNAP 10A PROTOTYPE SYSTEM (PSM-3)

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CONTENTS

CONTENTS

TABLES

FIGURES

FIGURES

FIGURES

I. SUMMARY

From April 18,1962 through October 11,1962, the SNAP 10A PSM-3 non-nuclear test vehicle underwent thermal, electrical, and hydraulic tests at the Santa Susana Test Facility of Atomics International located in Chatsworth, California. This report defines the test vehicle and facilities, describes the tests and their objectives, and presents an evaluation of the tests. In general, the SNAP 10A PSM-3 test vehicle met its design goals. The following table summarizes the system design points and test results.

TABLE I

SYSTEM DESIGN POINTS AND TEST RESULTS

	Design Point	Test Result*
Heat input to converter (kw)	27.9	27.9
Heat rejected by radiator (kw)	27.32	27.16
Heat radiated from the NaK lines and structure to the radiator (kw)	2.0	4.0
Heat transfer through TE elements (kw)	25.32	23.16
Conductance per element (watts/°F)	0.031	0.027
Temperature difference across TE element (°F)	262.0	279.0
Open circuit voltage (volts)	57.5	59.64
Electrical power (watts)	585.0	534.0†
Carnot efficiency, ηc (%)	19.7	21.3
Overall efficiency, ηo (%)	2.1	1.91
Device efficiency, $\eta o/\eta c \times 100$ (%)	10.67	8.98
Total system pressure drop (psi)	1.0	0.96
Heat barrier heat loss (watts)	40.0	33.0

*Test results converted to design conditions of 960°F core outlet temperature and 12.0 gpm NaK flow rate

†Extrapolation based on 16 operating modules

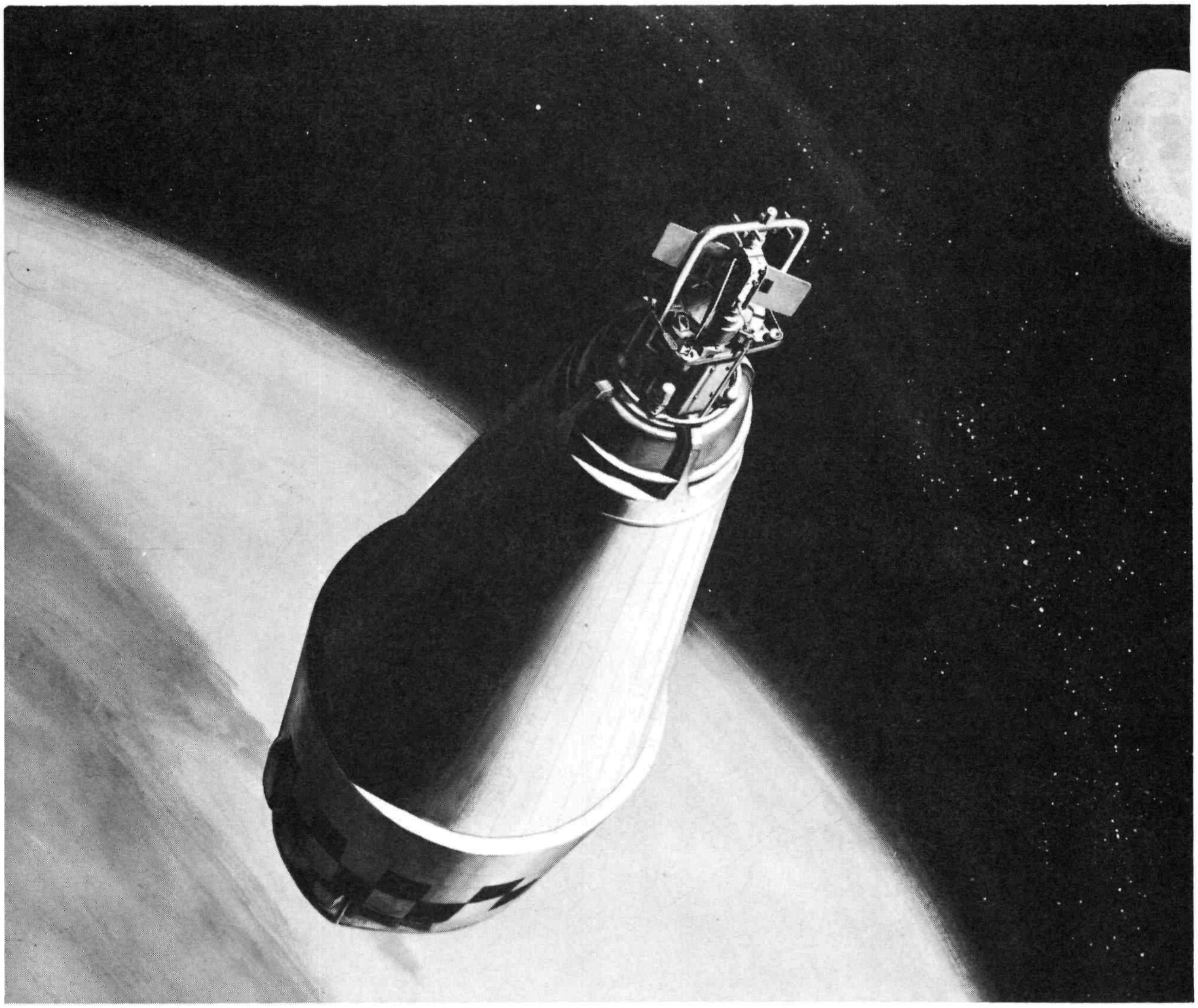

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Figure 1. SNAP 10A Nuclear Power System Mounted on an Agena Vehicle

II. INTRODUCTION

Many space programs need a reliable, lightweight, long-lived, relatively high-level power source. SNAP (Systems for Nuclear Auxiliary Power) systems are being developed to demonstrate the feasibility of using nuclear power for satellites. SNAP 10A, shown in Figure 1, is scheduled to be the first flight system using an operating nuclear reactor. Atomics International is developing it for the Atomic Energy Commission.

The PSM-3 (Nonnuclear System Prototype) was the first full-scale mockup of the SNAP 10A configuration in which NaK (sodium-potassium eutectic) was circulated at design temperature levels and in which the overall system performance was first evaluated. It was tested in a vacuum chamber to simulate, as far as practical, the expected space environment. Figure 2 shows the unit with the top portion of the vacuum vessel removed, installed in the test facility. All thermal and hydraulic operating conditions which a SNAP 10A would experience from prelaunch checkout to orbital operation were simulated within the capabilities of the test facilities and system prototype.

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Figure 2. SNAP 10A PSM-3 Performance Test Power System

III. TEST OBJECTIVES

Although, as indicated in Section IV of this report, the differences between the PSM-3 and flight system configurations were considerable, the same design philosophies were used for the two configurations. The test facilities used for PSM-3 will also be used for ground testing flight-type systems. Therefore, the major overall PSM-3 test objective was to evaluate these design philosophies and test facilities prior to the availability of the flight configuration. The specific primary test objectives were to:

a) Verify NaK fill and system cleanup procedures

b) Determine hydraulic, thermal, and electrical performance at various core outlet temperatures, NaK flow rates, radiant heater settings and electrical loads

c) Evaluate the non-nuclear performance and operation of the unit at full power for extended periods. This test includes determination of thermal performance, system and control response time, system stability, electrical performance, mechanical operation of the reactor control mechanism, operation of the NaK system, and structural behavior.

d) Determine operational characteristics of the SNAP 10A startup procedure

e) Conduct a small-scale NaK-plugging investigation

f) Evaluate component performance

g) Estimate flight system performance based on the PSM-3 test results

The secondary objectives were to:

a) Provide training in diagnostic data acquisition, reduction, and evaluation

b) Provide experience in operating the test facilities in support of the SNAP 10A Unit.

IV. SYSTEM DESCRIPTION

The following paragraphs contain brief descriptions of the major components of the PSM-3 system and of the test facilities.

A. POWER SYSTEM

The PSM-3 power system, built in the fall of 1961, reflected the engineering design prior to July, 1961. The instrumentation design for the system was not sufficiently advanced at that time to include any flight-type instrumentation or an instrument compartment. No lithium hydride-filled neutron shield was installed in the system, because its cost could not be justified by the limited amount of information which would be obtained from this initial nonnuclear thermal test. Only the empty upper section of the shield casing was included in the power system.

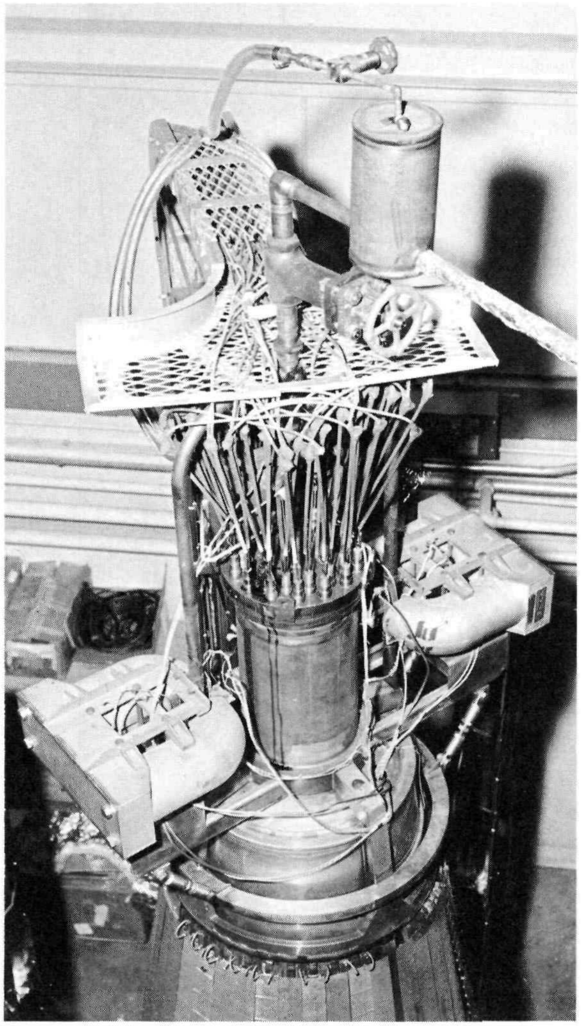

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Figure 3. SNAP 10A PSM-3 Top Head Assembly

1. Core Heater

An electrical core heater (Figure 3) simulated the nuclear reactor. The heater assembly included a stainless steel casing with 30 cartridge heater elements welded into the top plate. NaK entered through two inlet nozzles at the base of the core heater, flowed up past the heating elements and out the single nozzle at the top. The NaK flow area through the assembly was 12 in.^{2} or 2.5 times that of the nuclear core. To reduce the radiant heat losses, external heater surfaces were wrapped with aluminum foil during testing.

Each heating element (17.75 in. long, 12 in. active length) was clad in an Inconel sheath and rated at 4700 watts at 240 vac. The elements were wired in a three-phase wye power circuit to produce 33 kw total output at 120 vac.

To determine the thermal gradients along the shell, thermocouples were attached at six locations on the surface of the core heater. No simulated control drums or beryllium reflectors were installed at the core heater.

2. Power System NaK Pump

The flight system thermoelectric NaK pump was replaced with an externally powered dc conduction pump (Faraday type) for the PSM-3 tests. Figure 4 is a sketch of the pump. The operating principle of this pump was identical to that of the flight system; only the source of current differed.

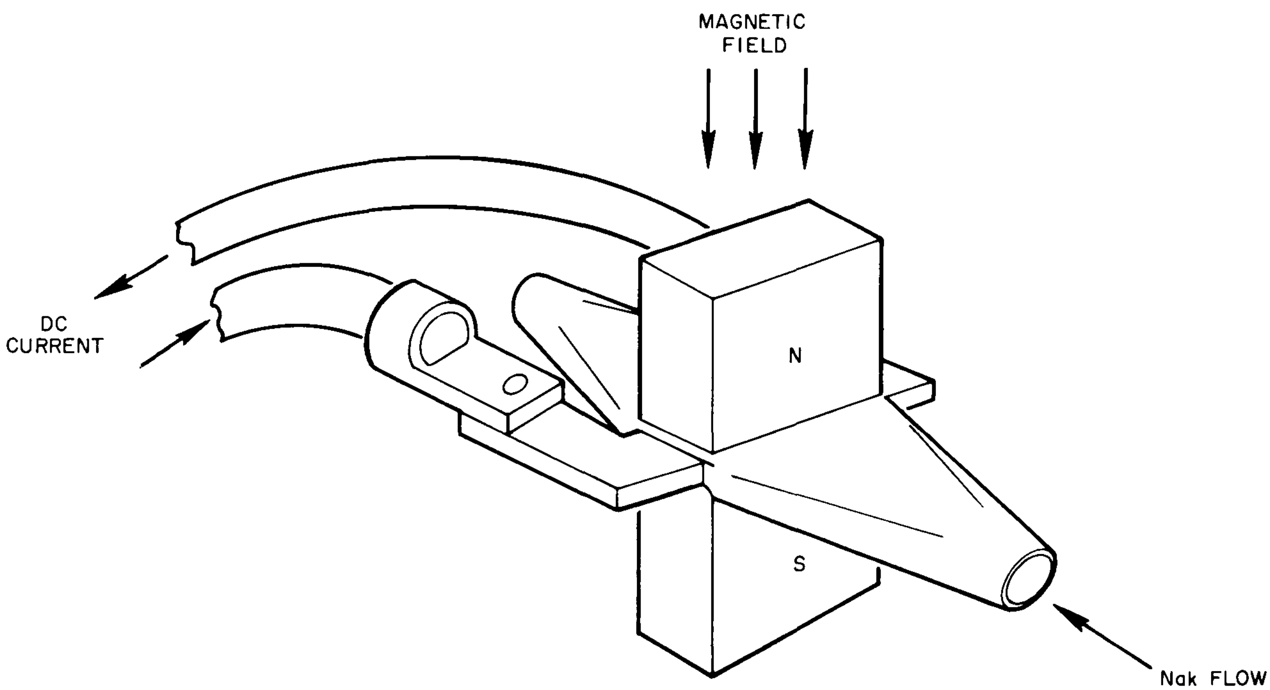

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Figure 4. PSM-3 NaK Conduction Pump

The pump, located on the core outlet NaK line, had a field magnet strength of 3100 gauss, with an air gap of less than 1/16 in. Pumping power was supplied by a variable high-current, low-voltage, dc power supply. Initially, a 500a, 10 vdc supply was installed, but was later replaced by a 1000a, 10 vdc system. Paired 4/0 cables were used for conductors. To measure the NaK pressure rise across the pump, which was the same as the total system hydraulic pressure loss, 1/4-in. diameter static pressure taps were located at the entrance and exit of the pump throat.

3. Thermoelectric Radiator-Converter

Power was produced at the radiator-converter section of the power system by thermoelectric elements installed on the NaK tubes. The flowing NaK heated the hot junction and heat rejection from the radiators cooled the cold junction.

The converter contained 40 parallel NaK tubes, each 87 in. long, welded between inlet and outlet manifolds. The PSM-3 manifolds were each in two half-rings and mounted so that the NaK which entered one half-manifold returned to the core through both return lines. Figure 5 shows this hydraulic loop schematically. This flow pattern equalized the pressure drop around the manifolds so that each of the 40 converter tubes had nearly the same flow.

The PSM-3 converter tubes were 0.595 by 0.155-in. flattened tubes (0.010-in. wall thickness). Each tube or leg was fabricated from three sections called modules. The module tubes were butt welded together and then the leg was fillet welded onto the 0.020-wall manifolds of oval cross-section. These 300 series stainless steel converter tubes and manifolds were spring mounted along the outer surface of the conical stainless steel converter shell. Figure 6 shows the converter section.

Lead-telluride thermoelectric material was used on the seven operating legs of PSM-3. The remaining 33 were built with dummy elements having similar thermal characteristics.

The encapsulated PbTe elements, aluminum radiators, and aluminum hot straps were brazed as a sandwich onto the module tube. Each module contained 26 PbTe elements, or 13 pairs of P and N elements. The odd numbered elements (1, 3, 5, etc.) were P-type (doped with 0.6% Na) and even numbered N-type (doped with 0.03% PbI_2). The PSM-3 radiators were coated with a dull black paint (PT404), which had an emissivity value of 0.86 at 600°F. A schematic of the TE (thermoelectric) legs and elements is shown in Figure 7.

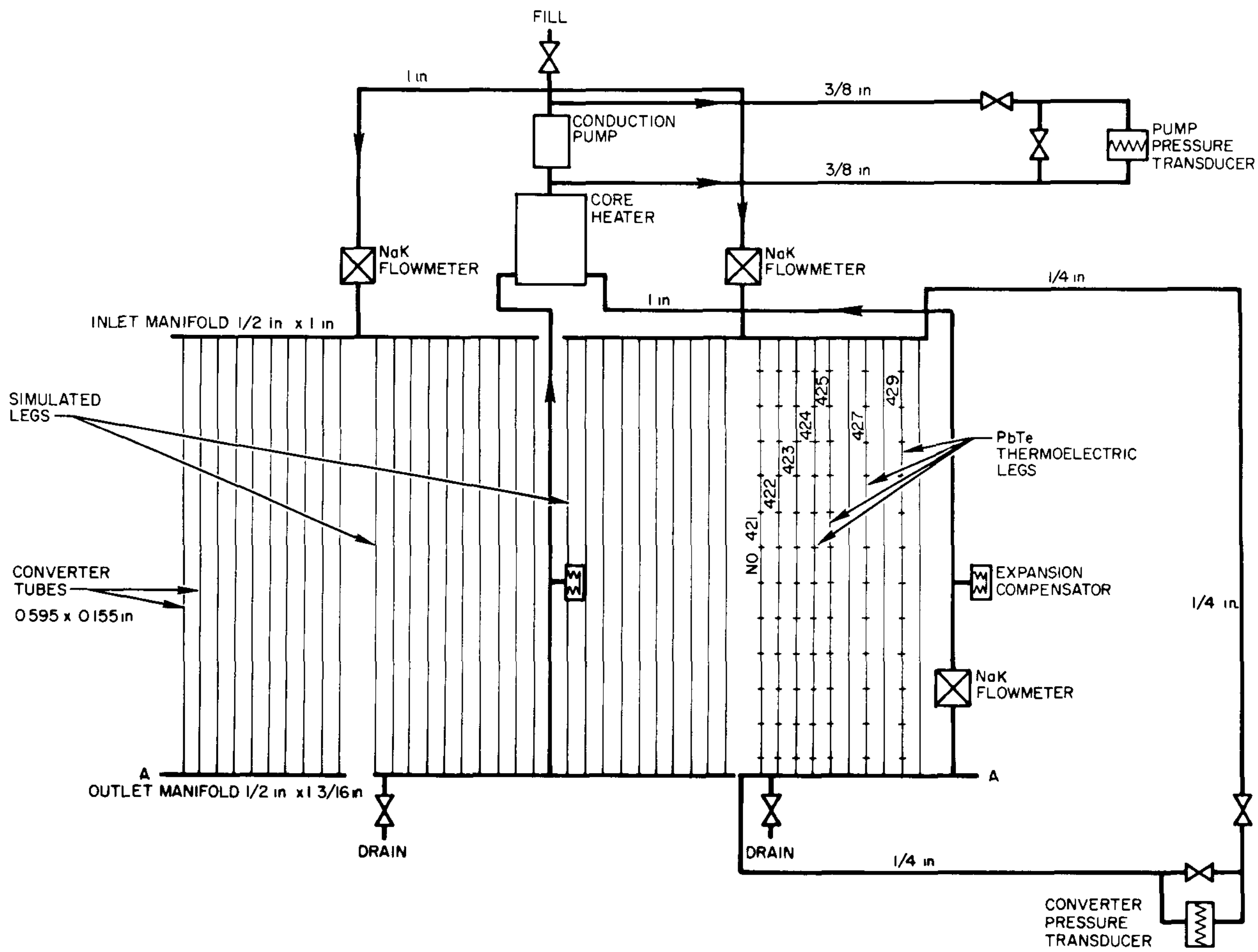

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Figure 5. Schematic of Converter Hydraulic Loop

The 33 simulated legs used an 0.25-in. length of 0.5 x 0.20-in. stainless tubing in place of the thermoelectric element. This dummy element was brazed directly onto both the tube and copper radiator. The same black PT404 paint was applied to the radiators on the simulated legs.

Two hundred sixty-one chromel-alumel thermocouples were installed on the PSM-3 converter section. Twenty were attached to the internal surface of one quadrant of the converter support shell, 24 on the tube walls at the converter tube inlets, 40 on the walls at the tube outlets and 177 on the radiators, hot straps, and tube walls.

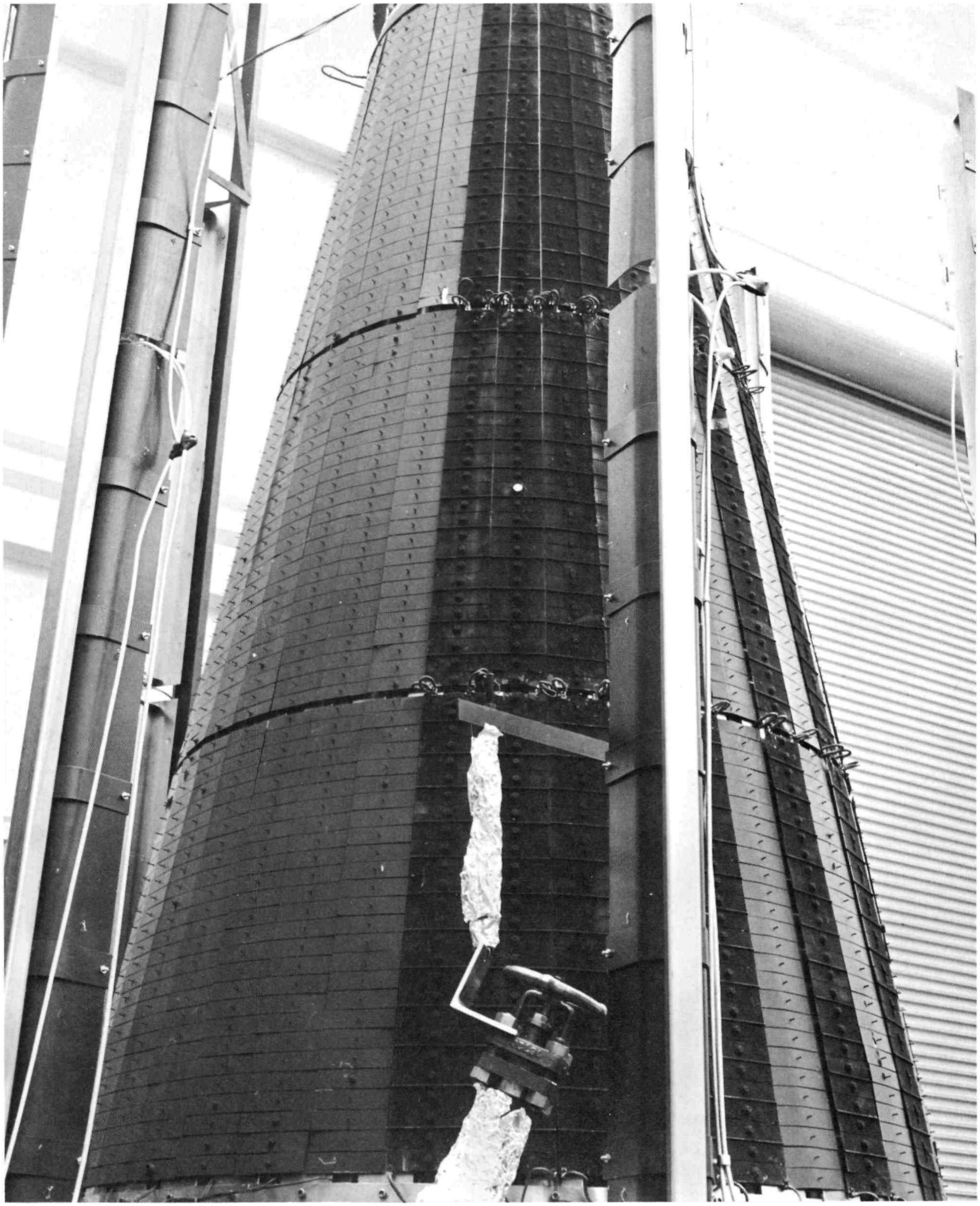

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Figure 6. SNAP 10A PSM-3 Converter (Darker shaded legs at right are lead-telluride active elements, lighter legs contain simulated elements)

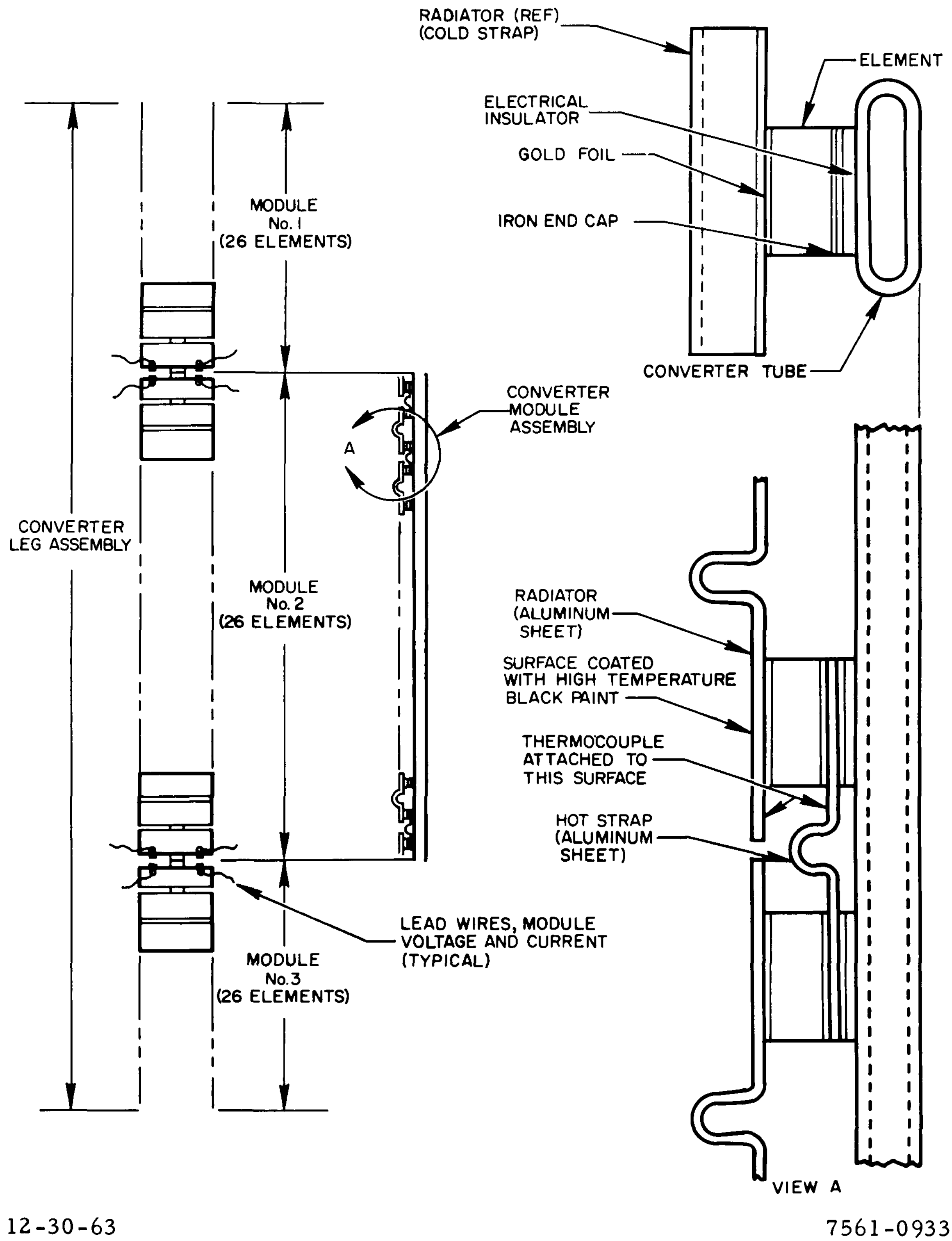

Figure 7. TE Converter Leg Assembly

4. Expansion Compensators

The expansion compensators were designed to absorb the 12.5% volumetric expansion of the NaK when the void-free power system was heated from ambient to an average temperature of 900°F. Two compensators were installed on the two return lines on PSM-3 and mounted against the inside of the converter support shell. Figure 8 shows one of the compensators installed on the converter shell. Each assembly included a 10-in. OD expanding bellows with 7 convolutions enclosed in a 10.5-in. OD flat cylinder. From the completely collapsed to fully extended position, each bellows provided 150-$in.^3$ of NaK volume. Varying the gas pressure applied to the outside of the expansion compensator bellows regulated the static pressure of the NaK system. An electrical limit switch was installed in each expansion compensator to provide a warning when the bellows were approaching the fully extended position.

5. NaK Flowmeter

NaK flow in the PSM-3 power system was monitored by permanent magnet liquid metal flowmeters. As the NaK flowed through the magnetic field, an electromotive force developed at right angles to both the flux lines and liquid metal flow path. The generated emf was then measured and, from previously obtained calibration data, the flow rate was determined. All three flowmeters were individually calibrated with flowing NaK in a separate test loop prior to installation on the power system. The calibration was conducted at a flow of from 0 to 12 gpm and NaK temperatures from ambient to 1000°F.

Three NaK flowmeters were installed, two on the converter supply lines and one on a converter return line. Figure 3 shows the two flow meters on the supply lines. The main frame supported the 150-lb flowmeters. Spring mounts between magnet and support bracket provided the necessary compensation for thermal expansion.

Two sets of output electrodes were attached to the tube throat of each flowmeter. One set monitored flow and the other warned of low-flow.

6. Heat Barrier

The heat barrier (Figure 9) located at the base of the power system thermally insulated the instrument compartment from the remainder of the power system. The barrier used on PSM-3 included 30 alternate layers of

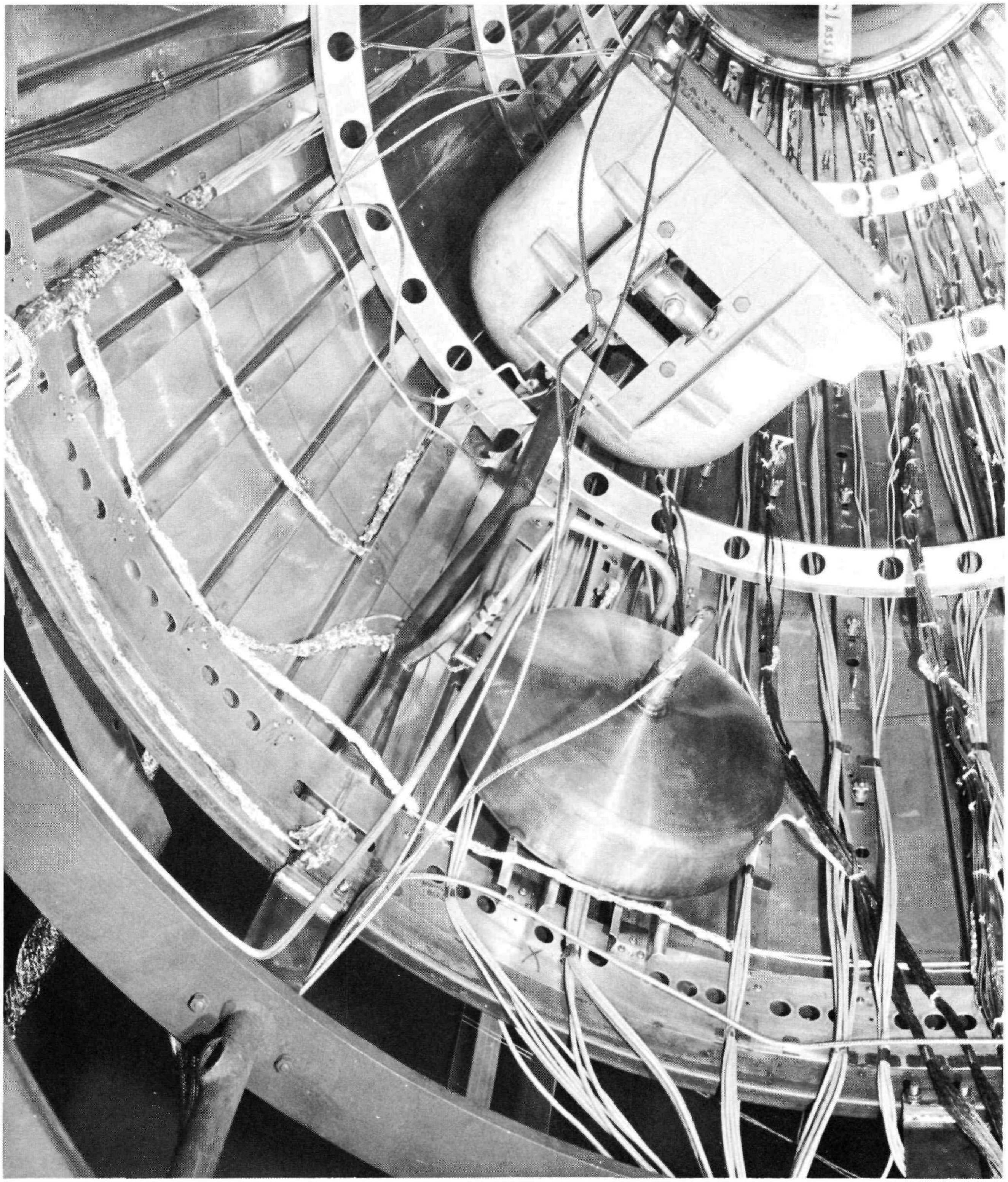

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Figure 8. PSM-3 Converter Shell Showing Expansion Compensator and Magnetic Flowmeter

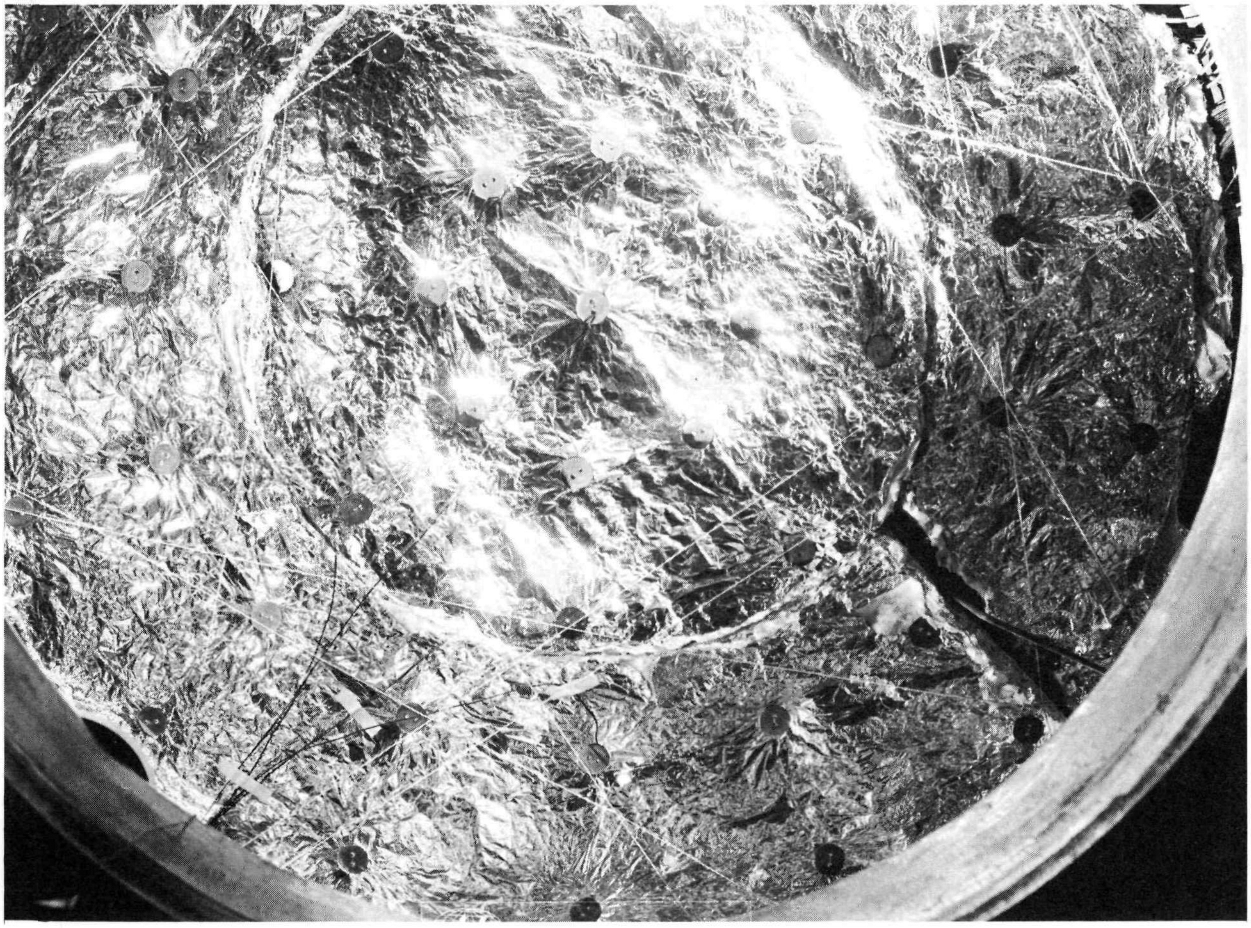

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Figure 9. Bottom View of S10A PSM-3 Heat Barrier Installed on Power System (Dark colored wires are thermocouples, light are fiberglass support strings)

0.0005-in. aluminum foil and 0.0048-in. fiberglass paper. Loose stitches of fiberglass thread in a quilted pattern held the sandwich assembly together. The two-piece barrier contained an annular ring with a removal center plug. The barrier was supported by a criss-crossing network of fiberglass string.

A black painted aluminum sheet called a radiation absorber was installed 3 in. beneath the heat barrier (Figure 10) in place of an instrument compartment. The absorber, which acted as the heat sink, was thermally insulated from the power system support stand and chamber wall.

Two chromel-alumel thermocouples were installed on the top and bottom of the heat barrier as well as on the absorber. On each surface one thermocouple was located at the center and the other on the annular section.

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Figure 10. Installation of Heat Barrier and Absorber on S10A PSM-3
(Slot cut in barrier and absorber to provide access for gas tube)

A wedge-shaped section of material was removed from the annular ring to allow for passage of an expansion compensator gas line (Figure 9). The heat barrier was installed within the plane of the lower torque ring at a somewhat smaller diameter than the barrier was designed for. This meant that the barrier material had to be slightly compressed about its diameter. Also, the bottom 1.0-in. wide annular surface of the lower torque ring was exposed to the radiation absorber. This surface will be shadowed in all future systems.

7. Miscellaneous Power System Hardware

a. Support Legs

Eight 4-1/2-in. long titanium legs, which support the weight of the power system were bolted to the lower torque ring. These support legs contain a saddle, post and base plate, and comprise the eight mounting points between the Agena and the power system. Three thermocouples were attached to one of the support legs.

b. Piping

To reduce the radiant heat losses, all the exposed external 1-in. stainless steel tubing was wrapped with aluminum foil after testing began.

B. TEST FACILITIES

The SNAP 10A PSM-3 test was conducted in Building 032, SNAP Complex Area, at the field test facilities in the Santa Susana Mountains, Chatsworth, California. Figure 11 shows the test facilities. Brief descriptions of the major systems in the test facility follow.

1. Vacuum Test Chamber

A vacuum test chamber simulated space conditions. The three-piece mild-steel chamber was 16 ft high by 8 ft in diameter. The internal walls were coated with a black, highly emissive paint ($\epsilon = 0.86$). Water circulated through copper cooling coils wrapped on the external surface at 2-in. increments.

Wiring for electrical power and instrumentation passed through the chamber wall at the 18 penetration ports on the vessel base. Hermetically sealed connectors were mounted onto the flange plates at the ports. Twelve 61 pin (20 ga.) connectors installed in four 6-in. diameter ports carried the 350 thermocouple circuits, and 28 seven pin (12 ga.) connectors installed in the 3.5-in. diameter ports carried the power circuits for the core heater, thermoelectric modules and radiant heaters. Power system pump current was carried through the vacuum vessel wall by two 0.75-in. diameter copper electrodes which were electrically insulated with ceramic sleeves and sealed with teflon packing. The NaK plumbing lines, which included the fill tubing, and differential pressure capillary tubing, were welded onto the flange plates in two 6-in. ports to form the vacuum seal.

Six 3-in. diameter view ports were installed on the chamber walls for viewing the power system during testing. The 20-in. diameter vacuum pumping port was located at the center of the lower cylindrical section of the chamber. A 3 ft diameter hinged cover at the center of the base provided access to the inside of the power system when it was mounted on the chamber base plates.

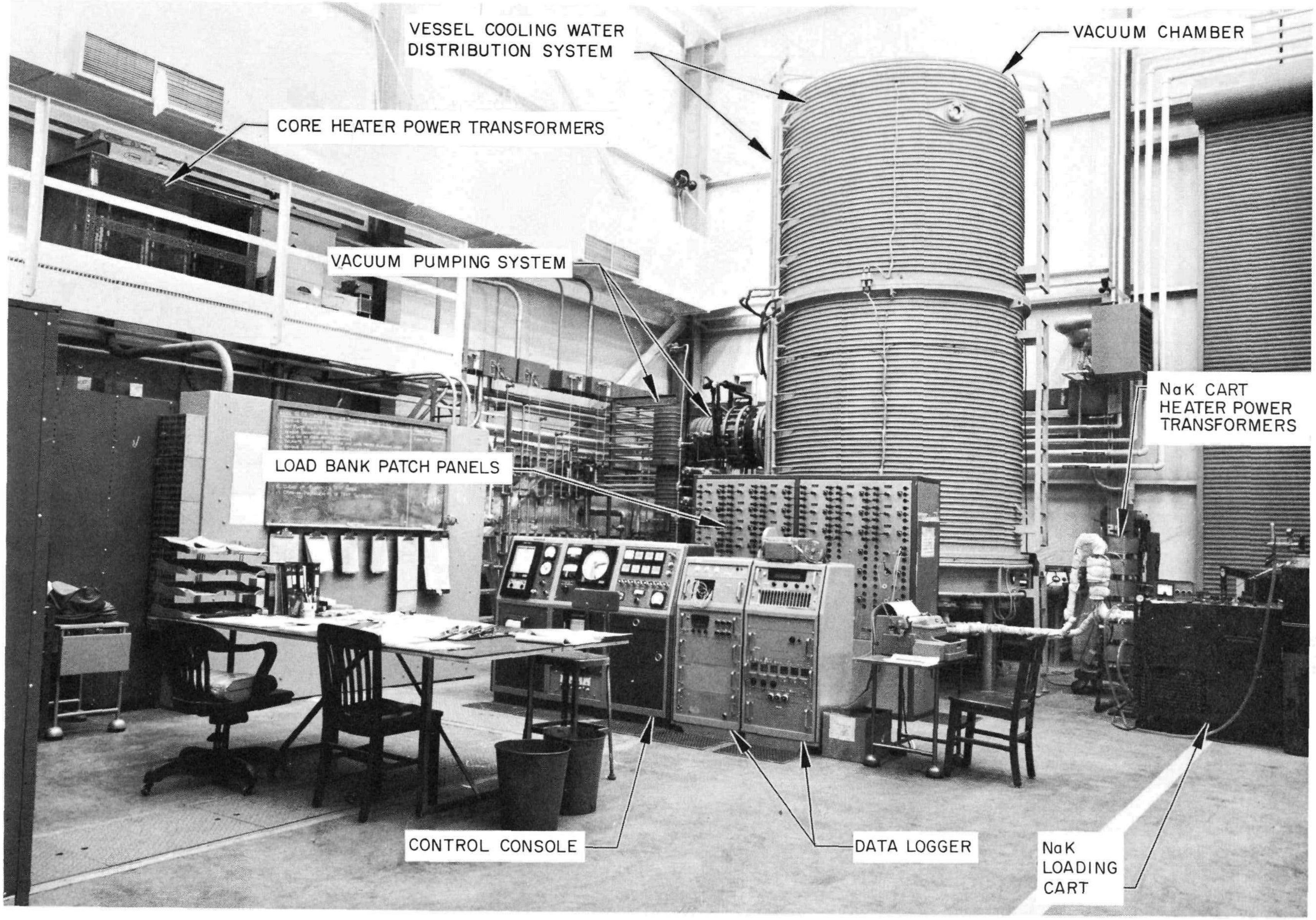

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Figure 11. SNAP 10A PSM-3 Test Facility

An ionization gage mounted on the vacuum chamber wall 3 ft beneath the pumping port monitored the vessel pressure in the range below 1×10^{-3} Torr (mm of Hg). Thermocouple vacuum gages on the 20-in. -diameter vacuum line monitored pressures from 1×10^{-3} Torr to 1 Torr and a Bourdon-type vacuum gage indicated pressures to atmospheric.

Twenty-three thermocouples attached to the internal and external surface of the vessel wall monitored the chamber sink temperature. One row of thermocouples 1 ft apart extended vertically from the top of the vacuum vessel to the base and a second row extended around the periphery at approximately the midpoint of the converter section.

2. Vacuum Pumping System

The test chamber was evacuated by a mechanical roughing pump and diffusion-type booster pump. The 300-cfm mechanical pump reduced the pressure in the vessel from atmospheric to less than 85 microns, at which pressure the 20-in. diameter 5800-liter/sec oil diffusion pump was opened to the vessel. The combination of the mechanical and the diffusion pumps was capable of evacuating the 800 ft^3 vacuum chamber to less than 1×10^{-5} Torr.

A freon 12-cooled cold baffle located in the 20-in.-diameter pumping line (1) permitted lower pressures in the chamber, (2) reduced backstreaming of the diffusion pump oil in the chamber and (3) condensed the vapors coming from the chamber to avoid contamination of the diffusion pump. A 20-in. diameter bellows section was installed between the vessel and pumping system to provide flexibility during installation of the pumping system and allowance for thermal expansion.

Three electrically actuated pneumatic valves on the vacuum lines permitted by-passing the diffusion pump during the initial phase of the evacuation. The diffusion pump was isolated from the remainder of the system by a 20-in. diameter valve at the inlet and 6-in. valve at the discharge of the pump. A small 5-cfm mechanical pump was plumbed into the diffusion pump outlet to permit evacuation and heat-up of the 20-in. diffusion pump prior to opening it to the vacuum chamber. Figure 12 shows a schematic of this system and Figure 13 a photograph of the diffusion pump section.

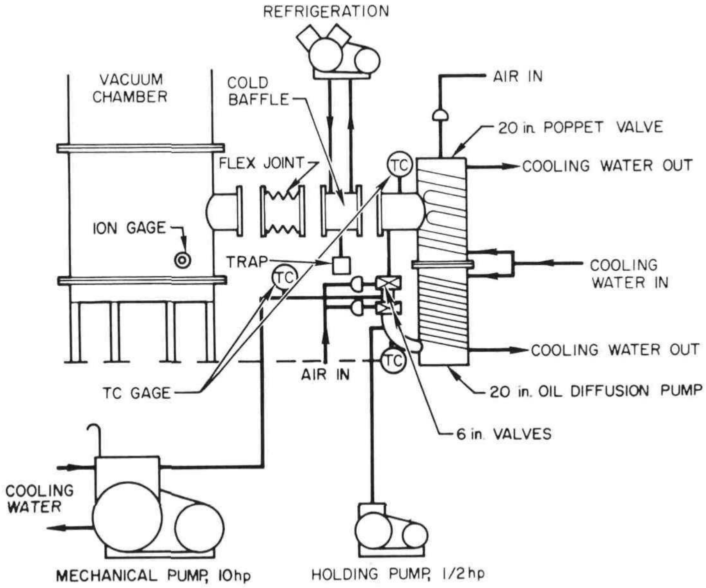

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Figure 12. Schematic of PSM-3 Vacuum Pumping System

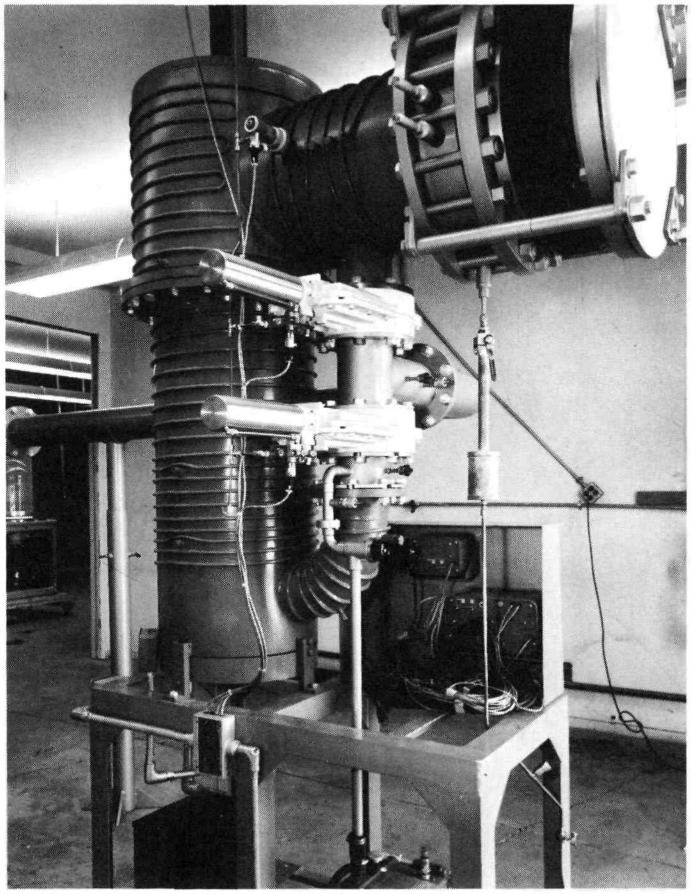

Figure 13. S10A PSM-3 Vacuum Pumping System

The electrical vacuum control panel was designed with many safety interlocks. If the chamber pressure suddenly increased or cooling water flow to the diffusion pump was lost, the pneumatic valves would automatically close, thus preventing cracking of the diffusion pump oil or backstreaming oil into the chamber. Also, the 6-in. diameter pneumatic valves had to be in the proper positions before the diffusion pump could be opened to the chamber. Pressure limit switches at the inlet and outlet to the diffusion pump prevented energizing the diffusion pump heaters until safe operating pressures had been reached.

3. Cooling Water System

A 50-gpm-at-65-ft-head centrifugal pump provided water-cooling flow for the vacuum chamber wall, diffusion pump casing, and mechanical pump bearings. Heat rejection from the cooling water was accomplished by a 100 kw evaporative water cooler. A water pressure relief valve installed in a bypass line limited the pump discharge pressure to 33 psig.

The cooling system was filled with distilled water to ensure maximum system cleanliness. Two cleanable filters installed at the pump discharge manifolds removed all solid particles from the circulating water.

The water flow to each of the three sections of the vacuum chamber was indicated by turbine flowmeters whose output was converted to a dc signal and recorded by the data logging system. Bimetallic indicating thermometers were installed at the inlet manifold and at each water outlet line.

4. NaK Loading Cart

A NaK loading cart provided a clean supply of NaK for the filling and flushing operation during NaK loading of the PSM-3 power system. The loading cart linear induction pump circulated the NaK past a 6-in. diameter by 21-in. long cold trap to remove oxides from the NaK. Refrigeration coils at the lower end of the cold trap maintained a thermal gradient down the pipe which caused the NaK oxides to precipitate out of solution. Also, a 5 micron filter removed any suspended particles from the NaK.

Valves were so arranged on the plumbing that circulation could be maintained either within the loading cart for cleanup of the NaK inventory or circulated through the power system for flushing purposes.

The supply tank in the loading cart contained 1.5 ft^3 of NaK, enough for 1.6 charges of the PSM-3 power system and fill lines.

A 30 kw 220 vac inline heater mounted at the discharge line of the loading cart permitted a hot flush of the power system without using the power system's heaters.

Figure 14 is a schematic of the loading cart and the unit itself can be seen at the right side of Figure 11, connected to the vacuum chamber.

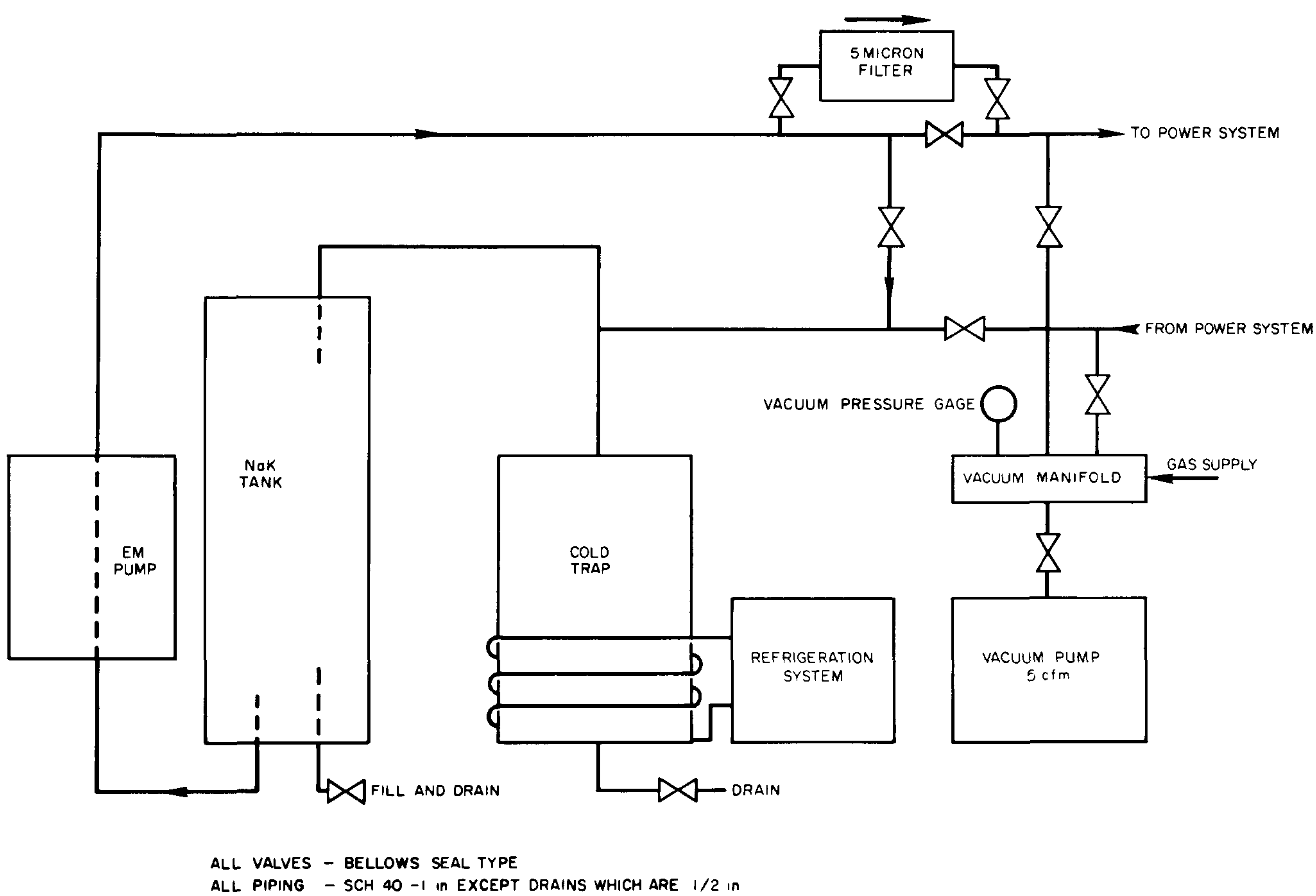

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Figure 14. NaK Loading Cart Schematic

5. Data Logger

The primary data recording instrument for the PSM-3 test was the 400 point digital data logger. Three hundred channels were used for chromel-alumel thermocouples and the other 100 for miscellaneous dc voltage and millivolt signals. The data were indicated on a digital voltmeter and automatically typed in engineering units with the decimal point correctly located. The digital voltmeter output was sent to the parallel-to-serial converter for proper alignment with the typewriter and punch tape attachment. The punch tape attachment included on the logging system provided the data in a form usable as input for a computer data reduction program.

The data logger included a 0°F thermocouple reference junction imposed electronically by a thermistor circuit. A 24 hr clock on the logger printed out the time at the start of each logger cycle. A complete 400 point cycle required about 7 min to complete. A patch panel permitted by-passing sections of logger points at will.

6. Control Console

The primary controls for the system test were located in the control console. PAT (Position Adjust Type) Model 60 temperature controller-recorder, located in the console, set the power input to the power system core heater. The controller regulated the motor drive on the 56 kva, 3-phase variable transformer either automatically by a feedback circuit from the temperature set point or manually. All tests on PSM-3 used manual heater power control. A pen recorder strip chart continuously recorded the core heater outlet temperature history on the controller. The electrical input to the core heaters was indicated on a wattmeter and voltmeter mounted near the controller.

The infrared radiant heater controls were also mounted in the control console. A manually controlled motor-driven 15 kva variable transformer supplied power to the eight radiant heaters. A switch on each of the heater circuits permitted setting the desired sun-shade simulation around the power system by simply switching off any number of heaters. A kilowatt meter indicated total power input to the heaters.

An eight position malfunction annunciator panel on the console provided a combination horn and light when any one of the following situations occurred:

a. Over temperature at core heater outlet (1000°F)

b. Low water flow to vacuum pump

c. Low water flow to vacuum chamber walls

d. Loss of vacuum in vacuum chamber

e. Low NaK flow in power system (0.5 gpm at any of the 3 flowmeters)

f. Over temperature at vacuum diffusion pump

g. Completely extended bellows in expansion compensators

h. Spare

A set of indicating instruments in the console backed up the data logger. A 40 point temperature indicator and 100 point dc voltmeter provided sufficient information to continue system operation in case of logger malfunction.

Three single-pen recorders were wired to each of the three NaK flowmeters to provide immediate visual indication of the flow conditions in the power system. Any flow disturbance caused by oxide plugging or pump power malfunction was quickly detected.

7. Thermoelectric Patch Panel

Each of the 21 lead-telluride thermoelectric modules installed on PSM-3 was electrically wired to a patch panel to permit monitoring of the current and voltage for each module and to facilitate wiring of various types of converter output circuits.

The patch panel consisted of 40 blocks or modules, one of which is shown schematically in Figure 15, each connected to a single TE module. Only 21 were used for PSM-3. The entire unit can be seen in Figure 11.

The dual set of leads from each end radiator of the TE modules was required to measure voltage output at the module while current was being drawn. Otherwise, the voltage measurement would include the I^2R loss in the lead wires.

By opening and closing the switch, the open and closed circuit conditions of the TE module could be monitored. The desired series or parallel circuits would be wired at the patch panel by 8-ga. jumper wires connected to the proper jacks.

8. Core Heater Power Circuit

The output of the 208 v, 56 kva, 3-phase, core heater variable transformer was wired in wye. Initially, the heater elements were similarly connected in wye, which limited the voltage across the elements to 115 vac. Only 32 kw of power could be put in the load at this voltage. This was less power than required to obtain the design operating temperature. To correct this

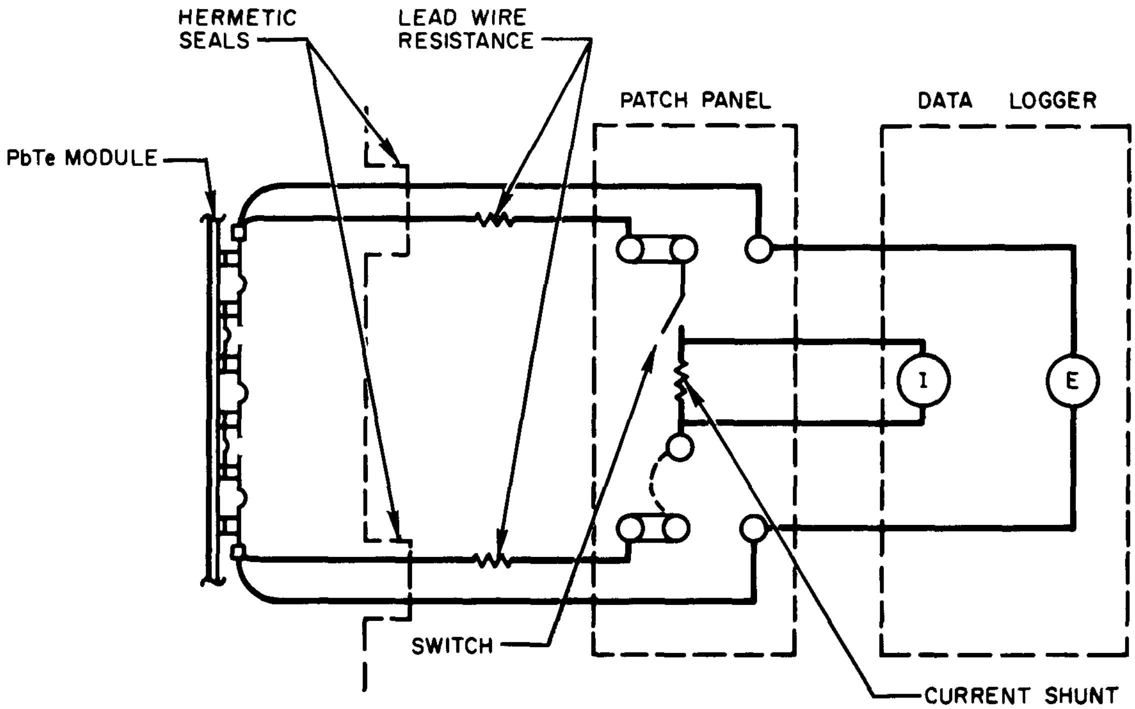

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Figure 15. TE Patch Panel Module Wiring Schematic

limitation, the core heater circuits were rewired to delta. Figure 16 is a schematic of the delta-wired circuit.

Four No. 3/0-size cables carried the power from the transformer to the electrical breaker panel, where the circuit was routed to the individual heater elements. Fifteen circuits, using asbestos insulated 12-ga. lead wires, carried the power inside the vacuum chamber to the 30 heater elements. Brass clamps connected the copper lead wires to the nickel extensions at the core heater. Ceramic beads provided the electrical insulation on the nickel leads.

9. Radiant Heaters

The eight infrared radiant heaters simulated the magnitude of the sun's heat input onto the power system converter but not the solar spectrum. Each of the eight units was rated at 1500 watts at 120 vac and equally spaced around the power unit. The heating filaments were nichrome wire installed in a quartz tube envelope. An electropolished stainless steel reflector concentrated most of the energy onto the power system converter (Figure 17).

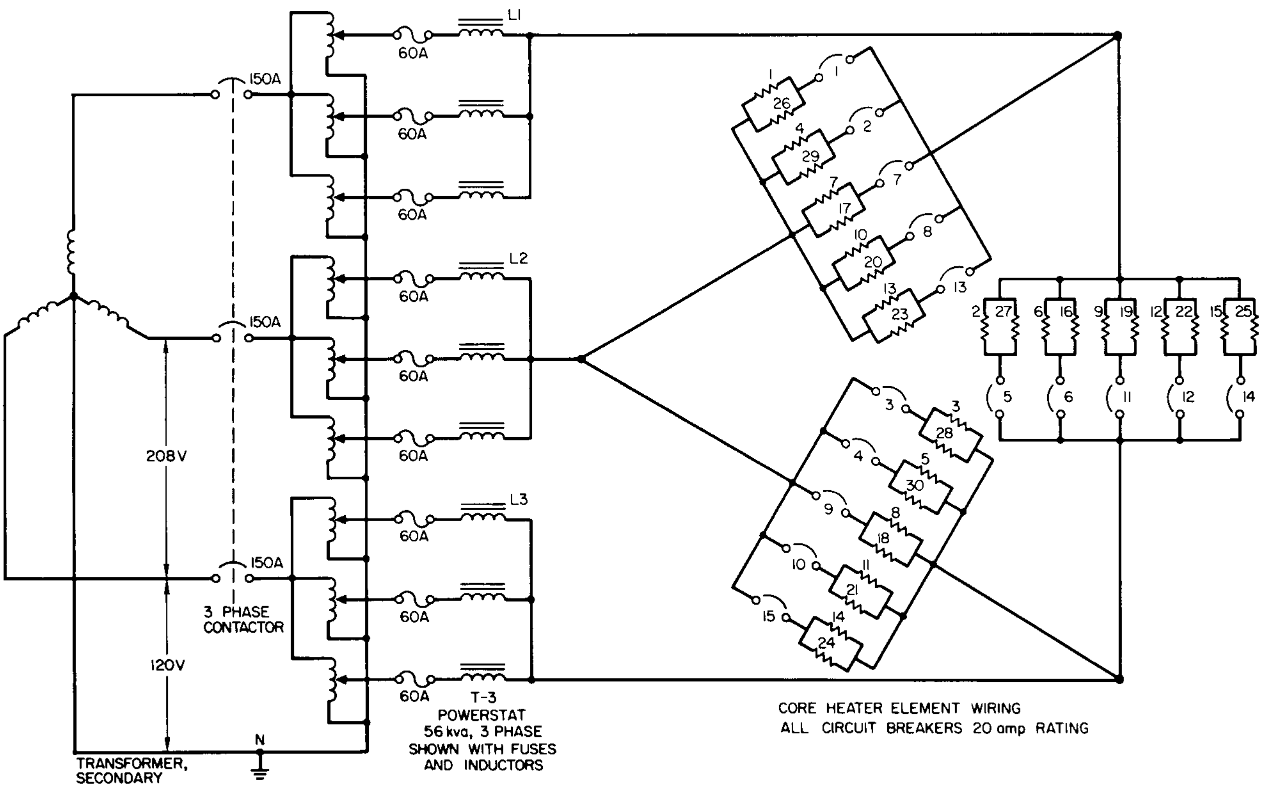

Figure 16. Core Heater Wiring Diagram

The 96-in. long heating element and reflector assembly was attached to an unistrut frame and mounted on the chamber base. The heating element consisted of two sections with a 1.5-in. space at the center. The lamps extended 4 in. below and 7 in. above the converter section and were located 1 ft radially from the lower converter manifold and 2 ft from the upper manifold.

The custom built reflectors radiated over an 87° included angle, the view angle between the heater filament and 50-in. diameter base of the power system. The reflector surface facing the chamber wall was painted black to minimize the reflector temperature.

A graphical analysis conducted with the designed reflector cross-section indicated that 2 to 3 times more energy would be radiated onto the power system directly opposite the lamps than between the lamps, 22-1/2° around the periphery.

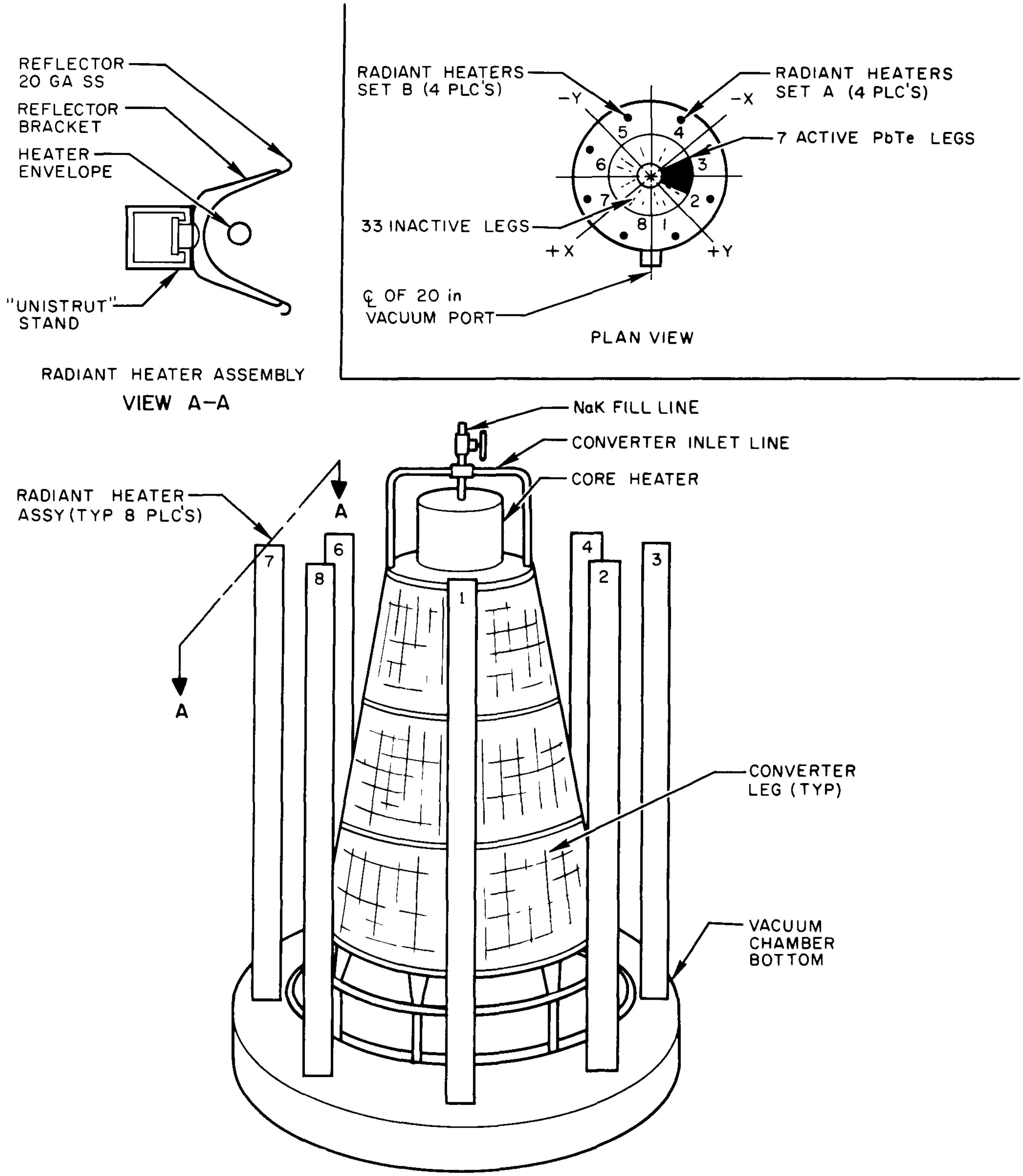

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Figure 17. Radiant Heater Arrangement

10. NaK Differential Pressure Transducers

The 0-1.5 psi differential pressure transducer which measured the pressure rise across the power system pump was located outside the vacuum chamber. NaK capillary lines (0.375-in. diameter) were routed from the 0.25-in. pressure nozzles at the pump to the transducer.

An identical differential pressure transducer utilizing 0.25-in. capillary lines measured the pressure drop down the converter tubes. The high pressure line was connected to the upper converter manifold and the low pressure line to the lower manifold.

These Statham Model PM80TC differential transducers indicated pressure from the deflection of a single diaphragm which actuated an unbonded strain gage. The unit was powered by a 28 vdc source and a mv signal was developed from a Wheatstone bridge circuit. The output was recorded by the data logger. Valves on the capillary lines permitted equalizing pressure on each side of the diaphragm and calibrating the transducer even during system circulation.

Installation of the differential pressure transducers is shown in Figure 5.

11. Miscellaneous Components

a. Fill Lines and Valves

The 1-in. stainless steel NaK fill line was connected to the top spool of the power system above the NaK pump. One-in. return lines were attached to each half of the outlet converter manifold. NaK valves were installed on each of these lines. These tubes were welded into a flange plate on a chamber penetration port. The NaK lines and NaK loading cart remained connected to the system during the entire PSM-3 testing program. The valves were closed during testing to isolate the power system from the loading cart.

b. 48 Point Indicator

An additional multipoint indicator was installed in the test facilities to monitor vacuum chamber wall temperatures, core heater surface temperatures, and heat barrier temperatures. This indicator was required because all other chromel-alumel thermocouple indicators in the facility were used to capacity.

c. Expansion Compensator Gas Pressure System

The NaK pressure in the power system tubing was set by the argon gas pressure applied to the expansion compensator bellows. This pressure was adjusted in the positive gage pressure range by an argon gas bottle supply, and in the negative gage pressure range by a 1-cfm vacuum pump. Argon gas was used to avoid possible oxide contamination of the power system in case of a fracture at the bellows.

The gas pressure at both expansion compensators was monitored by pressure transducers and recorded by the data logger. Bourdon type indicating gages mounted on the lines provided visual indication. A 230-in.^{3} accumulator on each compensator capillary line increased the gas volume, thus damping out the fluctuations due to power system temperature changes.

d. Argon Gas System

An argon system was provided for backfilling the vacuum chamber and for use in the expansion compensator gas system. An eight bottle manifold provided the argon supply. Four bottles (800 ft^3) of gas were required to backfill the chambers from a vacuum to atmospheric pressure.

V. TEST DESCRIPTION AND RESULTS

The test procedures followed and the results obtained during each phase of the PSM-3 tests are outlined in the following paragraphs. Detailed test procedures were prepared for each phase of the test program. These procedures indicated specific safety measures to be enforced as well as the method of conducting the tests. The test specification used is listed as Reference 1. All data reduction was done manually and it was consequently impossible to reduce all of the large quantity of test data obtained. Instead, typical or particularly significant results were noted and are reported here.

A. NaK LOADING

The NaK loading procedure was designed to fulfill two objectives in addition to simply filling the power system with NaK.

1) Remove all oxides and other contaminants from the NaK tube surfaces in the unit.

2) Leave a clean NaK inventory in the unit by removing all oxides and other contaminants from the NaK.

NaK was circulated for 24 hr in the NaK loading cart to cold trap or precipitate NaK oxides, prior to attachment to the power system. After hookup to the power system, the loading cart and power system were purged with argon and evacuated. NaK filling was accomplished with the power system under a vacuum to obtain a void free NaK system.

NaK was forced through a 5-micron filter in the loading cart and into the power system through the inlet line at the top. A schematic of the NaK loading system attached to the power system is shown in Figure 18. For several hours, NaK flowed into the top of the unit and out the return lines at the lower manifold, using the electromagnetic pump located in the loading cart. To remove oxides picked up in the power system, the NaK was continuously cold trapped by a refrigerated cold finger located in the loading cart. The small plenum chamber located on the NaK lines at the highest point on the power system was vented after NaK filling and circulation to remove any gas bubbles which may have been swept into the plenum.

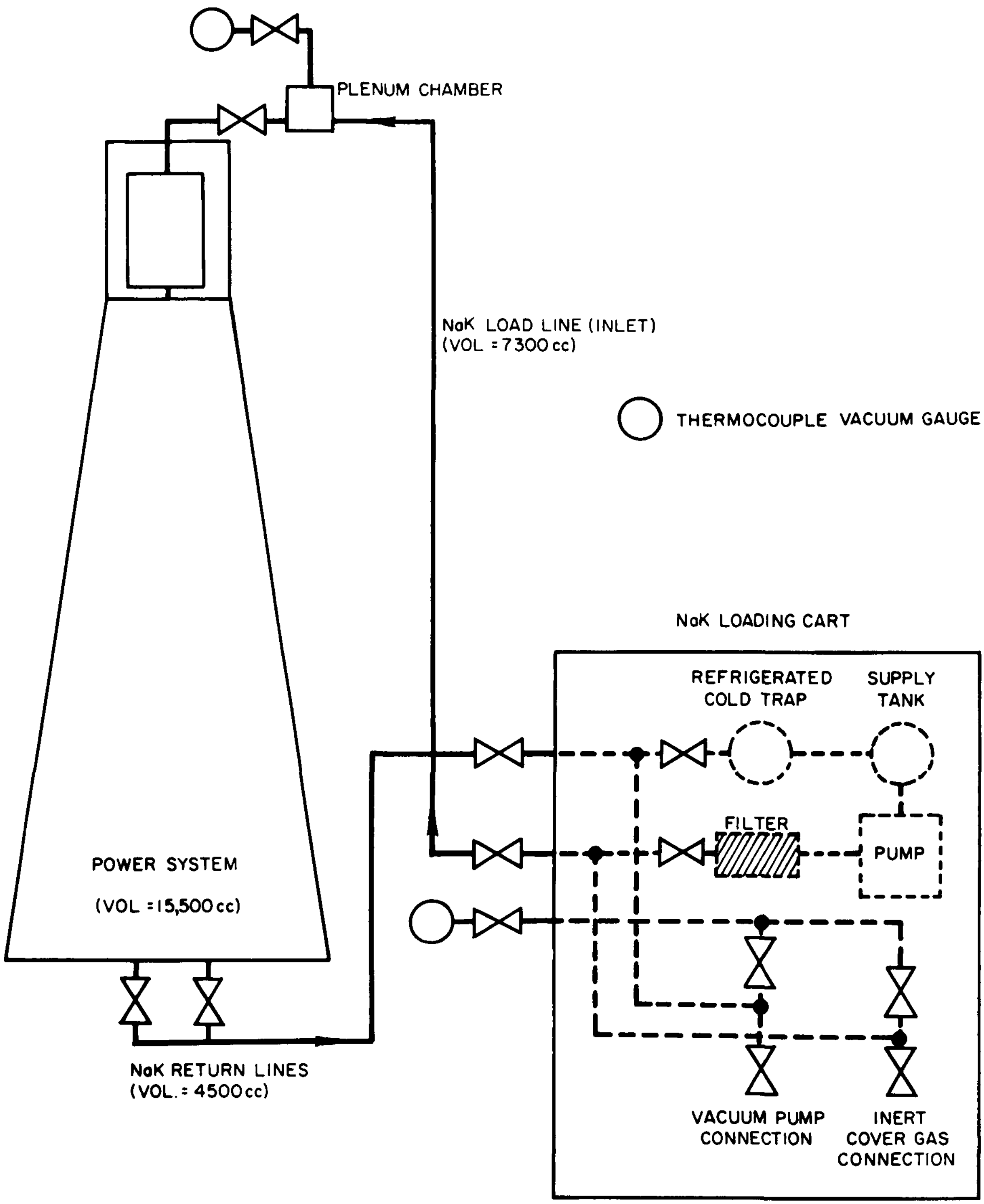

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Figure 18. PSM-3 Plumbed To Loading Cart

The final phase of the NaK loading operation was to assemble the vacuum chamber over the power system, evacuate the chamber to prevent oxidation of the converter elements, and heat the NaK to 700°F at not more than 2 F° per min. The core heater was energized and the pump power increased to provide greater NaK circulation than the loading cart could supply. About 10% of the NaK flow through the converter was shunted through the loading cart for cold trapping. Because the refrigeration system on the loading cart cold trap was found to be limited to a heat rejection rate of about 1 kw, only a limited amount of NaK could flow past the cold trap without overloading the refrigeration system.

Several times during the PSM-3 system test, the converter tubes and manifolds plugged with oxide. They were unplugged by insulating the converter section with aluminum foil and circulating the NaK at temperatures in excess of 500°F for an extended period of time. The contaminated NaK was cleaned by circulating the NaK past the cold trap in the loading cart, where the oxides precipitated out. In some cases, the oxide concentration was so high that the NaK inventory had to be dumped hot from the power system and replaced with a fresh supply.

The loading cart was used prior to NaK loading to conduct static leak-up tests on the system. With the piping evacuated to 25×10^{-3} mm Hg, a leak rate of 4×10^{-4} cc/sec (standard temperature and pressure) was measured. At a tube pressure of 1.9 mm Hg and above, the indicated leak rate was imperceptibly small. A helium mass spectrometer leak check, conducted at this time by purging the outside of the system with helium and monitoring the evacuated piping, disclosed leaks of the magnitude of 2×10^{-6} cc/sec (corrected to an air leakage). The difference in these two indicated leak rates was due to off-gassing of oxidized NaK within the tubes. One hundred $inches^3$ of NaK accidentally leaked from the loading cart into the tubing, where it became oxidized and absorbed moisture. The threshold pressure for off-gassing of this contaminant was apparently 1.9 mm Hg. Therefore, the actual air leak rate into the tubing prior to loading was about 2×10^{-6} cc/sec. This leak rate was considered acceptable for filling the unit with NaK. A detailed description of this activity is published in Reference 2.

On April 18, 1962, the PSM-3 power system and fill lines were evacuated to about 5×10^{-3} mm Hg and filled with 7.8 gal of NaK. The system was operated between 100 and 200°F at approximately 4 gpm total flow for several days. The

NaK oxides in the power system were flushed and cold trapped during this period. The NaK in the system was heated to 500°F and cold trapped over a 2 day period, using the loading cart inline NaK heater.

On the morning of May 1, 1962, the NaK flow in 16 to 20 converter tubes became restricted or stopped completely. Plugging was attributed to the inability of the cold trap in the NaK loading cart to handle the heat load of 4 gpm NaK flow at 500°F. The cold trap became warm, allowing NaK oxides to redissolve and circulate through the system. To alleviate this problem, flow through the loading cart was limited to 0.8 gpm. Total flow through the converter was increased to 7 gpm. This was done by increasing the system dc conduction pump power and by decreasing the load cart linear induction pump power. To maintain the system heater outlet temperature at 500°F, power to the loading cart in-line heater was decreased and the core heater energized. NaK circulation was maintained in this manner for 6 days at temperatures to 550°F. Only four tubes were successfully unplugged. On May 8, 1962, the system was cooled to 200°F and the top of the vacuum vessel was removed. A thorough inspection of the unit was made. Tubes 407, 415, 416, 417, 418, 421, 422, 425, 426, 427, 433, 436, 437, 438, 439, and 440 were "cold" to the touch. The converter tube outlet temperature profiles and thermal gradients along the plugged tubes are shown in detail in Reference 3. Many of the tubes were bowed, particularly at the base. An example of these bowed tubes can be seen at the left of Figure 19. Aluminum foil was draped around the converter to act as insulation in the vacuum environment, and the power system was heated to 700°F. After 4 days of operation, all the tubes appeared unplugged. However, upon cooling, tubes 435 and 437 were found to be still plugged as shown by Figure 33. One additional day of NaK circulation did not unplug these tubes. The aluminum foil was removed and the unit heated to 600°F to start the system tests. However, tube 435 failed in tension at the upper manifold, causing NaK to spray onto the vessel wall and adjacent radiant heaters. The failure area is shown in Figure 20. The NaK was drained from the system and the converter tube crack welded shut. The loading cart was removed from the fill lines and a new cold trap added. A clean charge of NaK was added to the loading cart and the power system filled by the aforementioned procedure (leak checking, NaK loading, flushing, cold trapping with the loading cart). Aluminum foil was again draped over the converter and

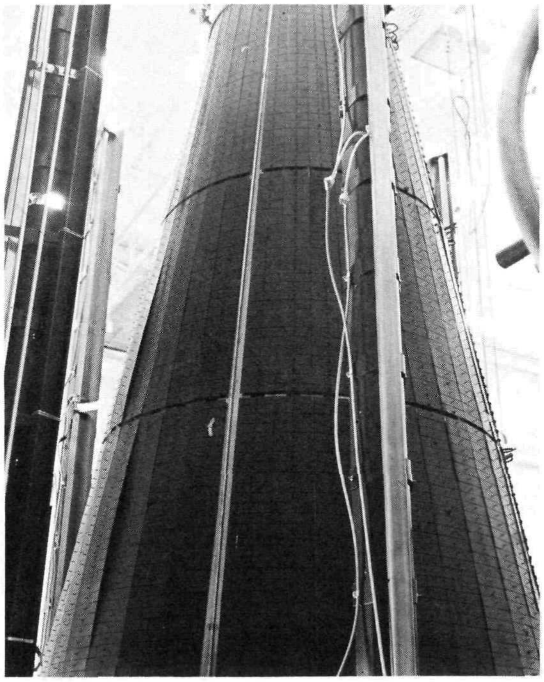

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Figure 19. Bowed Legs on PSM-3 Converter During NaK Loading Test

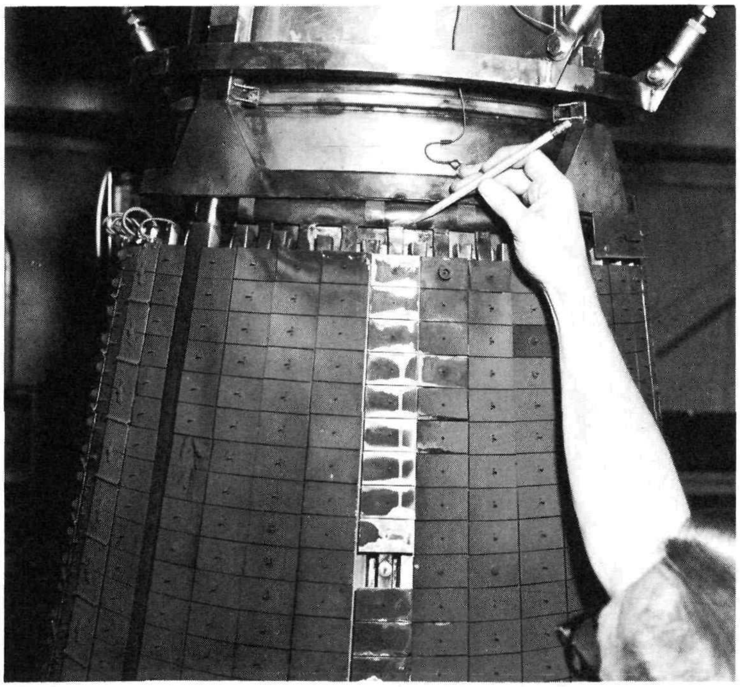

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Figure 20. Area of NaK Leak on Converter Leg No. 955

the NaK heated to 700°F during the flushing operation. The previously plugged tubes opened satisfactorily; when, however, the NaK was cooled to 130°F, oxide plugging reoccurred, this time in the inlet manifolds. The system was immediately reheated to 770°F where, after two days of NaK circulation, the manifolds unplugged. The NaK was drained from the unit hot (700°F) and discarded. Another clean charge of NaK was then added to the power system. No oxide plugging resulted from this, the third inventory of NaK introduced to the system.

On three more occasions during the PSM-3 system test NaK was drained from the unit to facilitate repair of NaK leaks and remove the contaminated NaK. NaK loading without a flushing operation utilizing the cold trap in the loading cart appeared to cause less oxide plugging problems than use of the cold trap.

B. SYSTEM THERMAL AND ELECTRICAL PERFORMANCE

The PbTe thermoelectric converter voltage and currents, along with system temperature, were measured throughout the PSM-3 thermal performance tests. On ten occasions, the internal resistance of the 21 PbTe thermoelectric modules were measured at ambient temperature with a Kelvin bridge. No direct resistance measurement could be made with an external instrument at any temperature above ambient, since the thermoelectric module itself was producing an output voltage.

Two hundred forty thermocouples were located at the radiator converter section of the power system to monitor temperature gradients on both the PbTe operating legs and simulated legs. Twenty-three converter tube inlet temperatures and all forty converter tube outlet temperatures were continuously monitored during the test program, to verify the satisfactory operation of each converter tube. Each of the seven PbTe thermoelectric legs were instrumented with thermocouples at twelve locations down their length. Four of the legs had thermocouples attached to the radiators only; the other legs were instrumented at the hot straps as well as the radiators.

Five simulated legs were instrumented at five locations to determine the thermal gradient down the converter tube as well as the temperature drop across the simulated element from tube to radiator. In addition, the converter shell was instrumented at twenty locations opposite these simulated legs, to determine the heat transfer from the converter legs to the shell and thermal gradients along the shell.

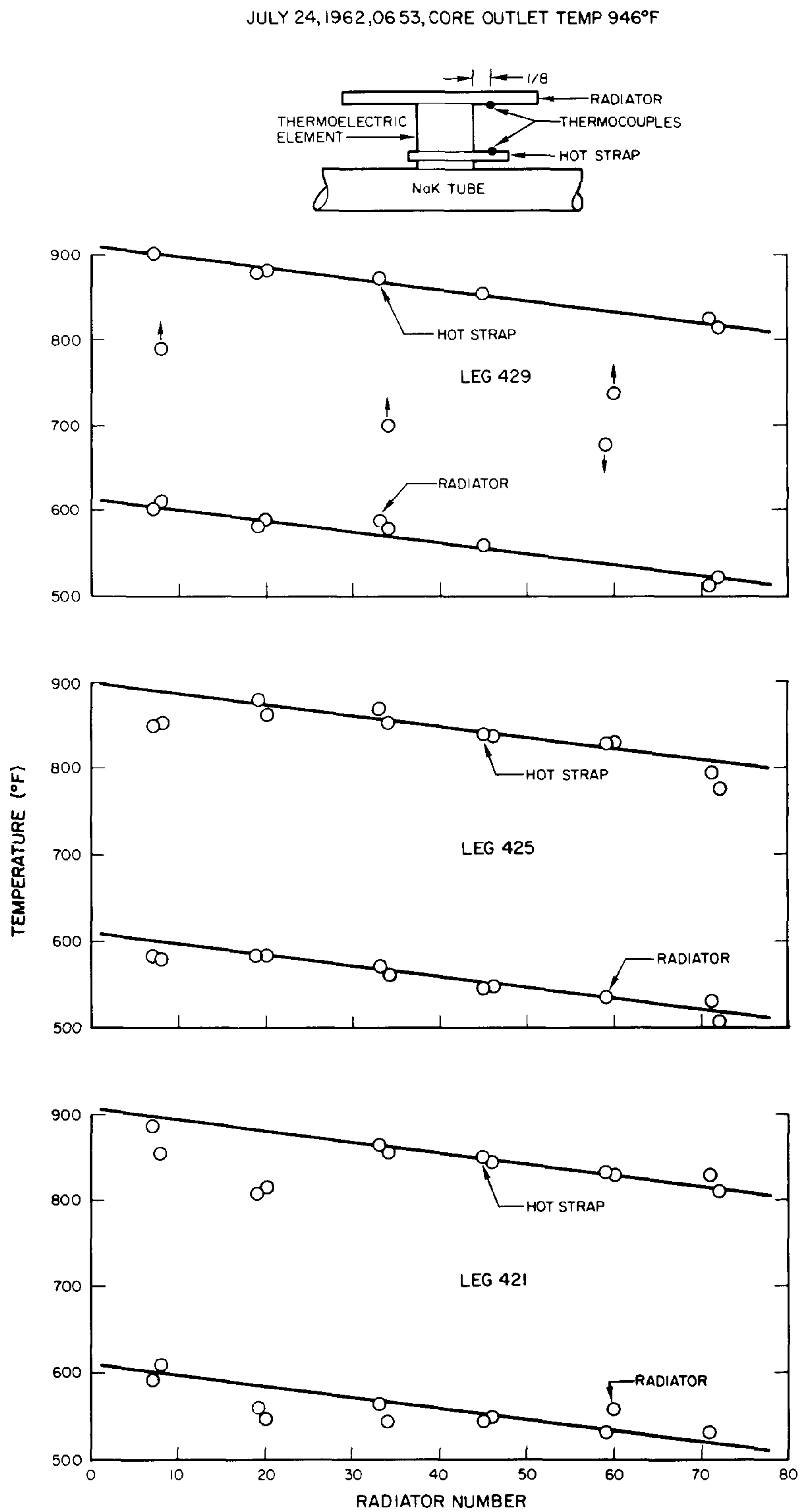
The following table is an overall heat balance on the converter and shows both the design point and test results at an average converter NaK temperature of 906°F.

	Design Point	Test Results*
Heat input to converter (kw)	27.9	27.9
Heat rejected by radiator (kw)	27.32	27.16
Heat radiated from the NaK lines and structure to the radiator (kw)	2.0	4.0
Heat transfer through TE elements (kw)	25.32	23.16

*The test results were extrapolated to the PSM-3 design conditions of 960°F core outlet temperature and 12.0 gpm NaK flow rate.

The heat input to the converter is equal to the heat lost by the converter NaK tubes and was obtained from $\dot{m}C_p\Delta T$ at the design point. The 27.16 kw rejected by the radiator was obtained by assuming that the radiator radiated to space with the same temperature distribution as that of leg 425 in Figure 22, except that the curve was shifted upward 20°F to be compatible with the converter inlet design temperature of 956°F. The value of 4.0 kw of heat radiated from the NaK tubes was calculated based on measured temperatures. Assuming that the temperatures for the flight system design were approximately the same as those measured and correcting for emissivity differences, it was estimated that 2.5 kw would be transferred from the NaK lines and structure to the radiator for the flight system design. This agrees quite closely with the design value of 2.57 kw. Subtracting the 4.0 kw from the total of 27.16 kw rejected yielded approximately 23.16 kw that was conducted through the thermoelectric elements. Using this value, along with the measured average temperature difference across the elements of 279°F, the conductance per element was determined to be 0.027 watts/°F, as compared to the design value of 0.031 watts/°F.

Figures 21 through 33 show typical temperature distributions for the converter. Figures 21 through 26 are curves of hot strap and radiator temperatures plotted vs radiator number at approximately 936°F core outlet temperature and show not only the temperature distribution but also the approximate temperature differences across the thermoelectric stacks. This information is presented for legs 421, 425, and 429. The information presented for leg 425 had fewer bad



12-30-63 7561-0939-3

Figure 21. Hot Strap and Radiator Temperature

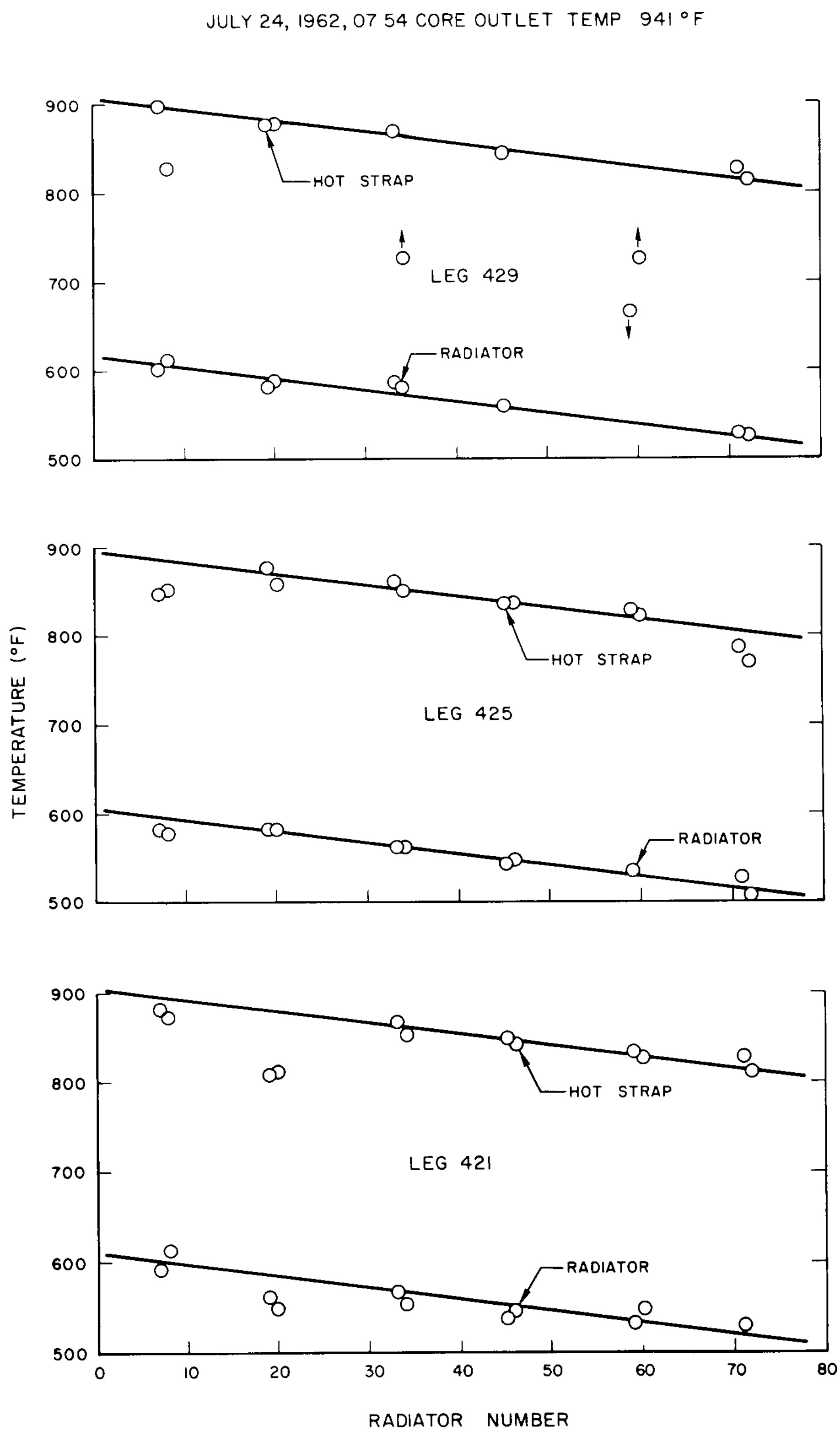


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Figure 22. Hot Strap and Radiator Temperature

JULY 24, 1962, 09:58, CORE OUTLET TEMP 944°F

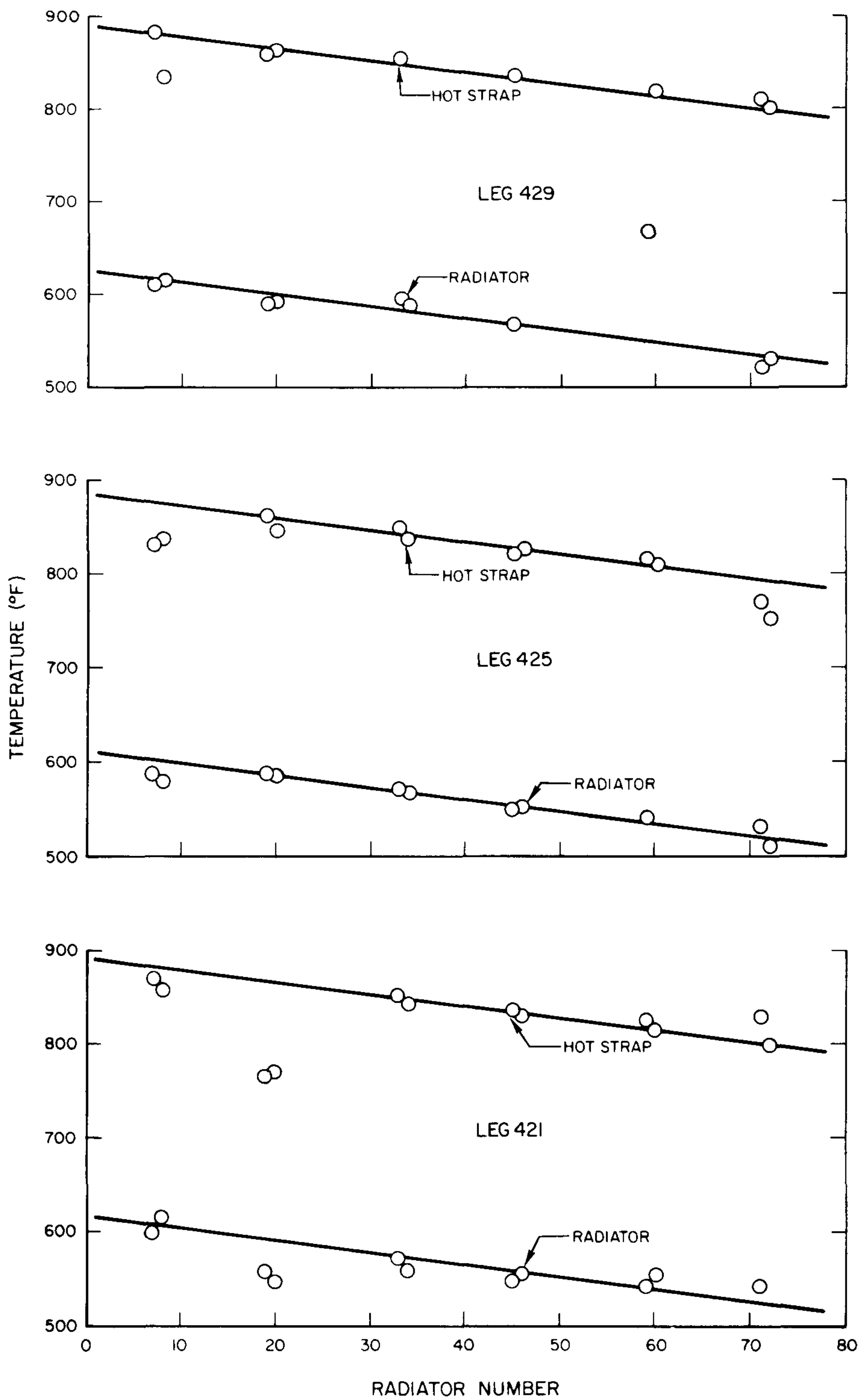

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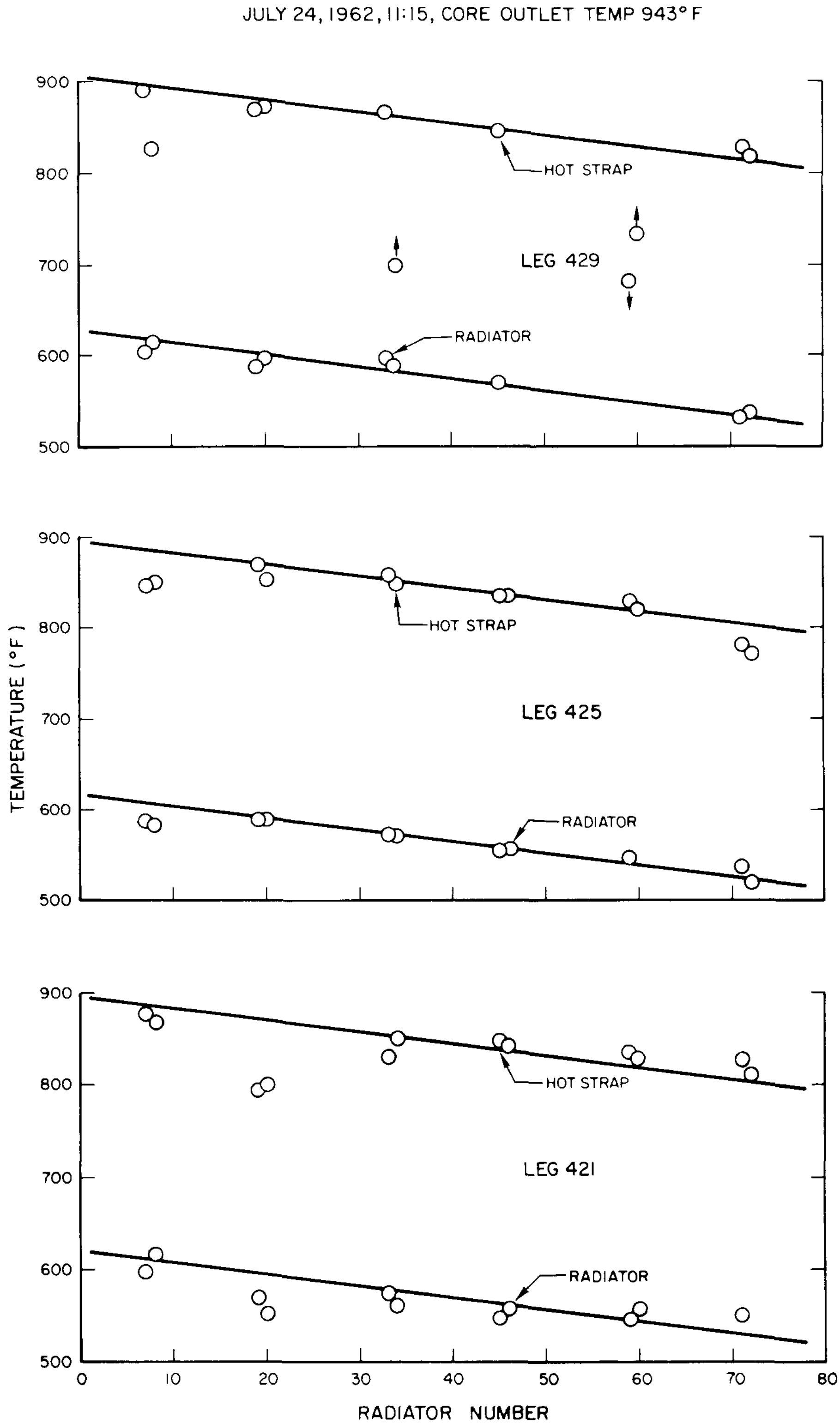
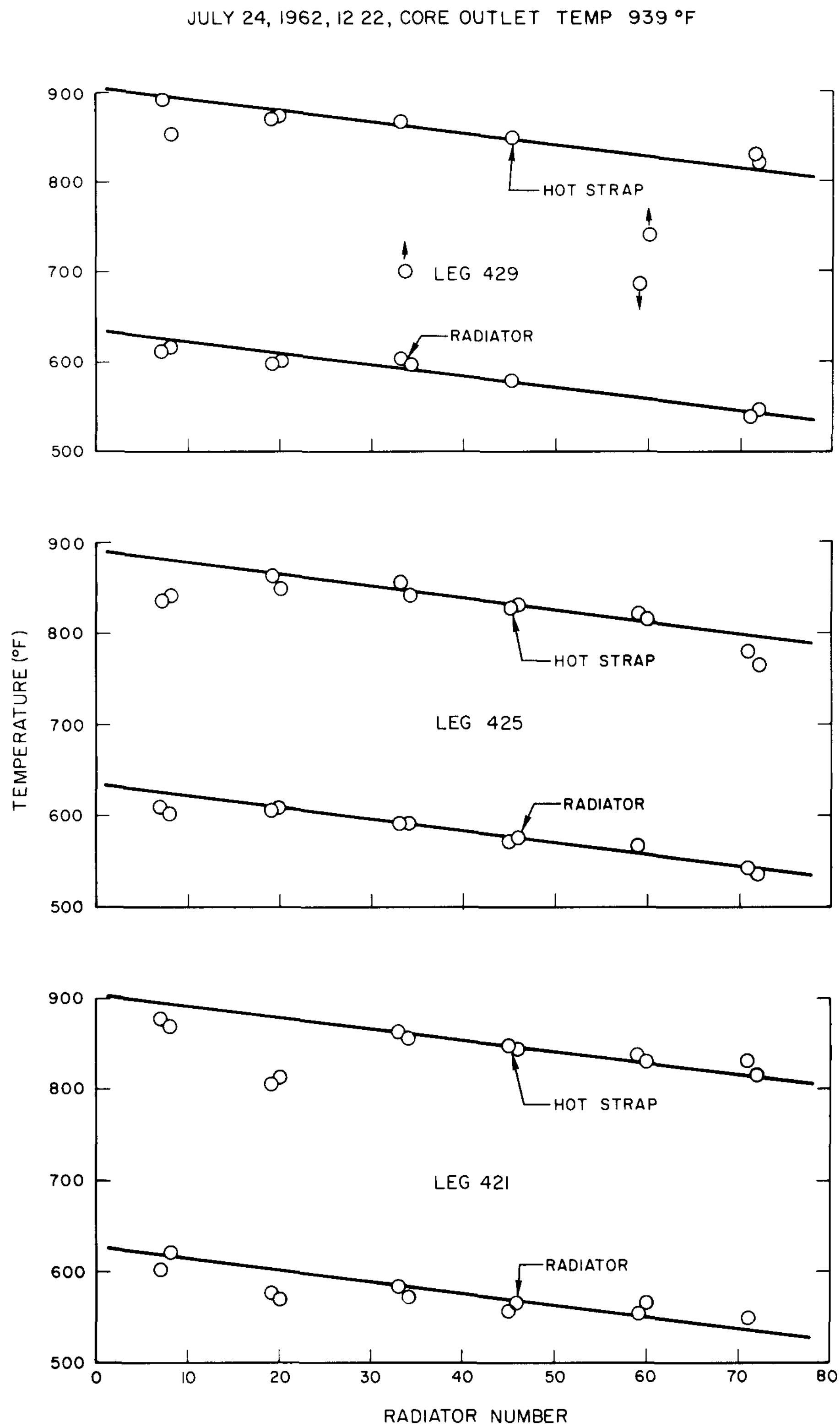
Figure 23. Hot Strap and Radiator Temperature



12-30-63 7561-0939-4

Figure 24. Hot Strap and Radiator Temperature



12-30-63 7561-0938

Figure 25. Hot Strap and Radiator Temperature

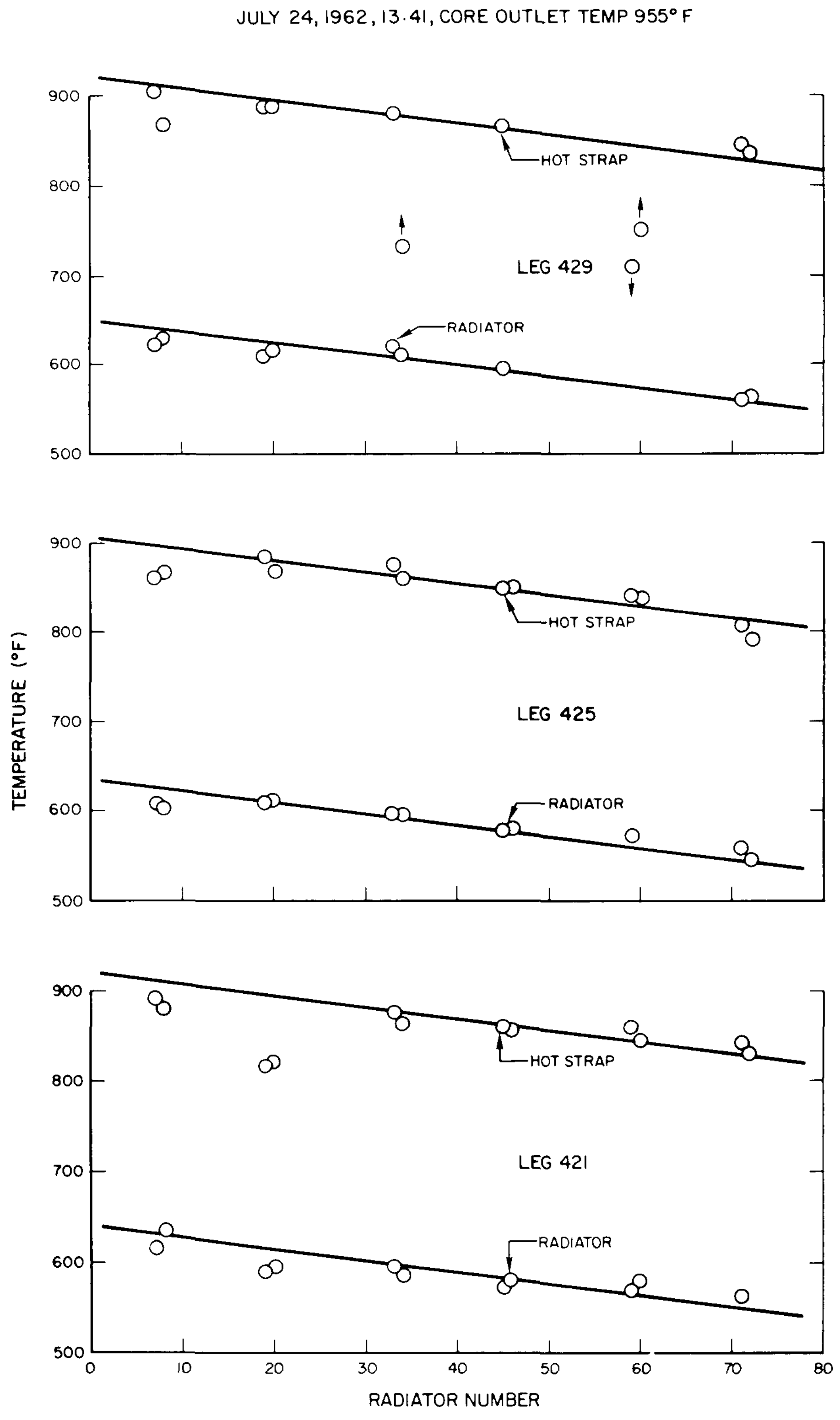


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Figure 26. Hot Strap and Radiator Temperature

data points and is, therefore, more representative of the true condition. The average temperature difference across the thermoelectric elements is 279°F. This agrees favorably with the design value of 262°F. Figure 27 shows hot strap, NaK, and NaK tube temperatures as a function of radiator number at a core outlet temperature of approximately 955°F. Figure 28 shows a typical converter shell structure temperature distribution at a core outlet temperature of 955°F. Figure 29 shows representative NaK tube temperature distributions. Figure 30 shows a typical system heat balance. It should be noted, in referring to Figure 30, that the heat input to the NaK is 27.6 kw and the sum of the heat losses is 27.9 which results in a 0.3 kw discrepancy. However, a discrepancy measurement error of only 1 or 2°F would result in the 0.3-kw discrepancy. Figures 31 and 32 present typical converter tube inlet and outlet temperatures as a function of converter leg number for core outlet temperatures of 623°F, 706°F, 804°F, and 944°F. Figure 33 shows converter inlet and outlet temperatures at a core outlet temperature of 530°F; in this case, however, legs 435 and 437 are oxide plugged. The calculated Carnot efficiency based on the hot strap and radiator temperatures contained in Figures 22 through 27 is 21.3% as compared with the design value of 19.7%.

Only seven of the 40 converter legs contained thermoelectric elements, and of these 21 modules, five were shorted out in the recording equipment leads. Therefore, the average module values discussed in the following paragraph are based on 16 operating modules. The values given for total system performance were derived by considering a total system of 120 modules that operated at the average values obtained for the 16 modules. Figures 34 through 36 are curves of calculated module internal resistance presented as a function of core outlet temperature. They are based on currents and voltages measured during the same time period with the exception of the points at approximately 945°F. The average internal resistance per module is 0.056 ohms. Figures 37 through 42 show module open circuit and closed circuit voltages and currents as a function of core outlet temperature. At the design temperature, the average open circuit voltage per module is 0.994 volts and the average current is 5.24 amps. The total system open circuit voltage, if the system contained 120 modules, would be 59.64 volts, which compares favorably with the design point of 57.5 volts. Figure 43 is a representative curve that shows the increase in internal resistance with time, temperature, and thermal cycling. The values given for ambient

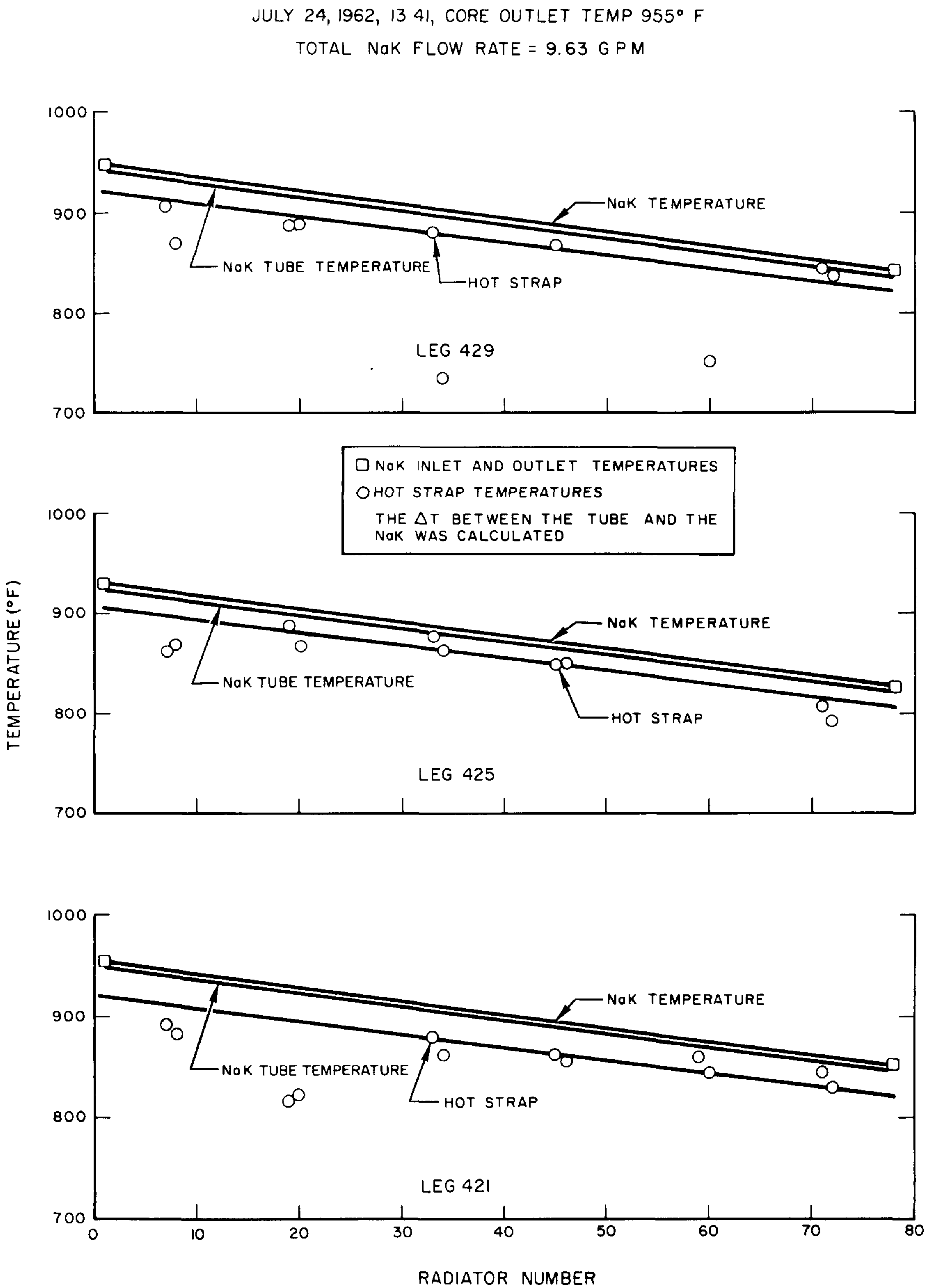

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Figure 27. Hot Strap, NaK, and NaK Tube Temperature

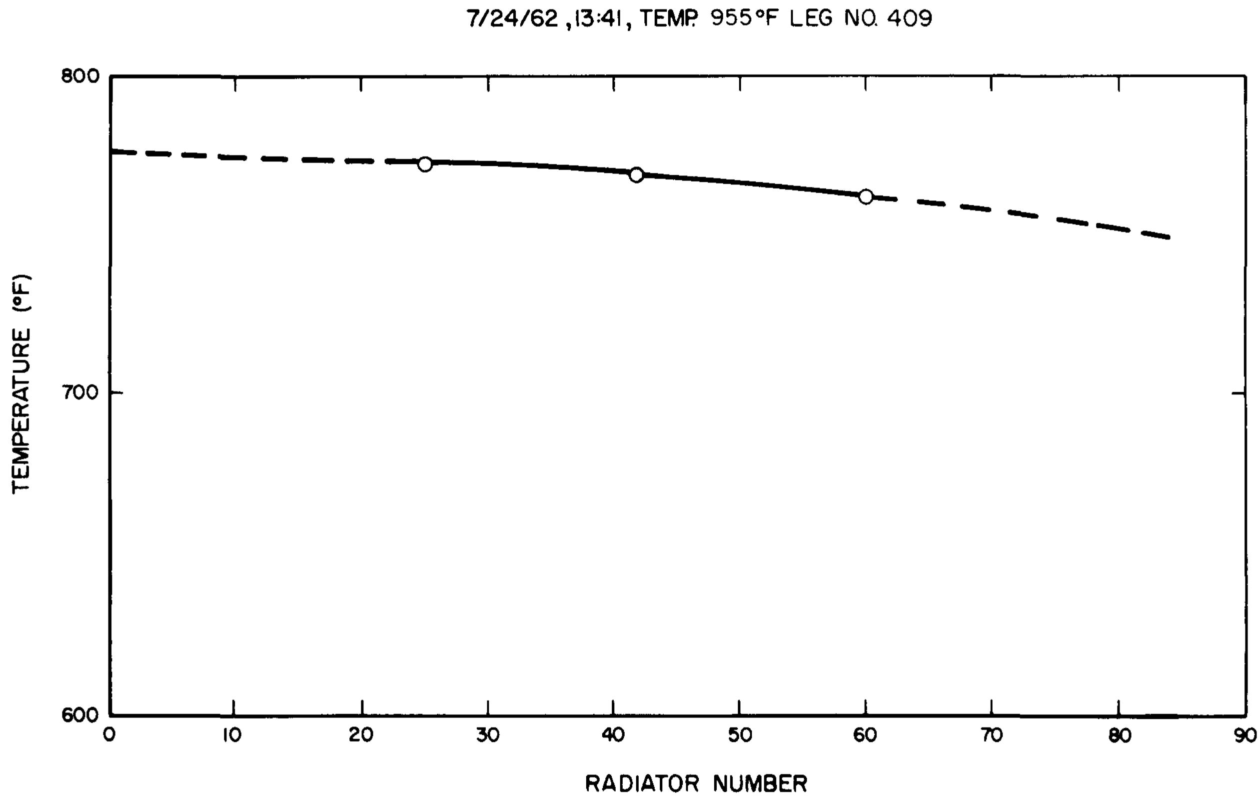

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Figure 28. Converter Shell Temperature Distribution

temperature are measured, and all others are calculated based on the measured voltages and currents. The core outlet temperature varied during testing approximately as shown in Figure 44 and 45. Emergency shutdowns on May 17, June 22, July 12, July 20, and July 24 all exceeded the PSM-3 test specification limitation of 2°F per min change in core outlet temperature. The latter three shutdown temperature histories are shown in Figures 47, 48, and 49. Figure 46 is a composite of Figures 43 and 44 and shows the measured module internal resistance and core outlet temperature histories.

Figure 50 shows the average electrical power per module versus average converter NaK temperature. The average power per module, based on matched internal and external load resistances, was calculated from the test data, using the following equation:

$$\overline{P} = \frac{\sum \frac{(E_{oc})^2}{4R_i}}{n} \quad , \qquad \ldots(1)$$

where

$\overline{P}$ = average power per module, watts

n = number of modules = 16

E_{oc} = measured open circuit voltage

R_i = module internal resistance, ohms

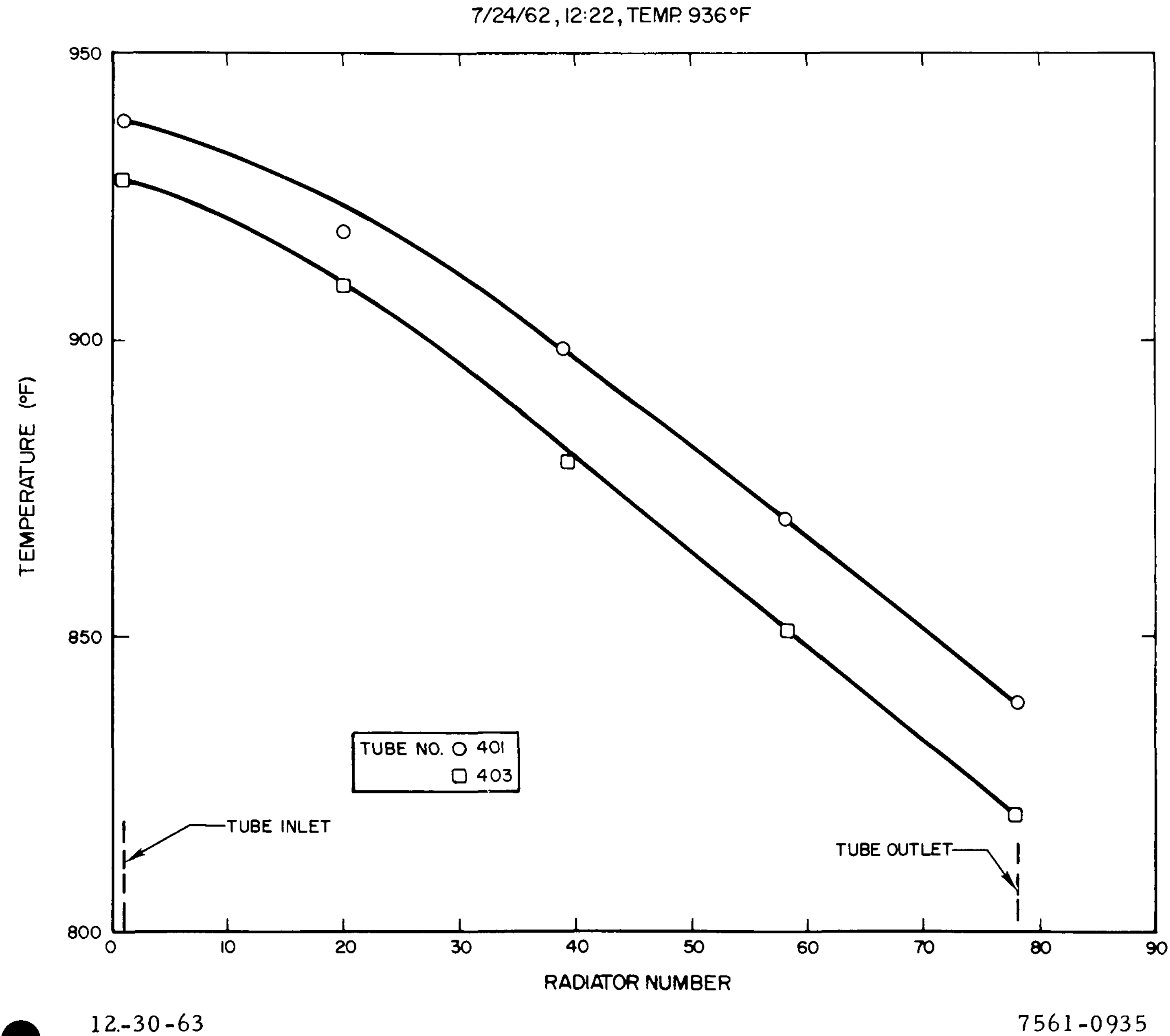

Figure 29. NaK Tube Temperature Distribution

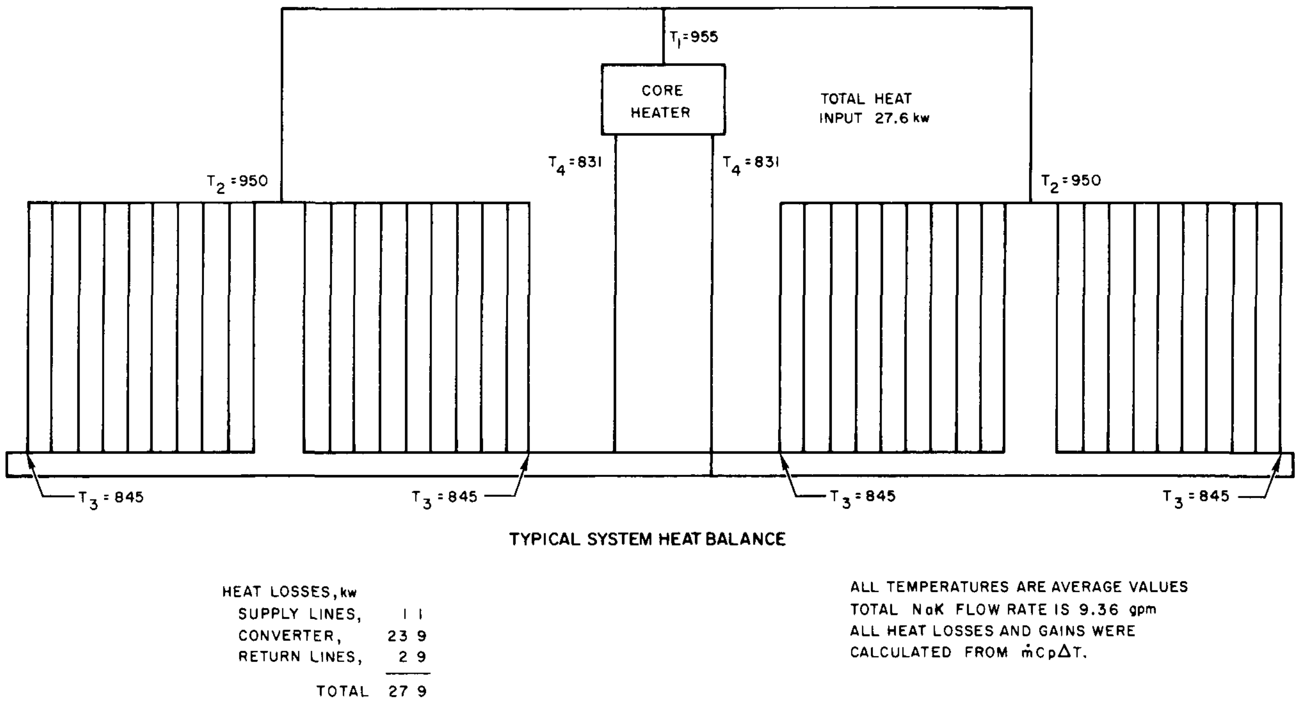

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Figure 30. Typical System Heat Balance

The design curve was determined by assuming that

$$\overline{P}_D = C_1 T^5 \quad , \qquad \ldots (2)$$

where

C_1 = constant

T = average converter NaK temperature, °F

Equation 5 was solved for C_1, since the design temperature of 1366°R and power of 4.88 watts per module was known. Using the determined value of C_1, Equation 2 was then solved for power at various temperatures. At temperature, the test data yields an average power of 4.45 watts per module or a total for the power system of 534 watts for 120 modules, compared to the design point of 585 watts.

The overall efficiency, obtained by dividing the total electrical power of 534 watts by the total power input to the converter of 27,900 watts, was found to be 1.91%, compared to the design value of 2.1%. The device efficiency is defined as the ratio of the overall efficiency to the Carnot efficiency and was determined

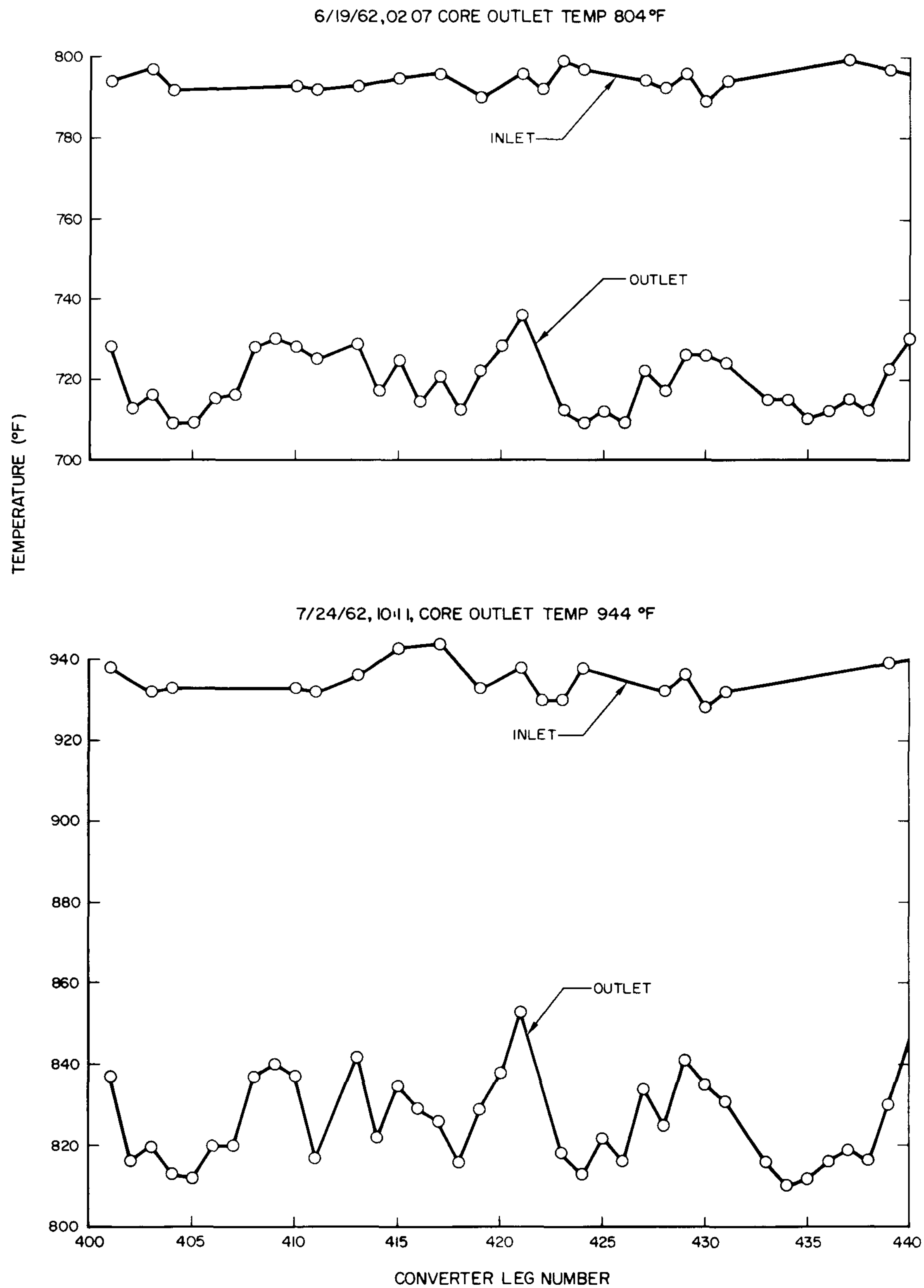

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Figure 31. Converter Inlet and Outlet Temperature

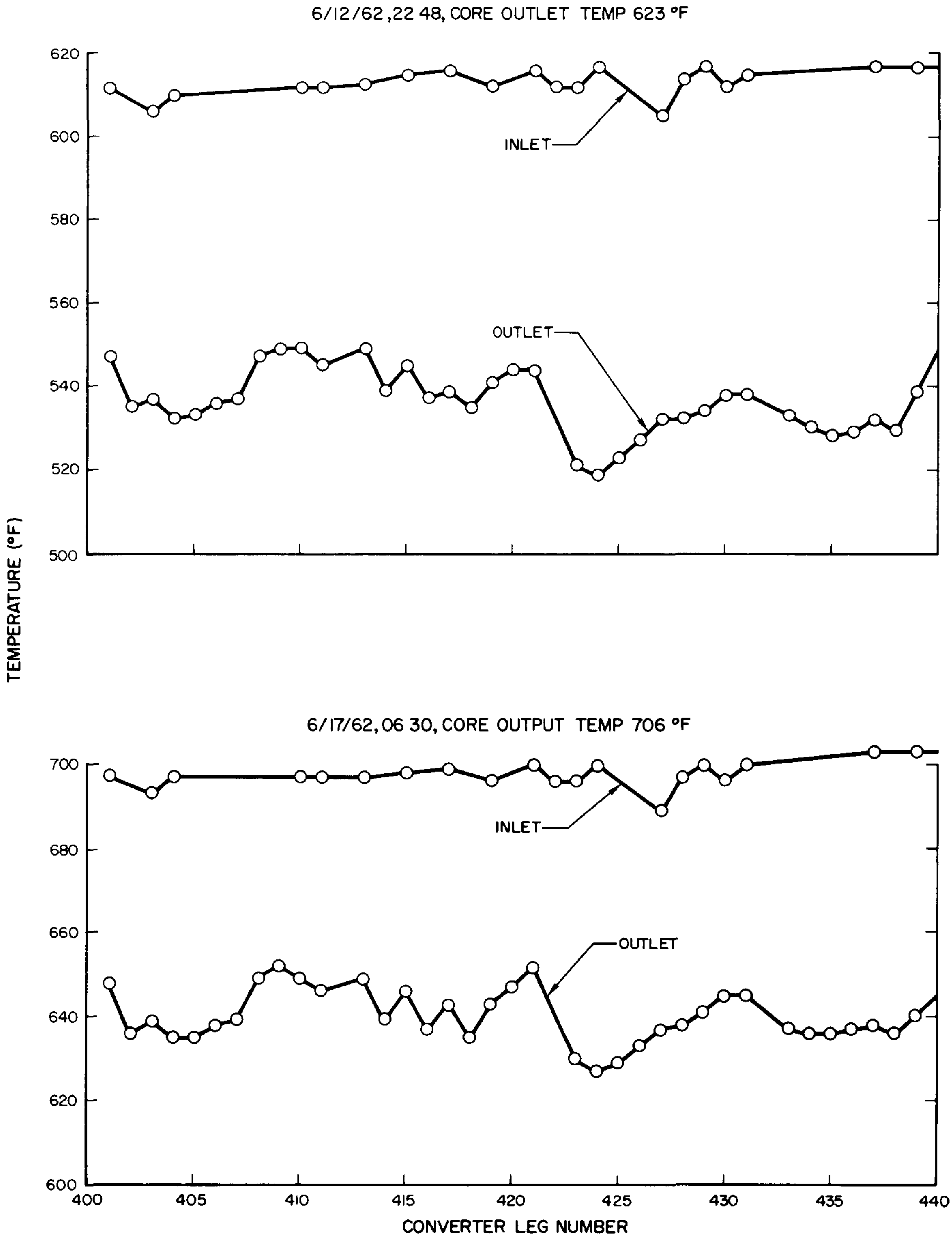

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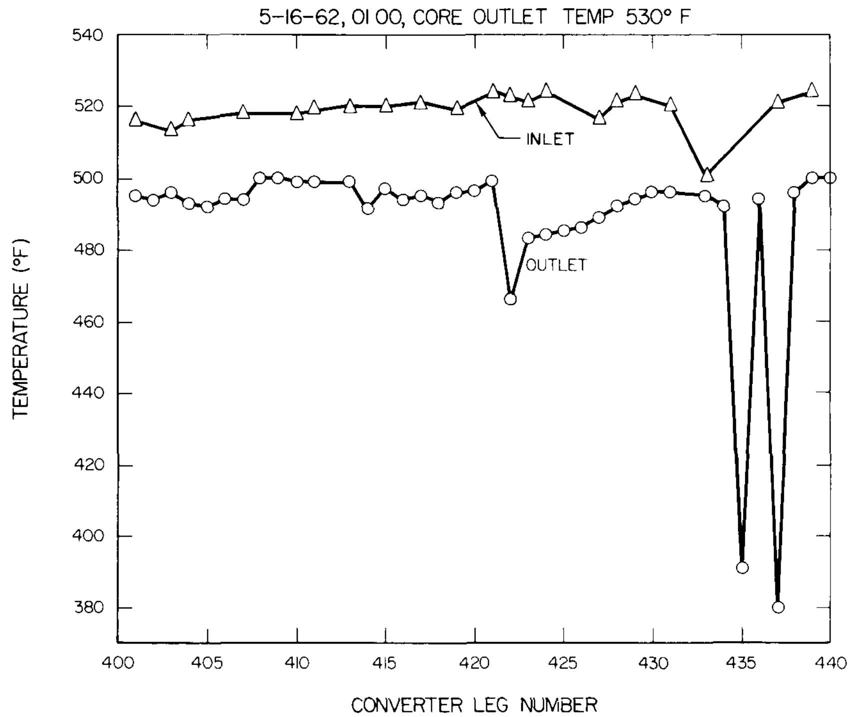
Figure 32. Converter Inlet and Outlet Temperature



12-30-63 7561-0931

Figure 33. Converter Inlet and Outlet Temperature — Plugged Condition

to be 8.98%, compared to the design value of 10.67%. Additional discussion and curves of converter performance can be found in Reference 8.

C. SIMULATED SPACE THERMAL ENVIRONMENT

The net heat exchange between a satellite and its environment will be strongly influenced by its position relative to the earth and sun and will, therefore, normally be time dependent. One exception to this is a satellite in thermal equilibrium in a constant sun-constant shade circular orbit. A constant sun-constant shade orbit is one in which half of the unit is constantly exposed to the sun and the other half is always in the shade.

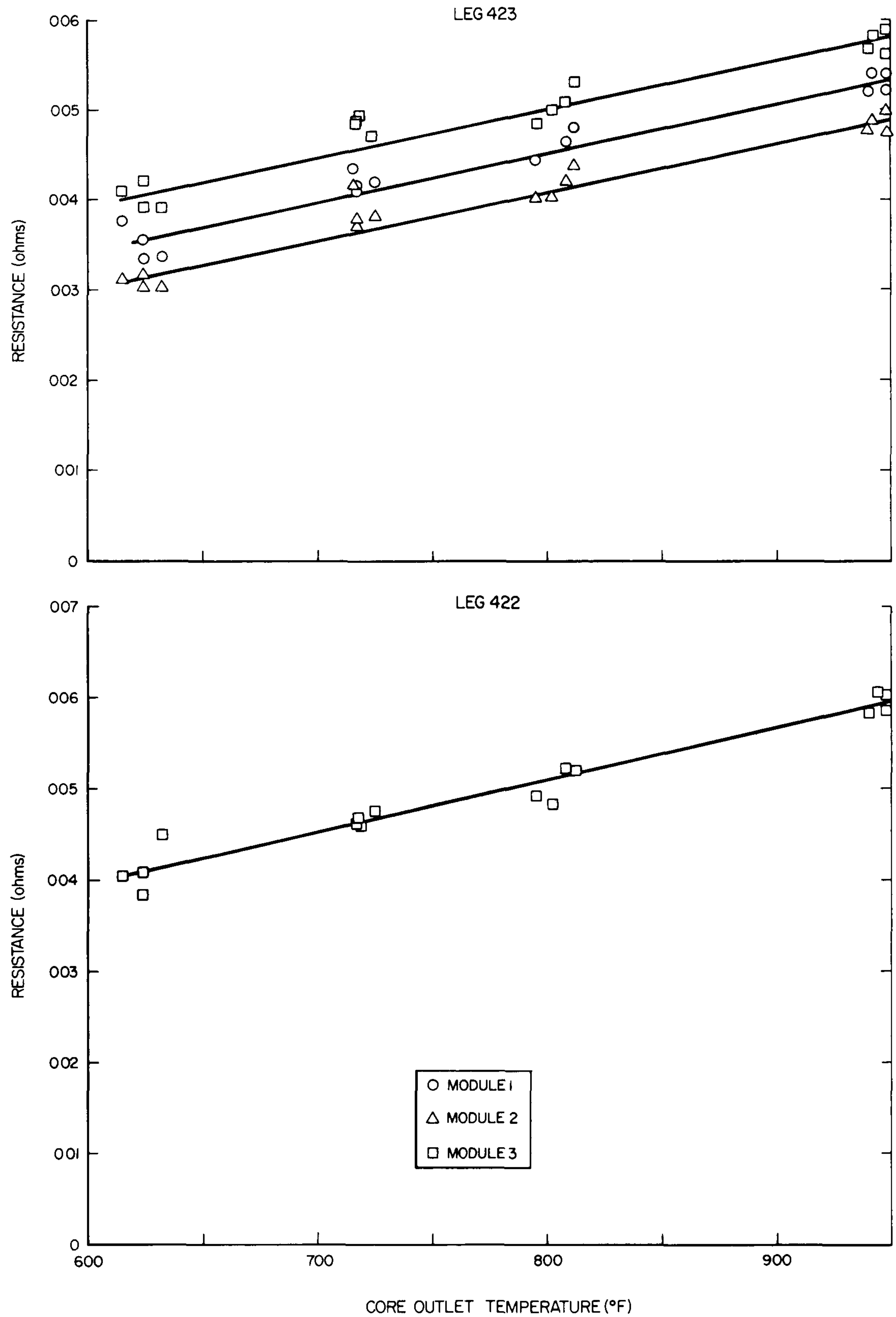


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Figure 34. Module Internal Resistance

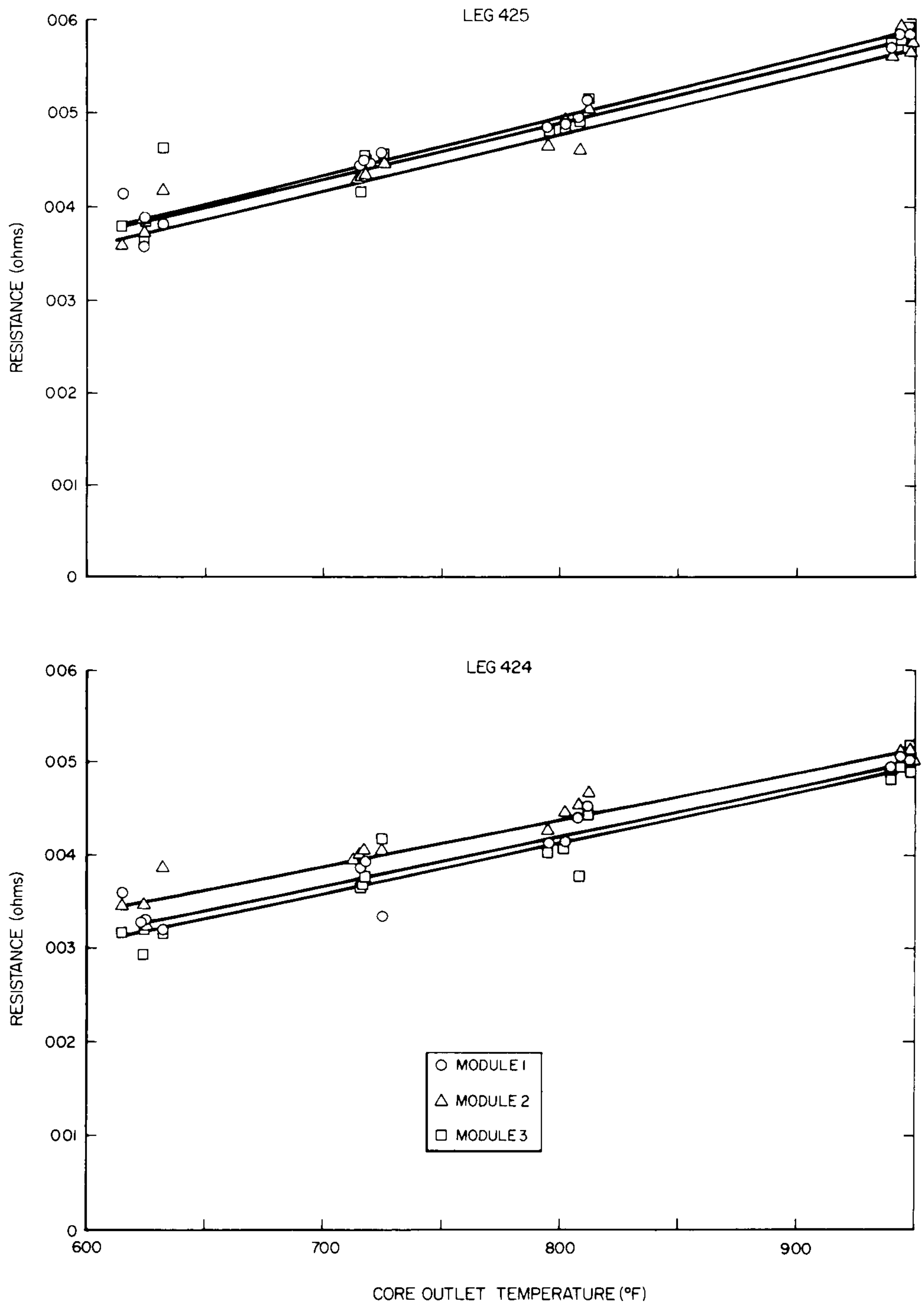

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Figure 35. Module Internal Resistance

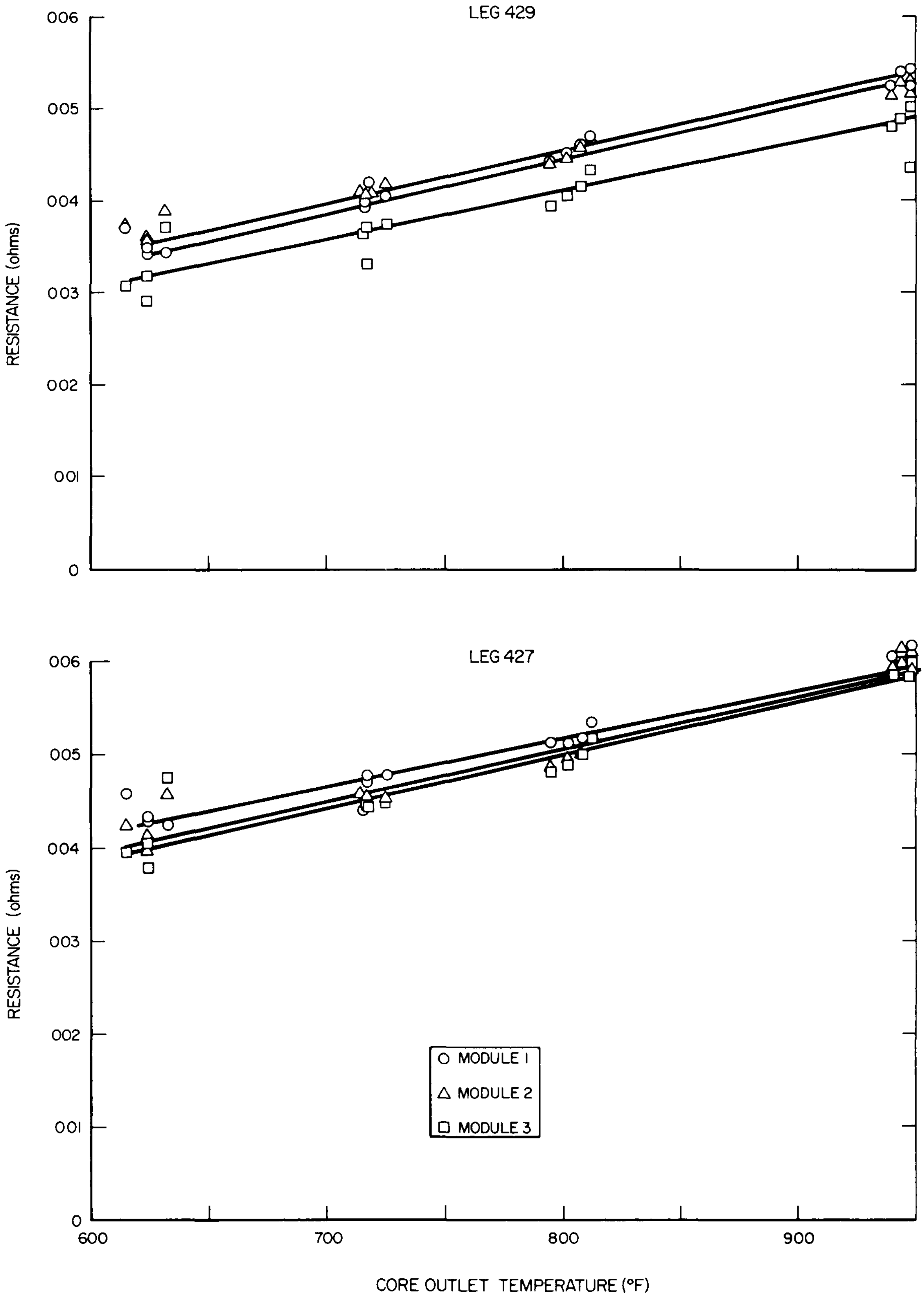

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Figure 36. Module Internal Resistance

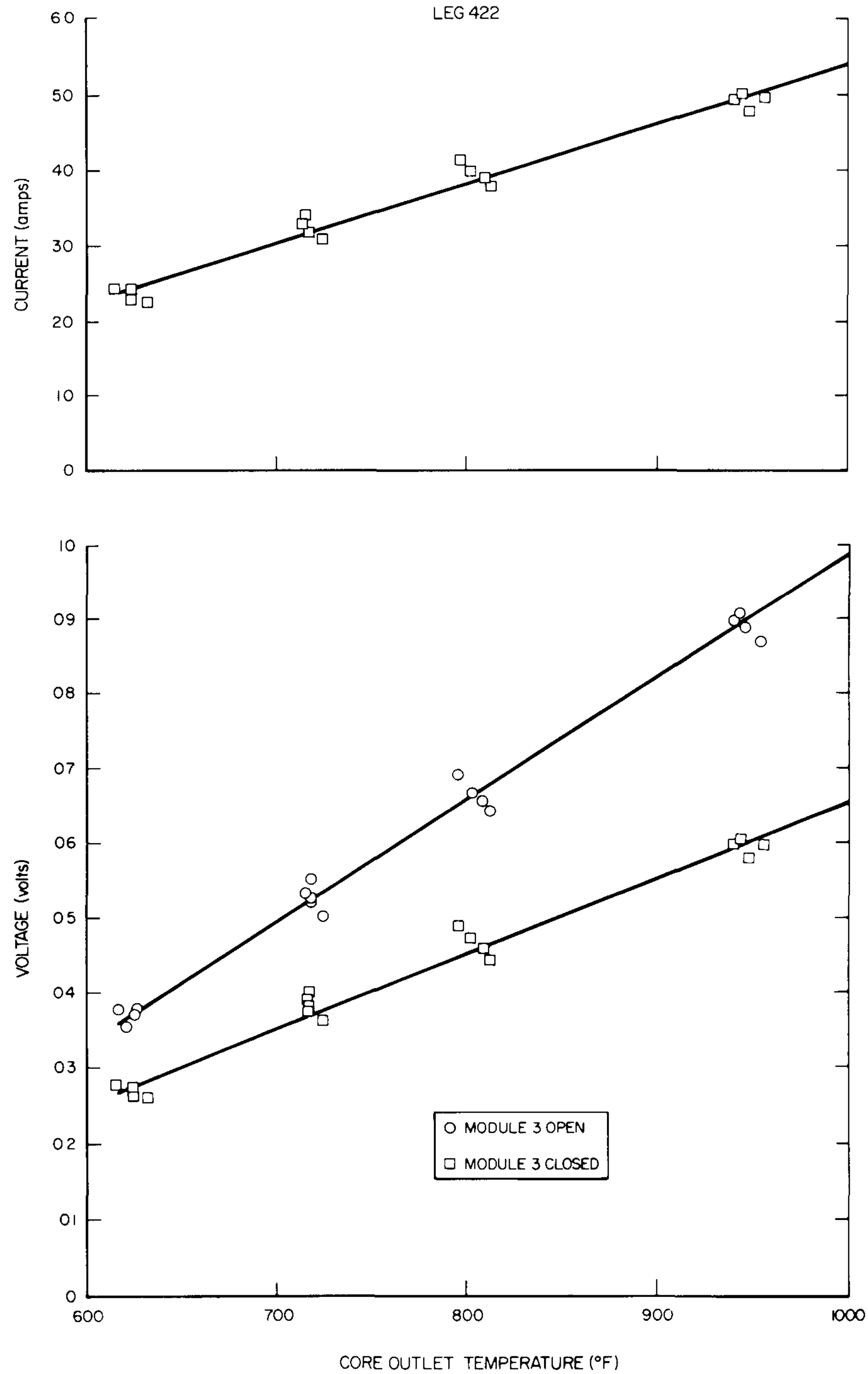

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Figure 37. Module Voltage and Current

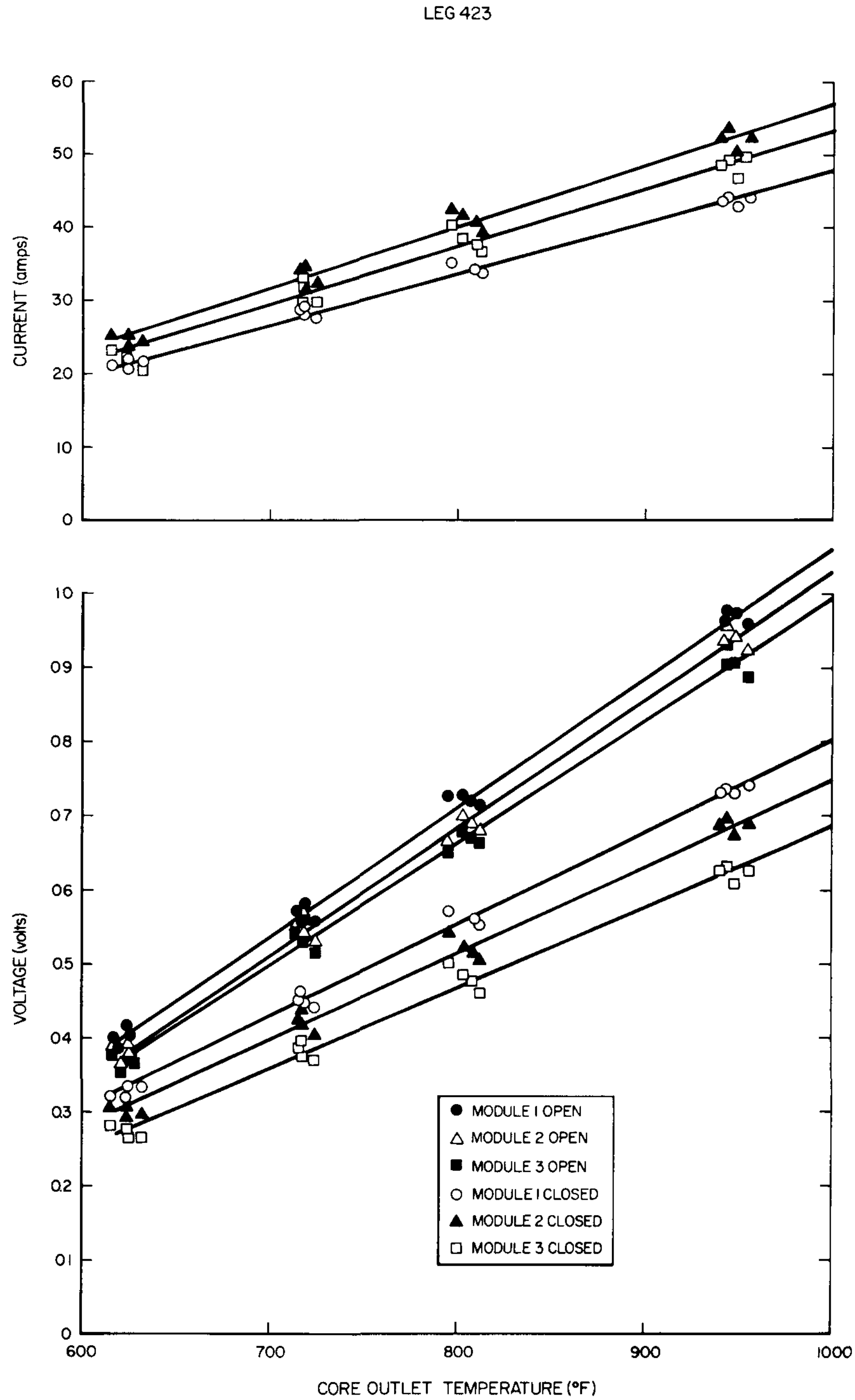

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Figure 38. Module Voltage and Current

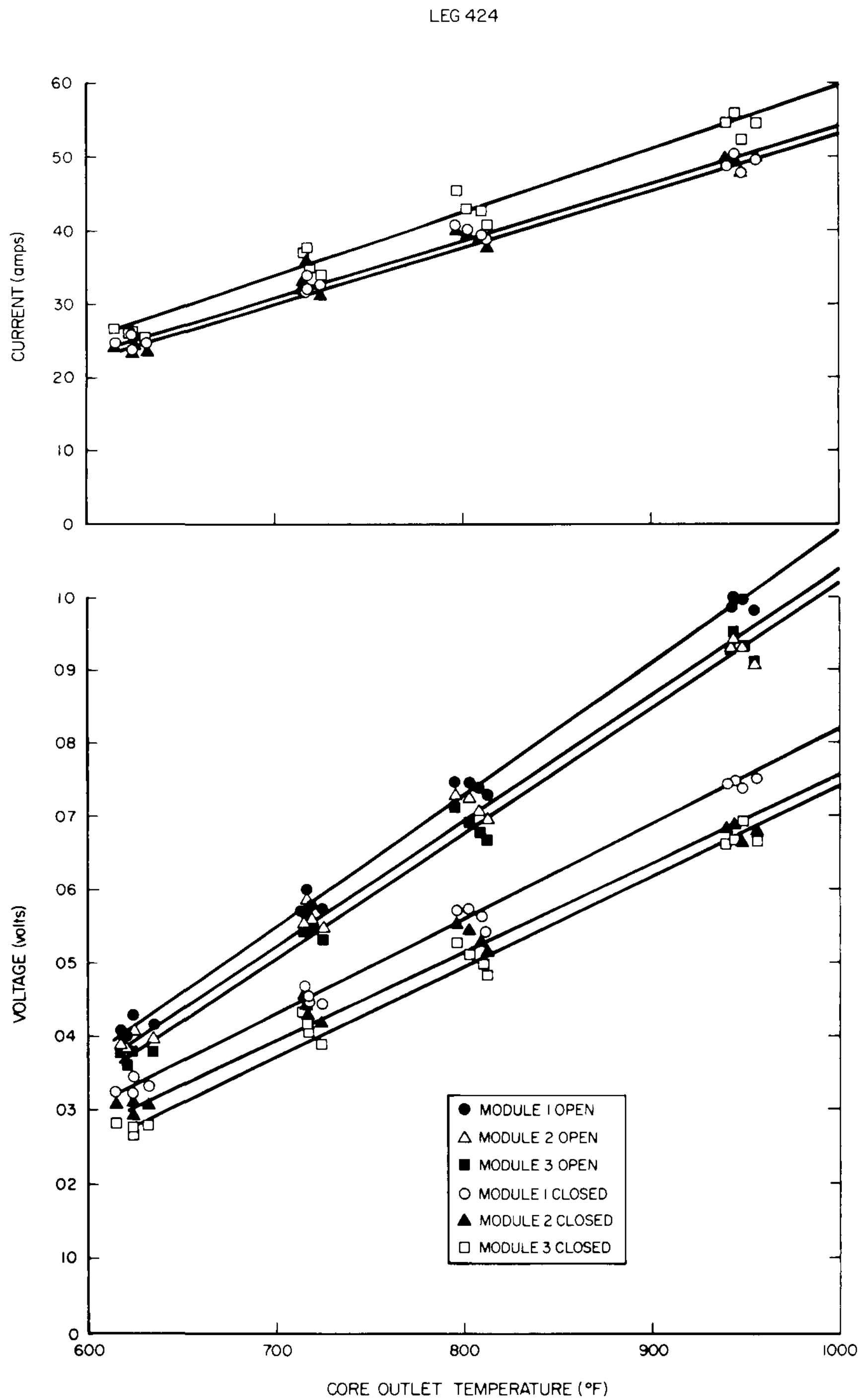

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Figure 39. Module Voltage and Current

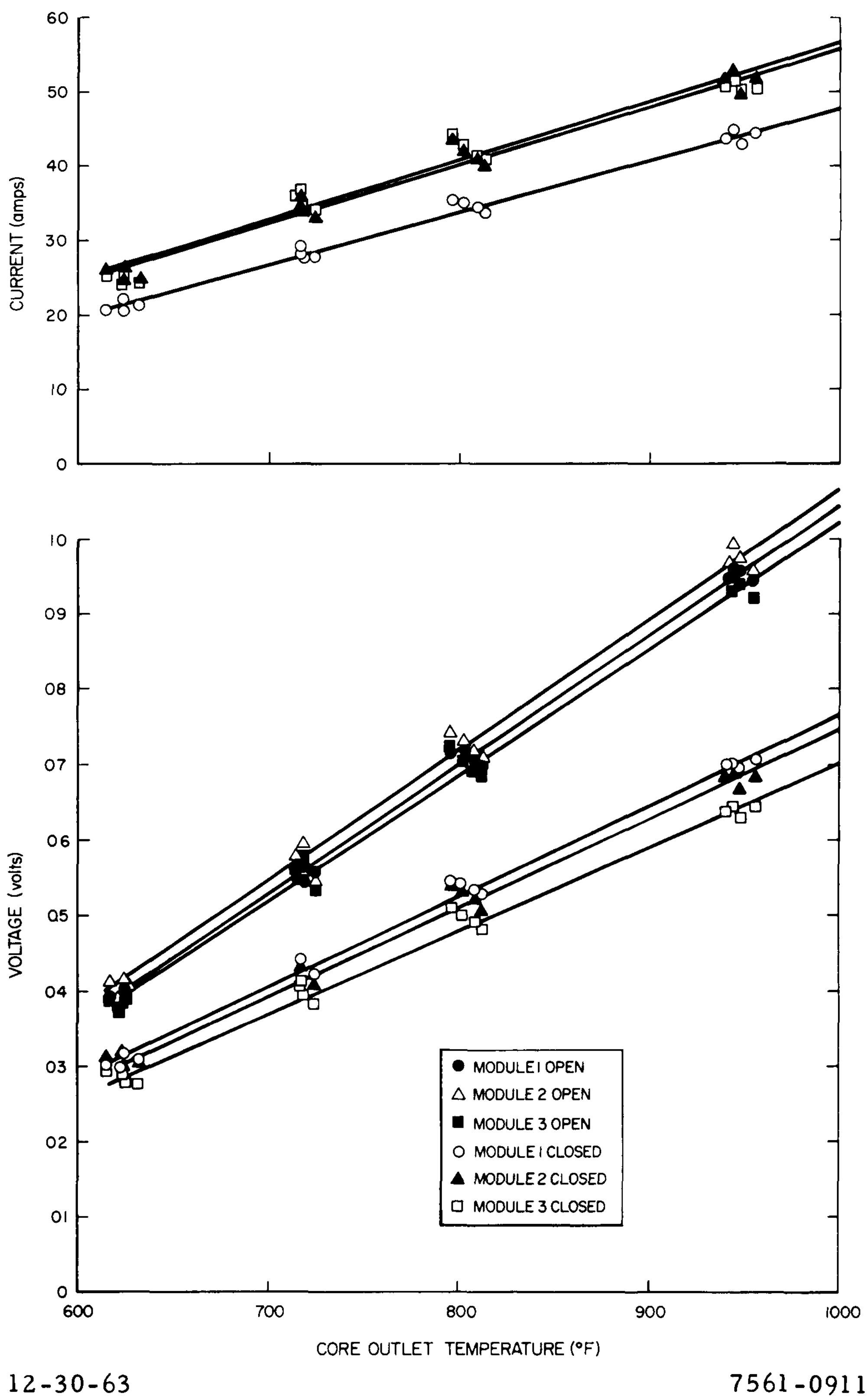

Figure 40. Module Voltage and Current

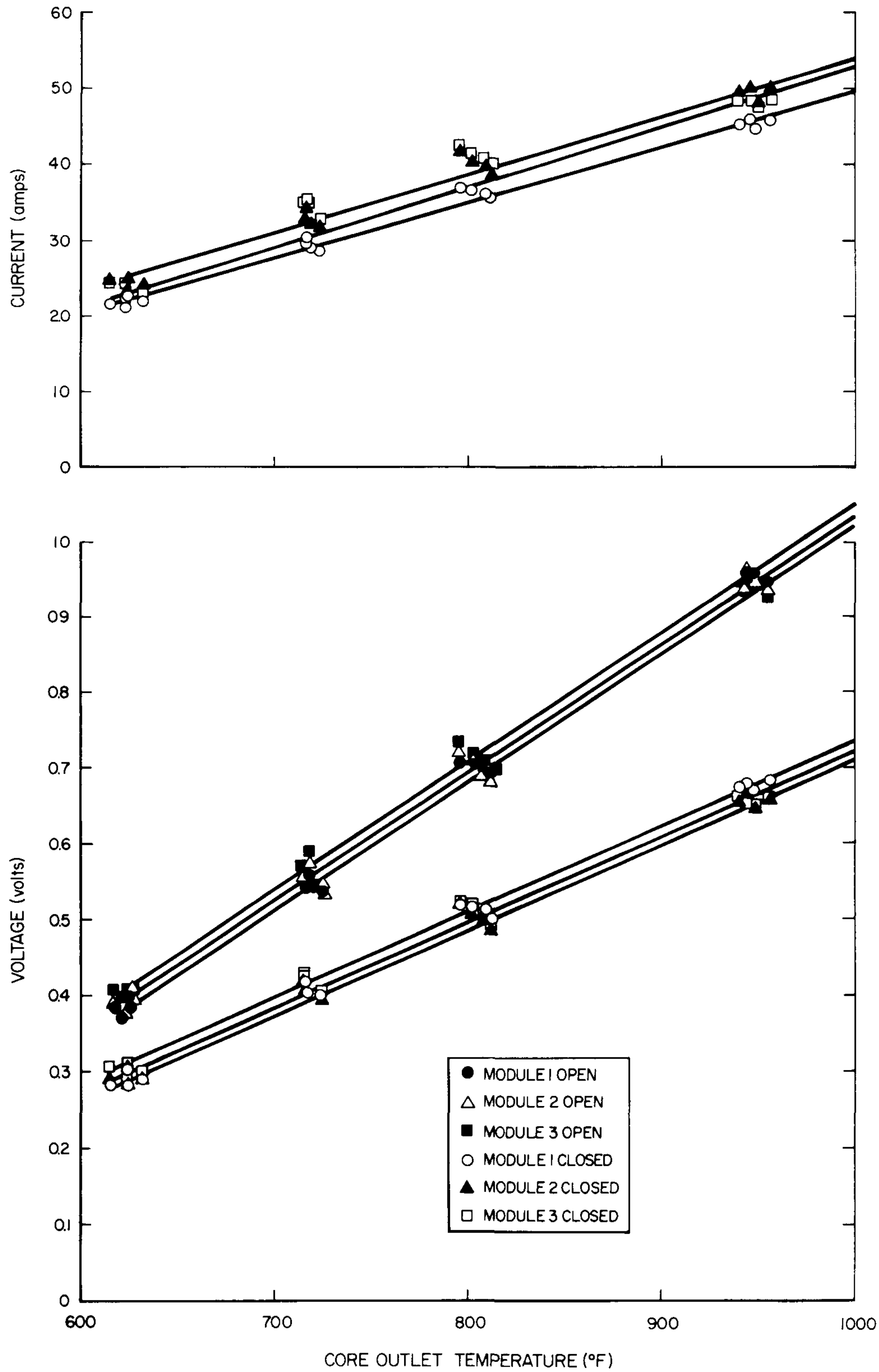

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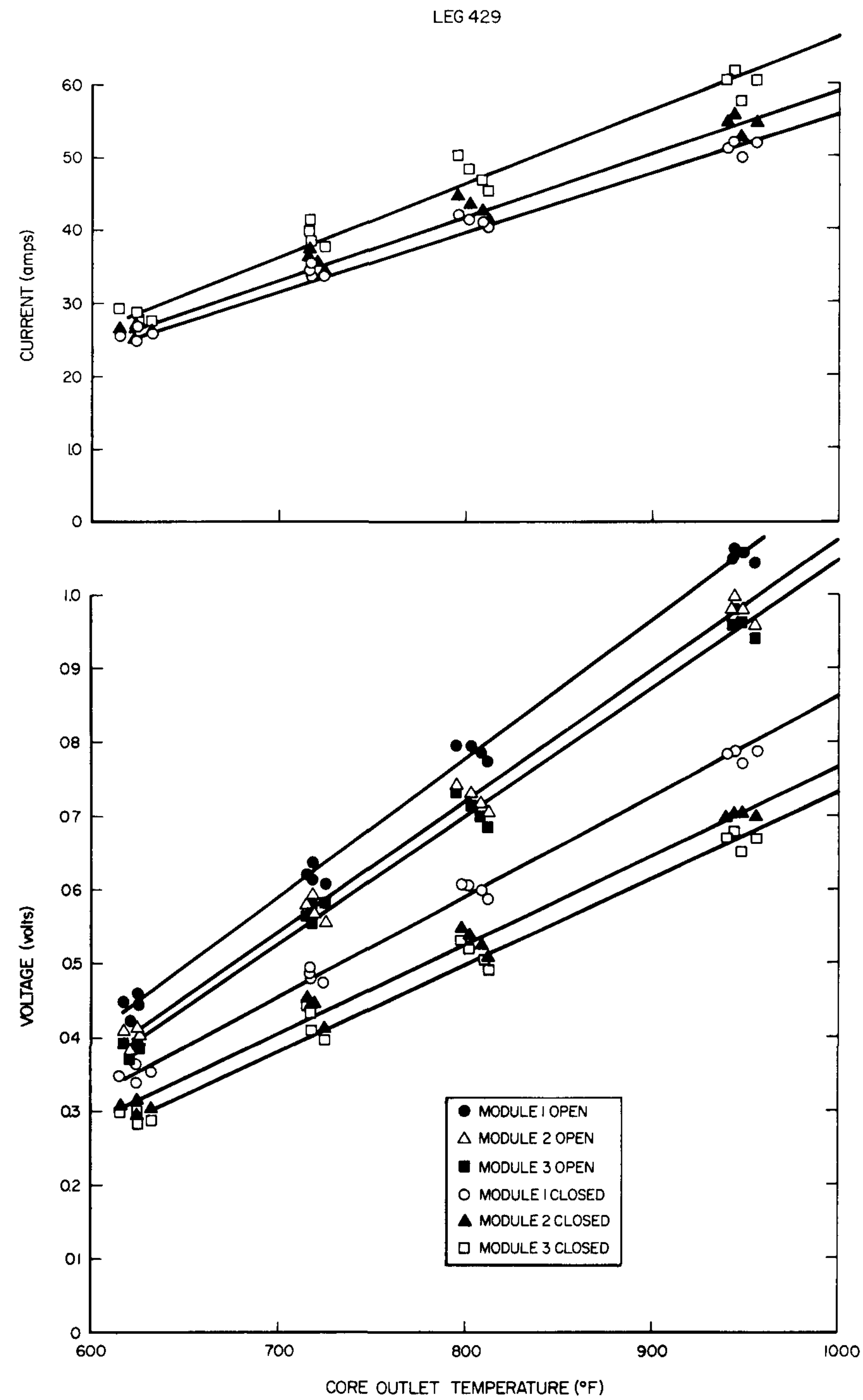
Figure 41. Module Voltage and Current



12-30-63 7561-0951

Figure 42. Module Voltage and Current

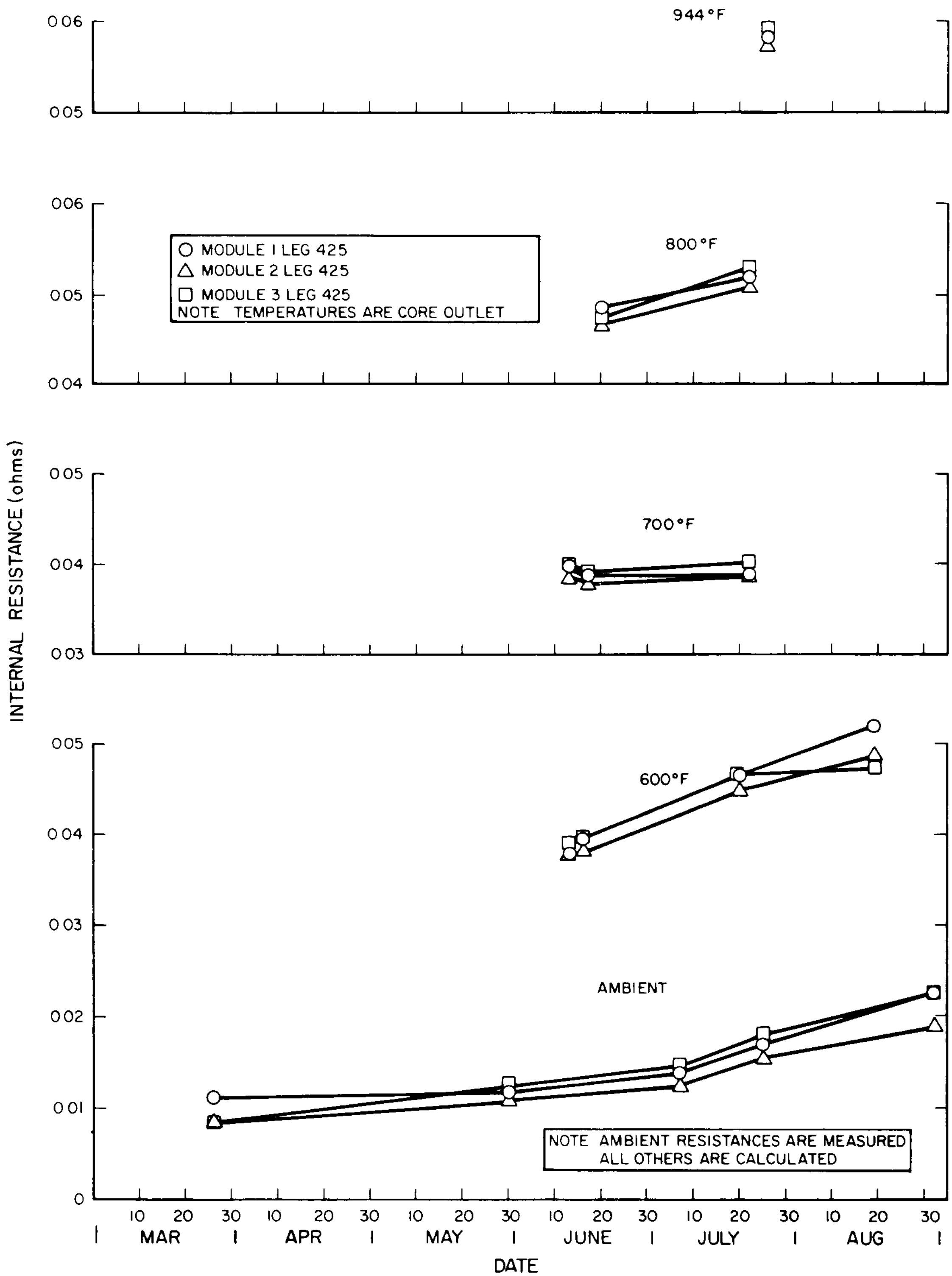


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Figure 43. Thermoelectric Module Internal Resistance

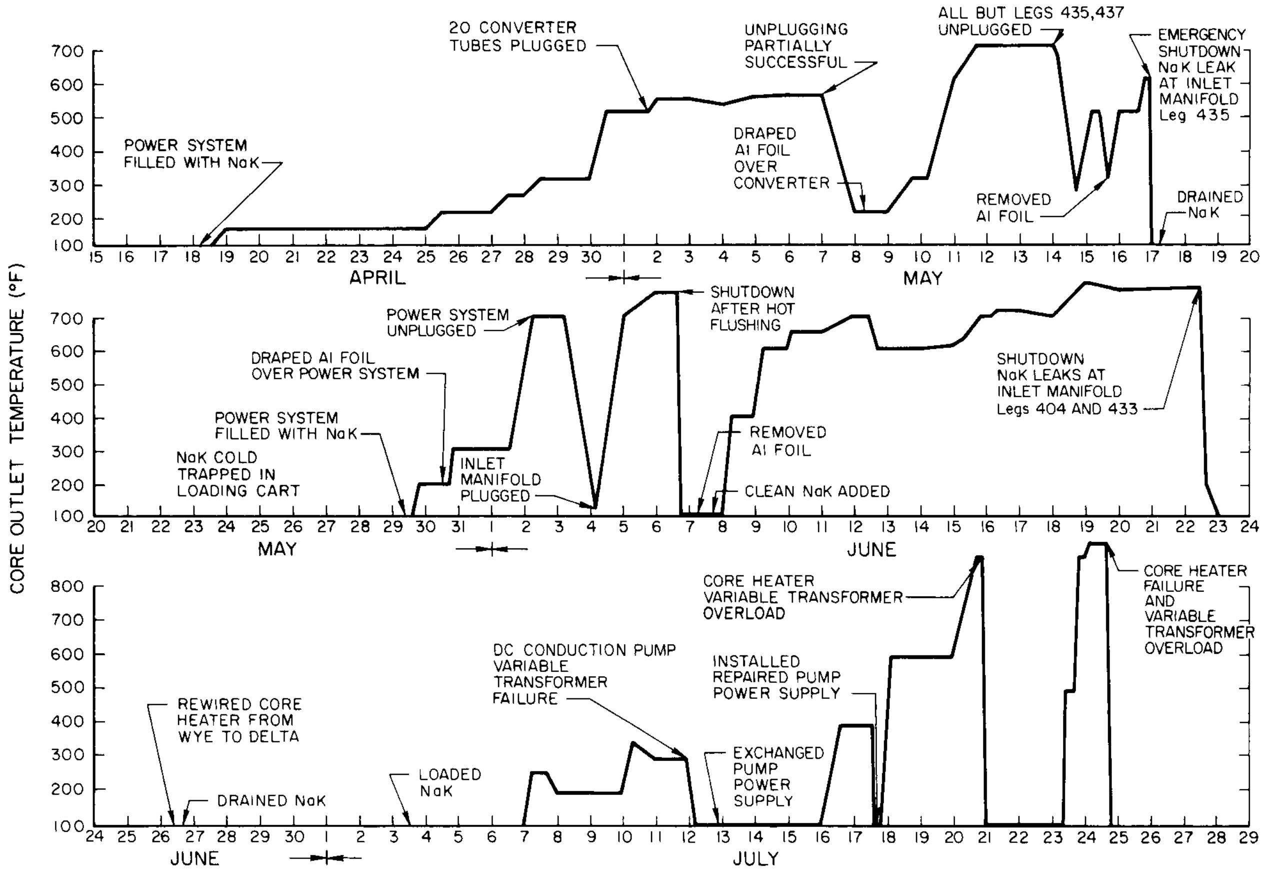

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Figure 44. S10A PSM-3 Core Heater Outlet Temperature History

The amount of direct solar radiation absorbed by the unit for this type orbit is given by

$$Q_{ds} = \alpha_s \, q \, A_p \quad , \qquad \ldots(3)$$

where

α_s = solar absorptivity of the satellite
= 0.9 for the PSM-3 SNAP 10A converter radiator

q = solar constant - 0.13 kw/ft^2

A_p = projected area exposed to sun, ft^2
= 20.8 ft^2 for the SNAP 10A converter radiator

Q_{ds} = (0.13) (20.8) (0.9) = 2.43 kw

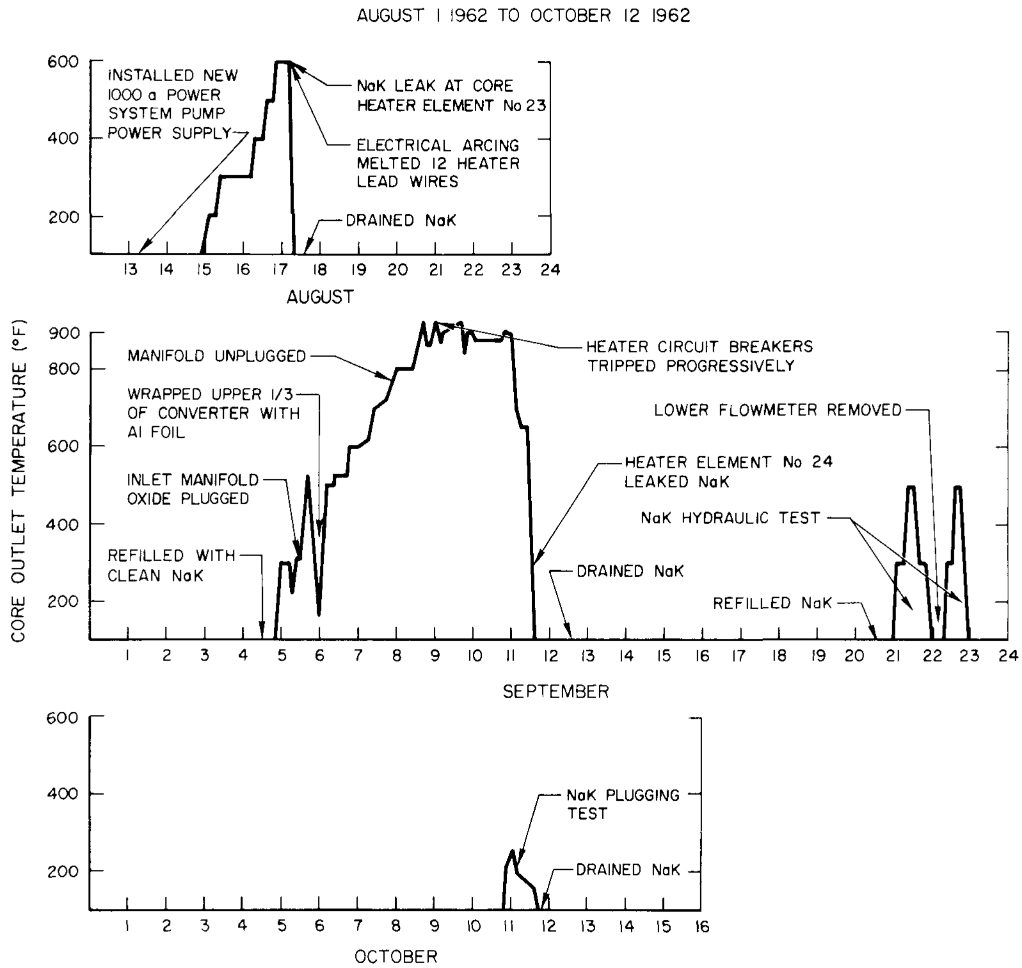

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Figure 45. S10A PSM-3 Core Heater Outlet Temperature History

The amount of solar radiation reflected from the earth's surface and absorbed by the satellite in a 700 mile orbit is given by,

$$Q_{rs} = F_{sie} A_s \alpha_s r_{es} q \, (0.125) \quad , \qquad \ldots(4)$$

where

0.125 = constant obtained for constant sun-constant shade 700 mile circular orbit

F_{sie} = view factor between the earth and the satellite = 0.102

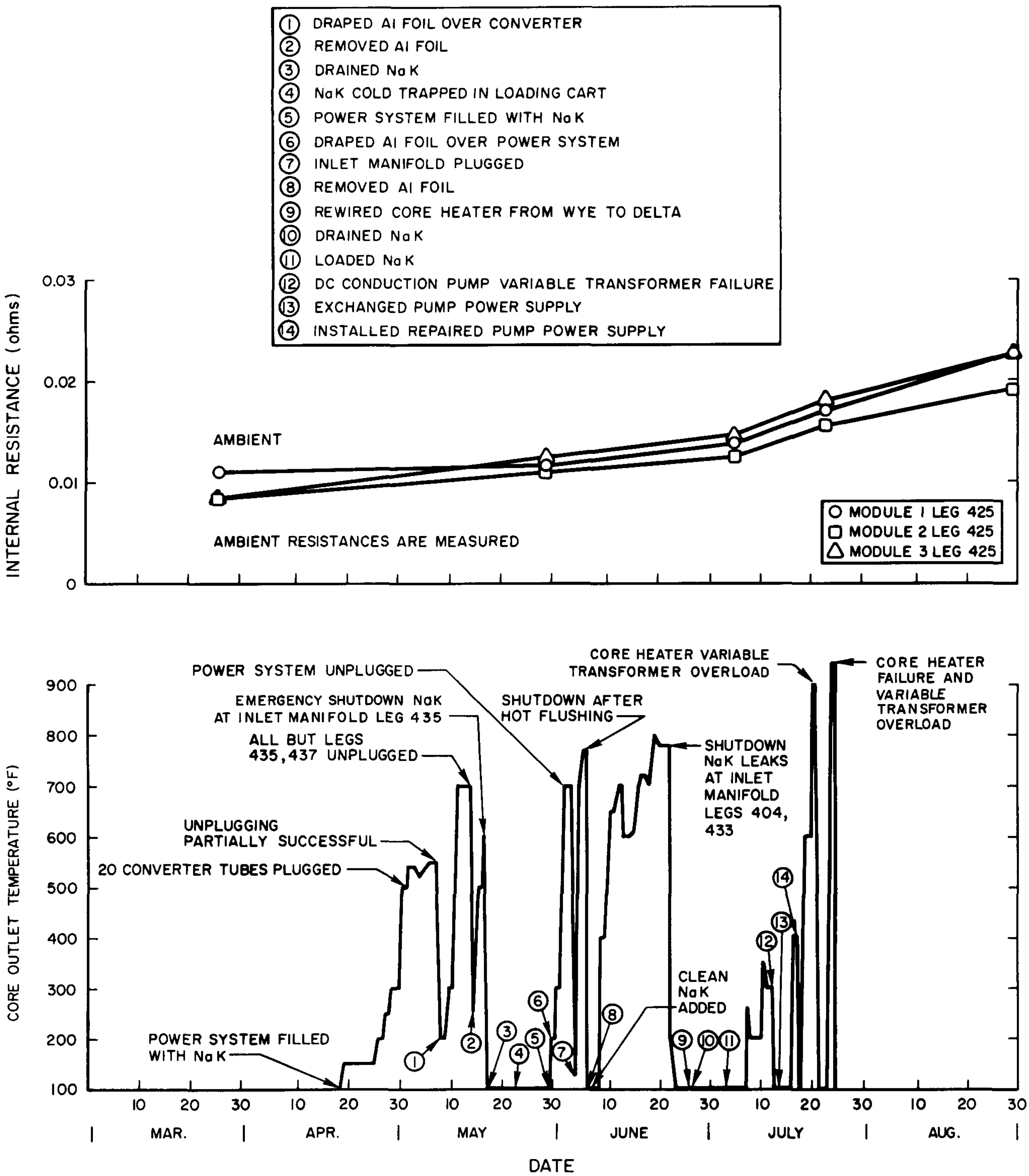

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Figure 46. Internal Resistance and Core Outlet Temperature Histories

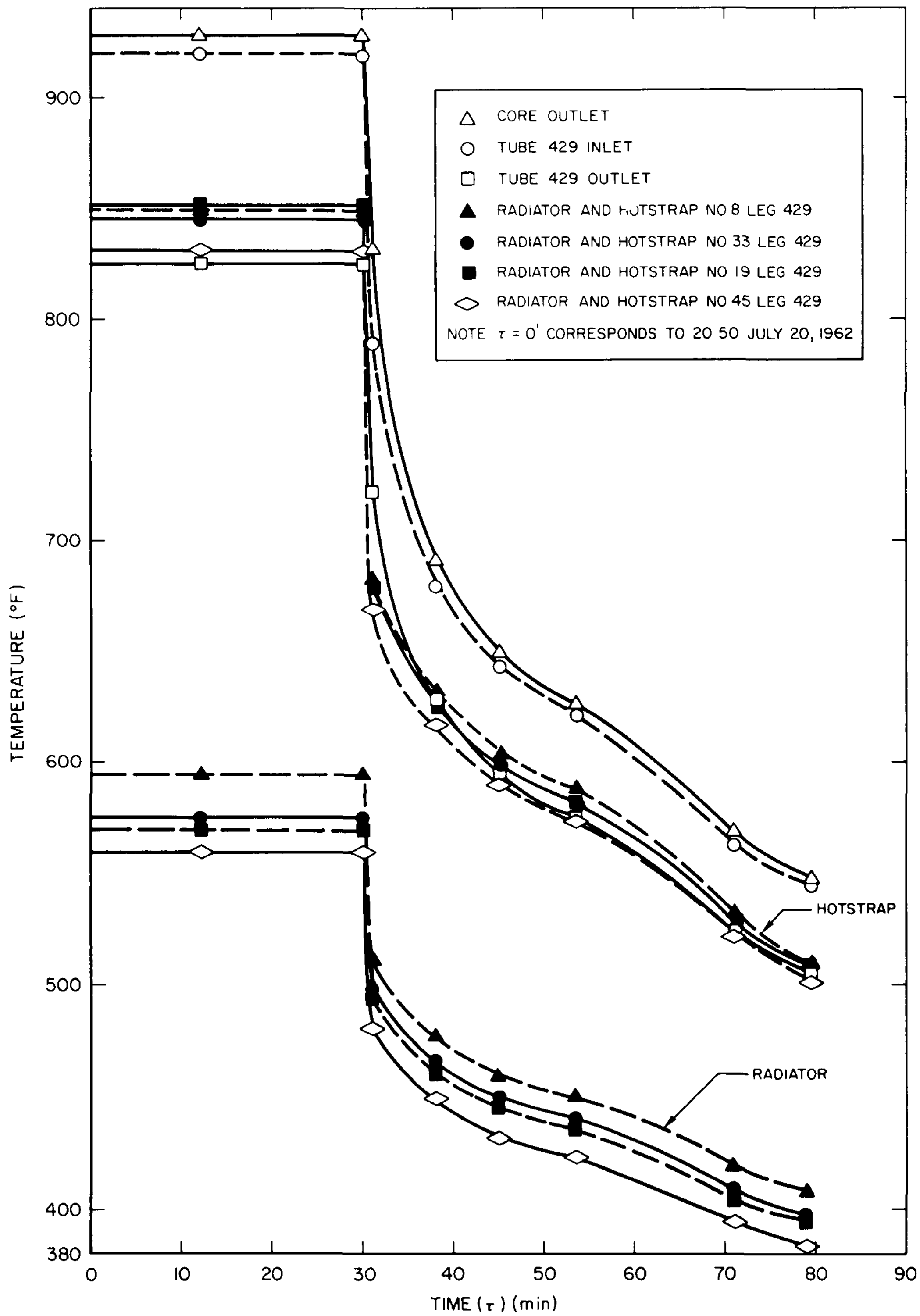

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Figure 47. Thermal Transient Emergency Shutdown
Heater Power Failure

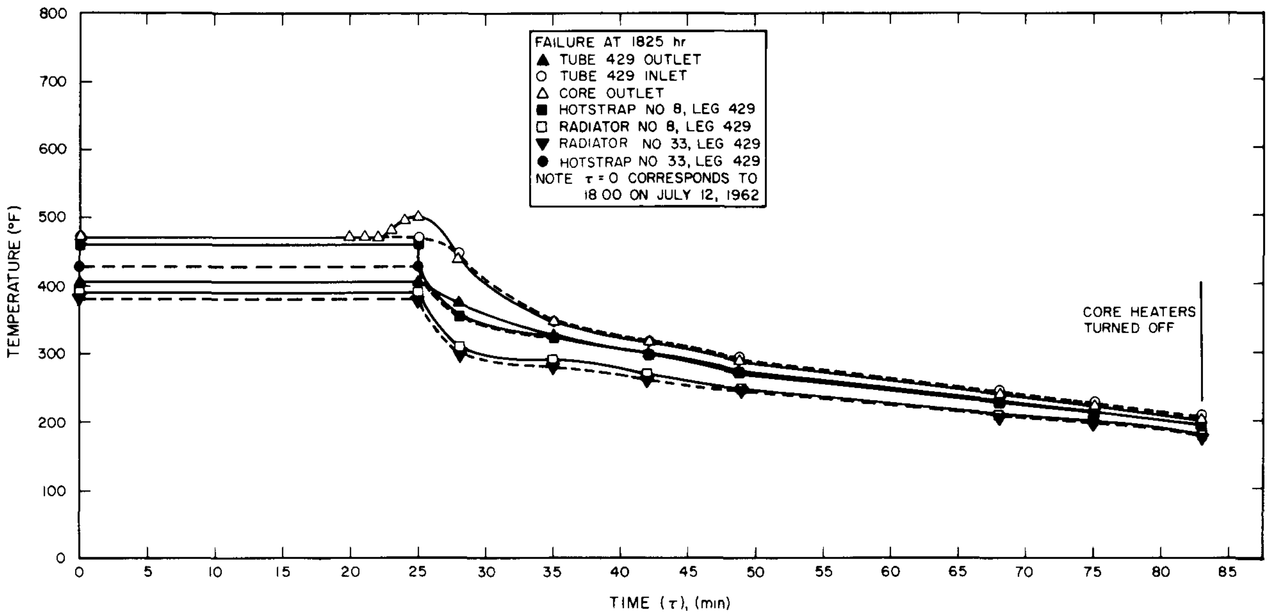

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Figure 48. Thermal Transient Emergency Shutdown — DC Conduction Pump Failure

A_s = surface area of the converter radiator = 62.5 ft^2

r_{es} = earth's solar reflectivity = 0.4

Q_{te} = (0.102) (62.5/2) (0.9) (0.4) (0.13) (0.125) = 0.187×10^{-2} kw

The heat absorbed by direct thermal radiation from the earth is given by

$$Q_{te} = F_{sie} A_s \epsilon_s \epsilon_e \sigma T_e^4 \quad , \qquad \ldots(5)$$

where

ϵ_s = emissivity of converter radiator = 0.9

ϵ_e = earth's emissivity = 1.0

σ = Stephan-Boltzman constant

$\sigma = 0.503 \times 10^{-12}$ kw/(ft^2-°R^4)

T_e = earth temperature = 450°R

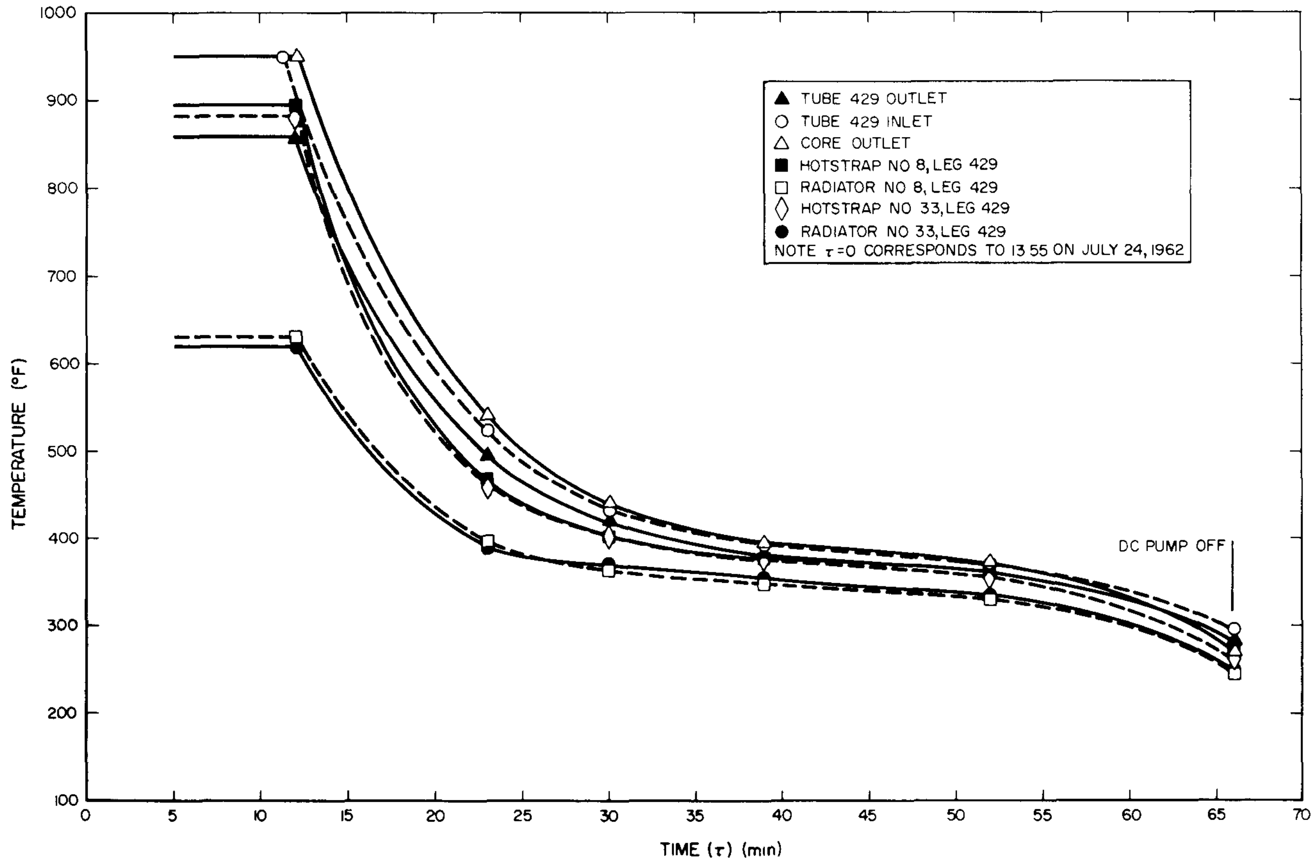

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Figure 49. Thermal Transient Emergency Shutdown Core Heater Failure

$$Q_{te} = (0.120)\ (62.5)\ (0.9)\ (1.0)\ (0.503 \times 10^{-12})\ (450)^4$$

$$Q_{te} = 0.118 \text{ kw}$$

The total heat absorbed from the environment is

$$Q_T = 2.43 + 0.187 \times 10^{-2} + 0.118 = 2.55 \text{ kw} \quad . \qquad \ldots(6)$$

This was the average heat load the vacuum vessel and radiant heaters were to supply during testing. The vacuum vessel nominally ran at an average temperature of 100°F, which would supply the following amount of heat:

$$Q_{VV} = \sigma \epsilon_{VV} \epsilon_s A_s T_{VV}^4 \quad ; \qquad \ldots(7)$$

$$Q_{VV} = (0.503 \times 10^{-12})\ (0.9)\ (0.9)\ (62.5)\ (560)^4 \quad ; \qquad \ldots(8)$$

$$Q_{VV} = 2.5 \text{ kw} \quad . \qquad \ldots(9)$$

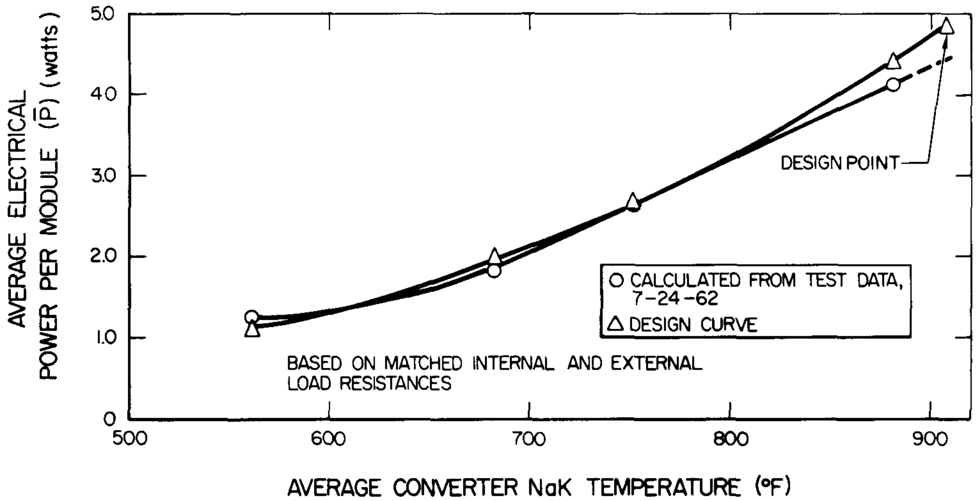

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Figure 50. Module Thermoelectric Power

It was determined, therefore, that under normal conditions during the PSM-3 tests, the vacuum vessel supplied all the heat required to simulate the average space environment, and that radiant heaters were not required for PSM-3. Because they were required for subsequent system tests, however, they were installed in the PSM-3 chamber, so that their performance in conjunction with a SNAP 10A Unit could be evaluated. The solar simulation tests were conducted and their effect on thermal and electrical performance of the system are published in Reference 7.

The biggest unanswered question was how much of the power radiated by the heaters actually reached the power system by direct and reflected radiation. As determined in Reference 4, approximately 3 kw of the 12 kw generated by the radiant heaters was absorbed by the power system. Since the converter radiators had an emissivity of 0.86, it was determined that 29% of the power radiated by the radiant heaters impinged on the unit.

D. HYDRAULIC CHARACTERISTICS

The total NaK system pressure loss was recorded continuously from the pressure taps located at the inlet and exit to the system pump. At each temperature level, the dc conduction pump was operated at three flows to evaluate the system's hydraulic characteristics. These three flows, denoted as minimum, nominal, and maximum, were selected at approximately the expected flow rate for a thermoelectric pump operating at that particular core outlet temperature.

In addition, the flow was varied from 0 to 14 gpm at ambient temperature. The flow could not be varied over a wide range at high operating temperatures, because excessive thermal cycling would result at some areas (such as converter tube outlets).

The total system pressure drop is plotted in Figure 51 as headloss in in. of NaK versus flow rate. To separate out the temperature effect as much as possible, headloss in in., rather than pressure drop in pounds per square inch, was used as the dependent variable. Pressure drop vs flow rate for various constant temperatures could not be plotted, because in some cases the data scatter was of the same order as the temperature effect. The system flow rates were measured by three magnetic flowmeters, one on each supply line and one on a return line. The presence of these magnetic flowmeters resulted in pressure drops higher than would be experienced normally, since the flowmeters were present only for test purposes and are not part of the actual system. It was necessary, therefore, to determine the pressure drop caused by the three flowmeters. Tests could not be run with all three flowmeters removed, because no means would then be available to measure the flow rate. Therefore, only the flowmeter on the return line was removed, since the meters on the supply lines were

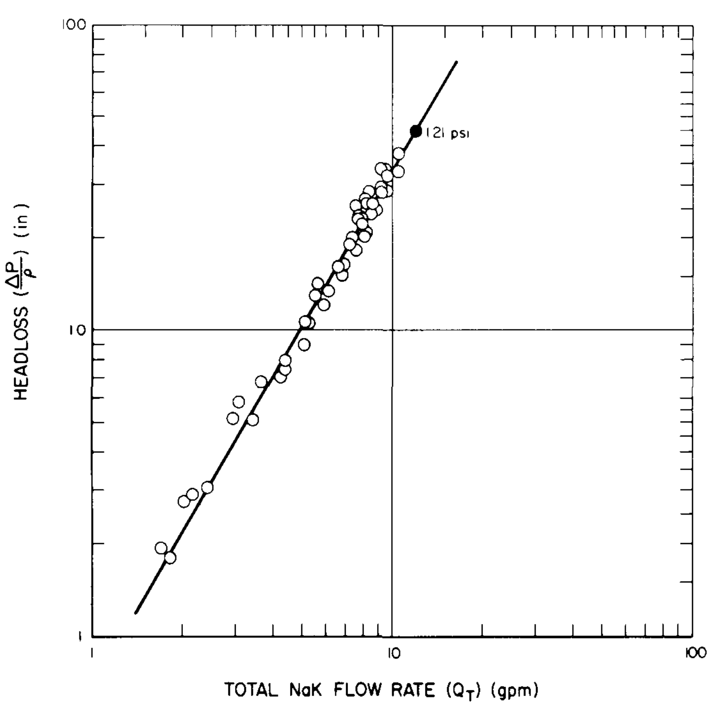

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Figure 51. PSM-3 Headloss —
All Flowmeters In

required to measure the total flow rate. With the one meter removed, headloss vs flow rate for various temperatures was measured (Figure 52). Subtraction of the curve in Figure 52 from that in Figure 51 yielded the headloss caused by one flowmeter; it is shown in Figure 53. Because the two flowmeters on the supply lines are in parallel, the total headloss caused by the three flowmeters was approximately twice that caused by the single flowmeter on the return line. Doubling the values shown in Figure 53 and subtracting from the curve of Figure 51, resulted in Figure 54 which shows the net system headloss with all three

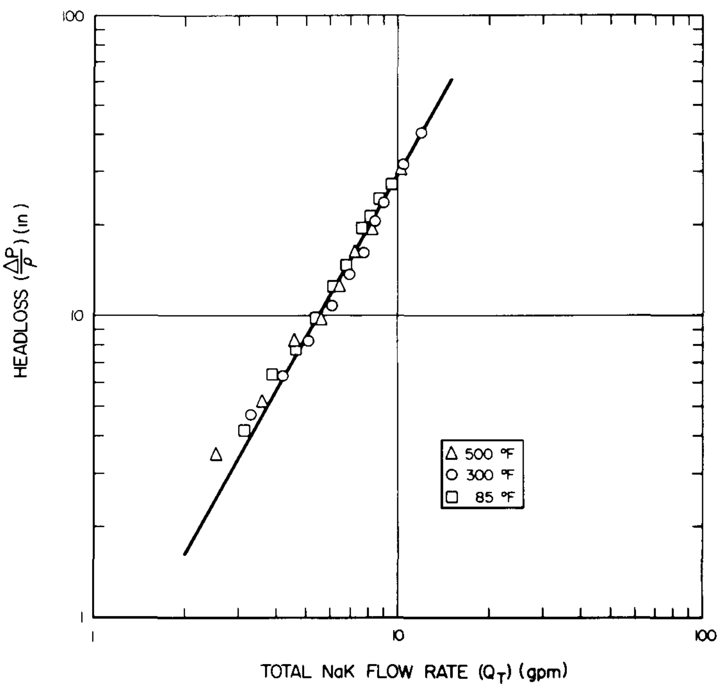

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Figure 52. PSM-3 Headloss — One Flowmeter Removed

meters removed. At the design flow rate of 12.0 gpm, the experimental headloss is 36.8 in. or 0.96 psi at 960°F core outlet temperature. This compares favorably with the design point of 1.0 psi. An attempt was also made to extrapolate this data to the flight system. At 13.25 gpm, the design flow rate for the flight system, the PSM-3 system had, from Figure 54, a net system headloss of 44 in. or 1.2 psi. It has been estimated that the flight system pressure drop will be 0.08 psi less than PSM-3. Subtracting this from 1.2 psi, an estimated flight system pressure drop of 1.12 psi was obtained which approximately meets the flight system design requirement of 1.1 psi. Additional curves showing the system pump and hydraulic performance are included in Reference 5.

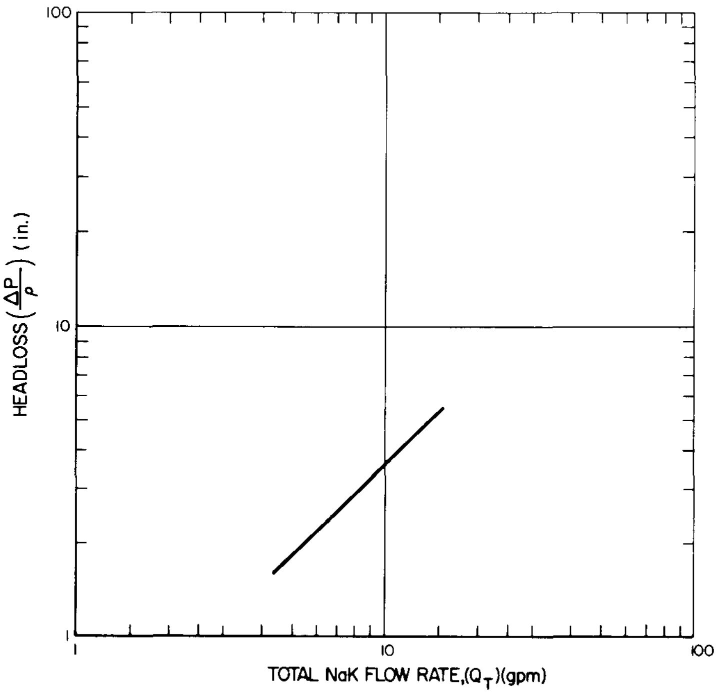

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Figure 53. Headloss for One Magnetic Flowmeter

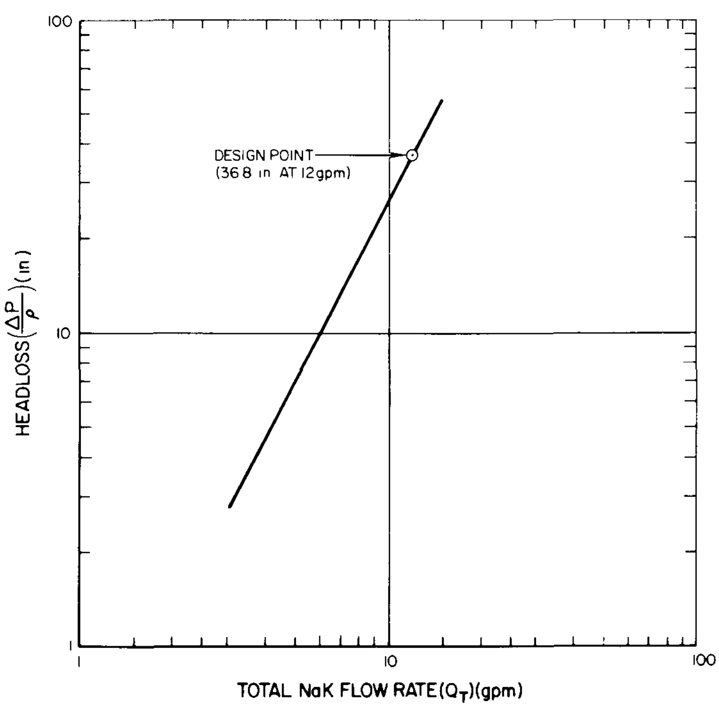

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Figure 54. PSM-3 Headloss — All Flowmeters Removed

Because the NaK flow rate in each of the 40 legs of the unit was not measured, the distribution was determined analytically. It was assumed that the heat flux per converter leg was constant over all legs of the converter. The validity of this assumption was checked by calculating the actual heat flux from each leg and applying it to the flow rate calculations for one case. The resulting difference in flow distribution was negligible and, therefore, the much shorter method based on equal heat flux per leg was used.

$$q_i = \frac{\bar{\rho}_i Q_i \bar{C}_{p_i} \Delta T_i}{7.48} = \text{constant} \quad , \qquad \ldots (10)$$

where

q_i = heat loss per leg, Btu/hr

$\bar{\rho}_i$ = average NaK density, lb/ft^3

Q_i = leg NaK flow rate, gpm

$\bar{C}_{p_i}$ = NaK average specific heat, Btu/lb-°F

ΔT_i = leg inlet minus outlet temperature, °F

Assuming that $\bar{C}_{p_i}$ does not vary appreciably from leg to leg, we obtain from Equation 10,

$$Q_i = \frac{K}{\bar{\rho}_i \Delta T_i} \quad , \qquad \ldots (11)$$

where K is constant.

The total flow rate is given by

$$Q_T = \sum_i Q_i = K \sum_i \frac{1}{\bar{\rho}_i \Delta T_i} \quad ; \qquad \ldots (12)$$

$$K = \frac{Q_T}{\sum \frac{1}{\bar{\rho}_i \Delta T_i}} \quad . \qquad \ldots (13)$$

Since Q_T was measured and $\overline{\rho}_i$ and ΔT_i determined from temperature measurements, Equation 13 was solved for K. Knowing K, Equation 11 was then solved for the flow in each converter leg. Representative normalized flow distributions for various test conditions are shown in Figures 55 through 59. The data points

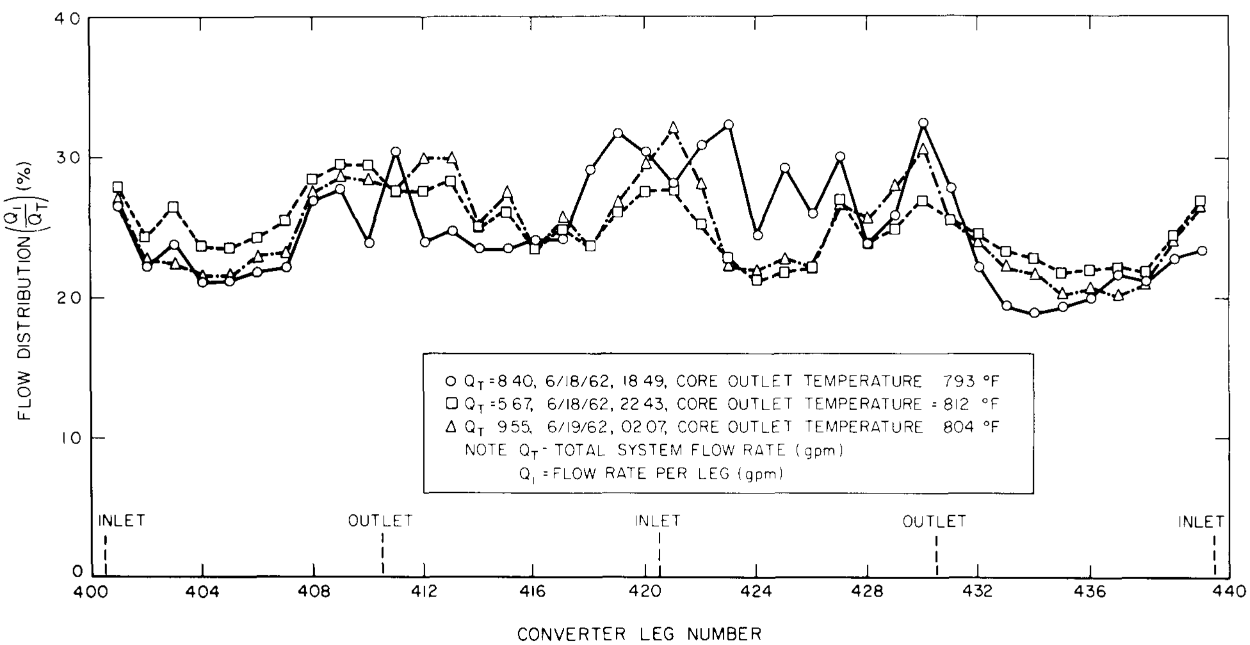

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Figure 55. Converter NaK Flow Distribution

were connected only for clarity and were not intended to imply that the flow rate changes linearly from leg to leg, since each leg has its own discrete value. Comparison of these results makes it evident that the normalized flow distribution (Q_i/Q_T) was not a significant function of temperature level. It was possible, therefore, to establish a mean flow distribution curve based on the curves in Figures 55 through 58. To indicate the deviation from the mean that could be expected, the 360 data points (9 cases at 40 points per case) were separated into classes by comparing Q_i/Q_T ranges, mean values, second moments about the mean, and physical location of the legs in the system. It was assumed that the 360 data points were random. It was, therefore, possible to establish a $\pm 1\sigma$ limit for the normalized flow distribution. These ± limits and the mean flow distribution are shown in Figure 59. The average flow rate through legs 401-420 was 2.6%, and the average flow rate through legs 421-440 was 2.4%. The average

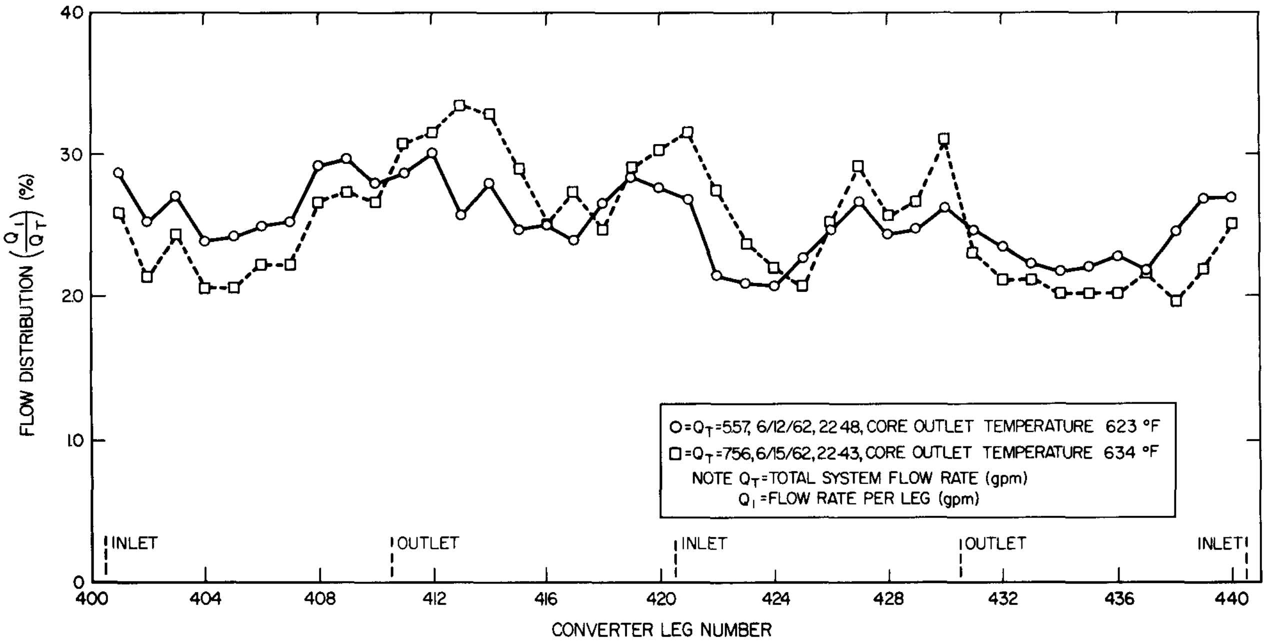

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Figure 56. Converter NaK Flow Distribution

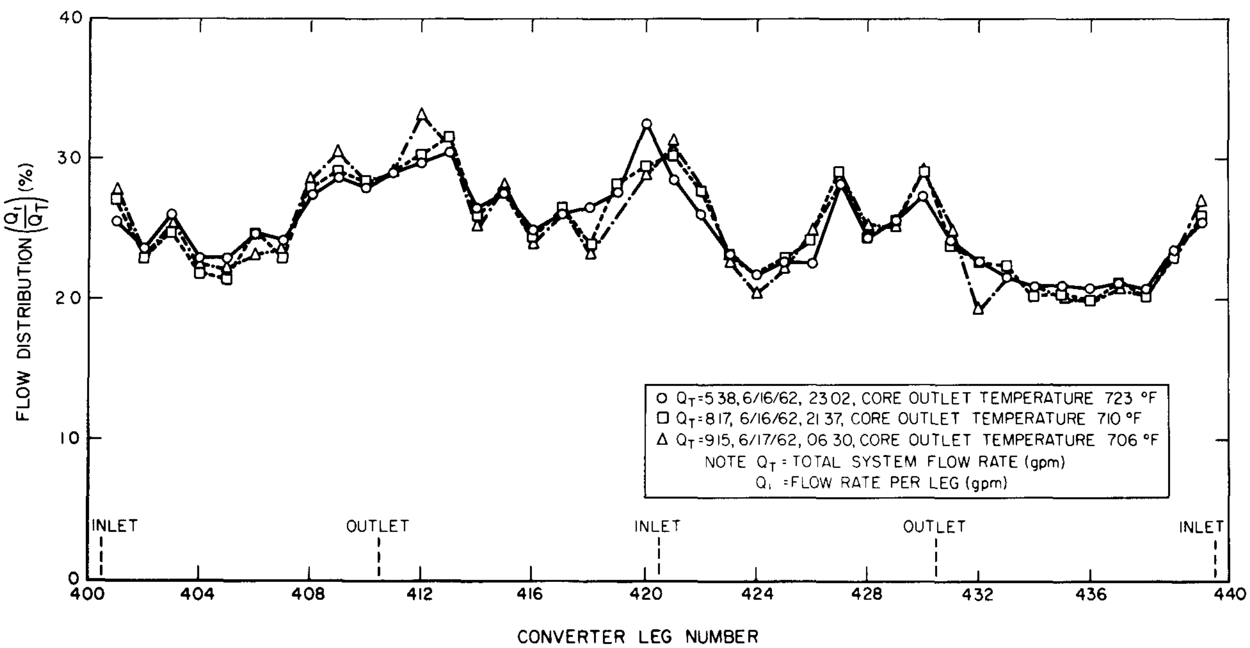

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Figure 57. Converter NaK Flow Distribution

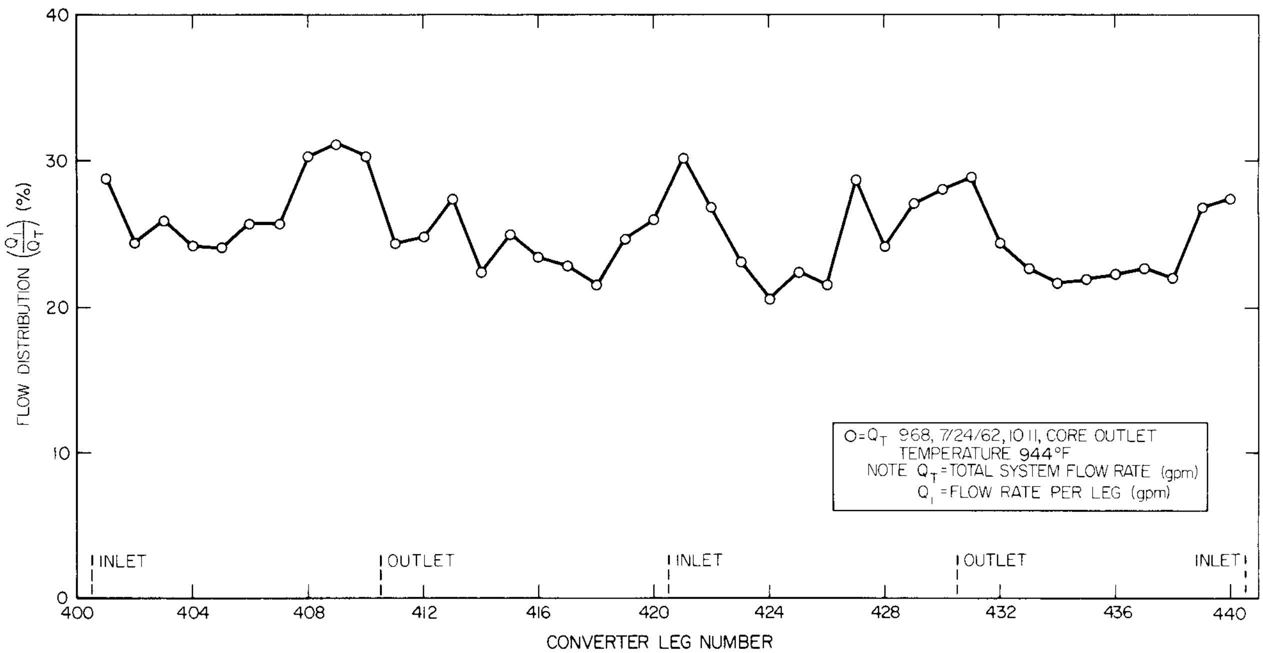

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Figure 58. Converter NaK Flow Distribution

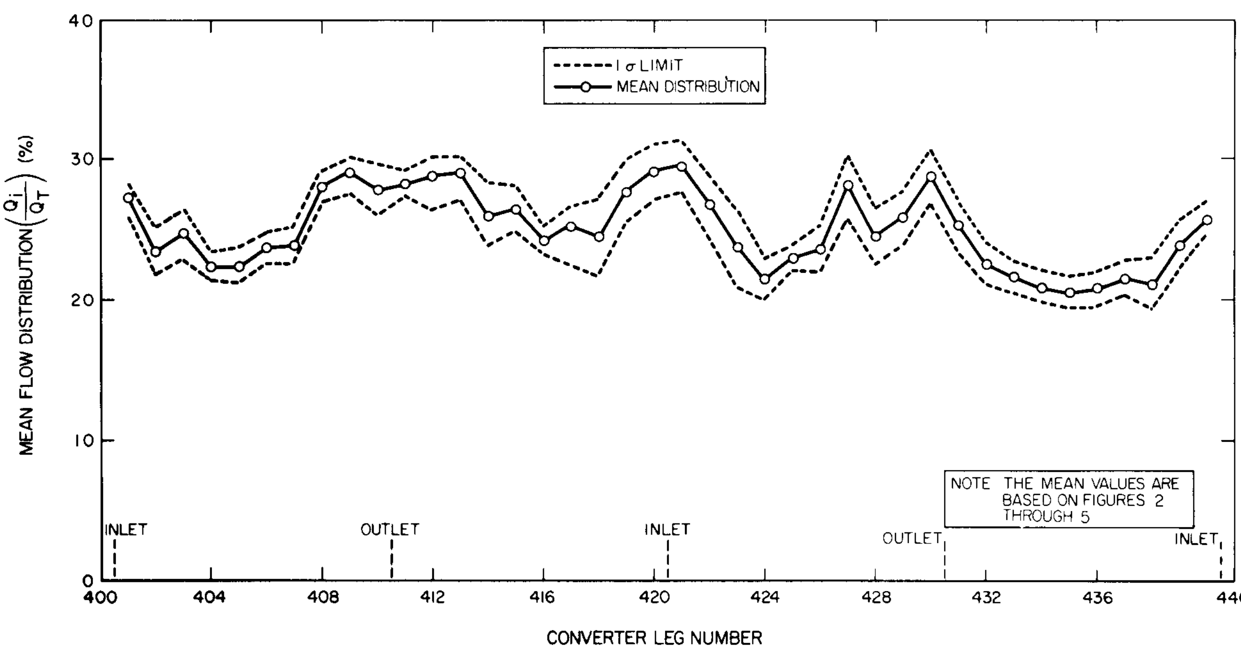

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Figure 59. Mean Converter NaK Flow Distribution

for 421-440 was low because of the presence of the -X flowmeter in the 421-440 return line, which increased the flow impedance. The flow distribution in a space environment would be, for all practical purposes, the same as that shown in Figure 59. Calculations were made which show that the difference would be nominally less than 2%. In other words, if a leg on earth had 2.5% (Q_i/Q_T) flow, in space it would be 2.5 ± 0.05%. The derivation of the equation used in these calculations is shown in Appendix B. Determination of the design electrical power of 585 watts for the unit was originally made assuming that 2.5% of the flow occurs in each leg. The departure of the mean curve from this, as shown in Figure 59, results in an electrical power loss of less than 3 watts. It can be concluded, therefore, that the flow distribution experienced in PSM-3, even when extrapolated to zero gravity conditions, does not create a significant electrical power loss.

E. HEAT BARRIER

Heat transfer from the converter section to the instrument compartment area was held to a minimum by the multilayer aluminum and fiberglass paper heat barrier. The barrier was installed and tested on PSM-3 to:

1) Determine if the heat barrier would transmit less than the 40-watt limitation imposed by heat rejection rate of the instrument compartment.

2) Discover problems and limitations with the installation and use of this design of heat barrier.

The barrier was installed on the unit and instrumented with thermocouples during most of the test program. The temperatures at the heat barrier surface and absorber surface were recorded continuously. Only the data obtained during the steady-state conditions were used to calculate the heat transfer through the barrier.

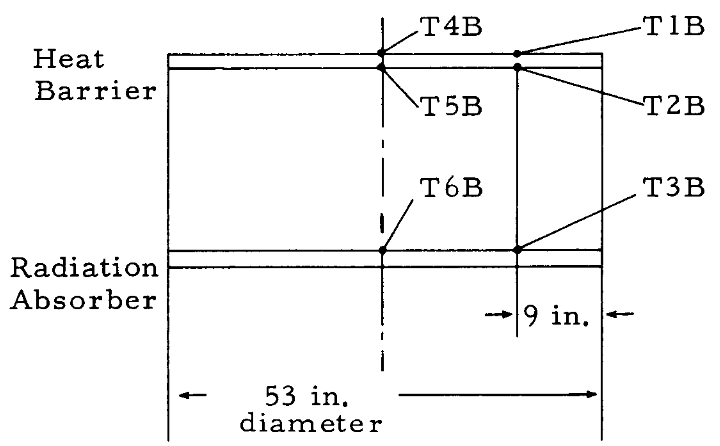
The core outlet temperature was varied from 97°F to 936°F and the temperatures of the barrier and absorber recorded. The temperatures are shown in the following table:

TABLE II

HEAT BARRIER TEMPERATURE PROFILE

Core Outlet Temperature (°F)	T1B (°F)	T2B (°F)	T3B (°F)	T4B (°F)	T5B (°F)	T6B (°F)
97	127	87	80	123	86	78
200	134	77	75	142	76	74
303	246	100	89	251	100	84
400	298	101	88	305	81	80
507	354	114	101	364	107	90
600	450	142	120	459	138	108
700	524	152	128	532	148	112
800	600	172	145	608	165	126
936	702	205	171	711	193	144

The thermocouple location was as shown below:



The amount of heat transferred between the heat barrier and the absorber during the test is given by

$$Q_{exp} = \sigma \left[\frac{1}{\frac{1}{\epsilon_{HB}} + \frac{1}{\epsilon_S} - 1} \right] \int_0^A \left[T_1^4 - T_s^4 \right] dA \quad , \qquad \ldots (14)$$

where

ϵ_{HB} = heat barrier emissivity = 0.08

ϵ_S = absorber emissivity = 0.85

T_1 = heat barrier lower surface temperature, °R

$$T_1 = \left(\frac{T_{2B} - T_{5B}}{1.46} \right) R + \left(T_{5B} + 460 \right)$$

R = distance from heat barrier center

T_s = absorber surface temperature, °R

$$T_s = \left(\frac{T_{3B} - T_{6B}}{17.5} \right) R + \left(T_{6B} + 460 \right)$$

A = surface area of heat barrier, ft^2

The theoretical heat flux through the heat barrier considering radiation only is given by

$$Q_{theo} = \frac{\sigma A}{30} \left[\frac{1}{\frac{2}{\epsilon_{HB}} - 1} \right] \int_0^A \left[T_u^4 - T_1^4 \right] dA \ , \qquad \ldots (15)$$

where T_u = heat barrier upper surface temperature, °R, and

$$T_u = \left(\frac{T_{1B} - T_{4B}}{1.46} \right) R + \left(T_{4B} + 460 \right) \ . \qquad \ldots (16)$$

Using the data given in the preceding table, the two equations were integrated and evaluated at the nine core-outlet temperatures. The results are shown in Figure 60. In addition, a heat barrier effectiveness (η) defined as Q_{theo}/Q_{exp} was evaluated and is also shown in Figure 60. η is a factor which takes into account the departure of the actual heat flux from the theoretical caused by conduction between layers of aluminum and by other miscellaneous effects. At 1000°F core outlet temperature, the barrier upper surface temperature was approximately 750°F, and the lower surface temperature was at 215°F. To determine the approximate heat loss at design conditions, the theoretical heat loss based on 750°F and 100°F design temperatures was computed to be 21.9 watts. Using η equal to 0.665 at 1000°F core outlet temperature from Figure 60, the estimated actual heat loss was solved for,

$$\eta = \frac{Q_{theo}}{Q_{exp}} \ , \quad Q_{exp} = \frac{Q_{theo}}{\eta} \ ;$$

$$Q_{exp} = \frac{21.9}{0.665} = 33 \text{ watts} \quad . \qquad \ldots (17)$$

This means that, at heat barrier upper and lower surface temperatures of 750°F and 100°F, respectively, the heat loss would be 33 watts. This satisfies the heat barrier design requirements, since it was specified that, at these temperature conditions, the heat loss be less than 40 watts.

F. PLUGGING TEST

Design specification for the flight system SNAP 10A requires the NaK to have a plugging temperature less than 20°F. A plugging test was conducted on PSM-3 to determine if this specification could be met for a representative NaK inventory.

The plugging test (Figure 61) was conducted by cooling the NaK in one converter tube (403) and monitoring the flow to determine when plugging occurs. Cooling was provided by Freon 12 refrigerant flowing through two copper lines which were banded axially along the lower 3/4ths of the converter tube. A permanent magnet type flowmeter was placed over that tube to indicate the NaK flow. Temperatures were indicated by thermocouples attached at 12-in. increments along the back surface of the converter tubes.

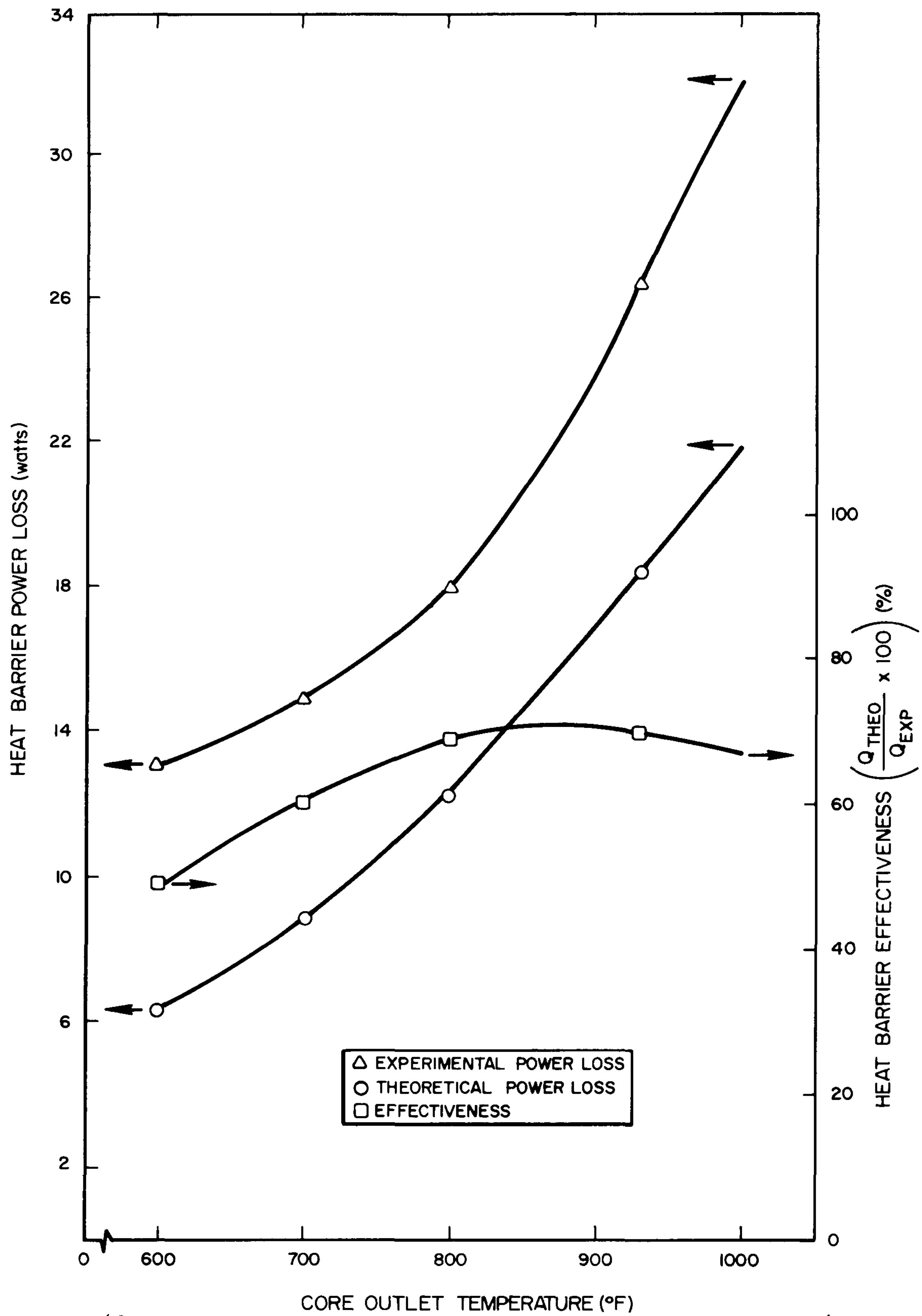


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Figure 60. Heat Barrier Effectiveness

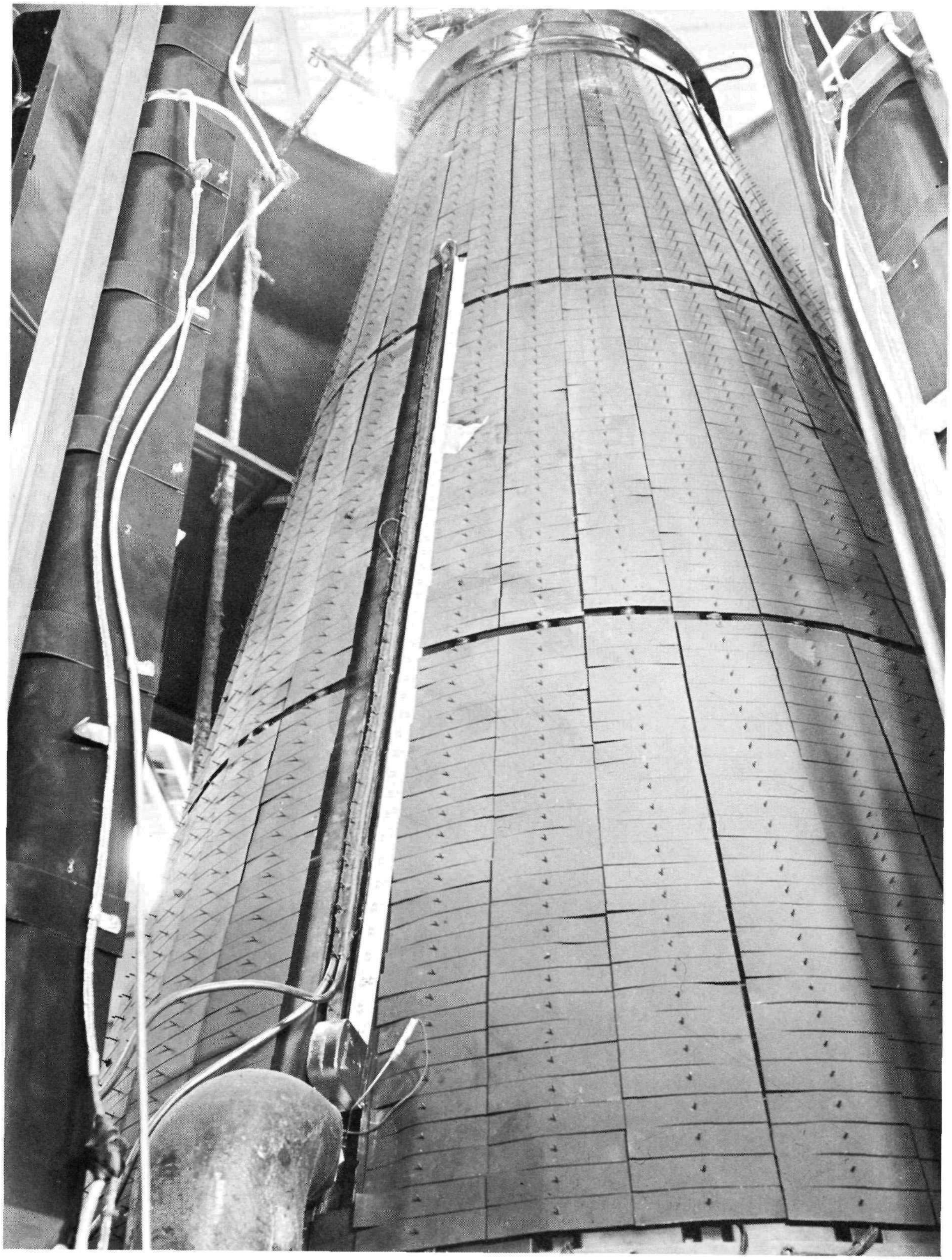

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Figure 61. S10A-PSM-3 Plugging Test Installation on Converter Tube

The total system NaK flow was set at 10% of design flow (1.2 gpm). The refrigerant flow was manually throttled to maintain a constant tube outlet temperature. The tube NaK outlet temperature was set at 25 ± 5, 48 ± 2, 59 and 68 ± 2°F during this test. The flowmeter output was recorded on a continuous pen recorder to graphically illustrate plugging in the tube. The NaK temperatures were recorded by the data logger and a portable potentiometer.

The plugging tests were conducted on the 6th charge of NaK introduced to the system. The previous 5 system charges had been drained to facilitate repair of NaK leaks and to clean up the highly oxidized NaK. The test results follow.

TABLE III
PLUGGING TEST RESULTS

Core Outlet Temp., °F	Min. NaK Temp., °F	Leg 403 Initial Flow Rate, gpm (%)	Leg 403 Flow Rate After Valve Opening (Qa), gpm (%)	Time to 50% Restriction of Qa, Minutes
200	67-70	0.03 (5)	0.095 (15.9)	70
195	46-50	0.06 (10)	0.172 (28.7)	105
185	59	0.06 (10)	0.195 (32.5)	200
80	23-32	0.06 (10)	0.084 (14)	75

Column one is the core outlet temperature, which did not change appreciably during each run. Column two shows the minimum temperature of leg 403. The minimum temperature was held nearly constant throughout the test. Columns three and four, respectively, show the flow rates through leg 403 before and after the freon valve was opened. In both columns the numbers indicate the total system NaK flow rate. The numbers in parenthesis refer to the percent of design flow rate. For example, in run four, in order to have 0.084 gpm through leg 403, under normal conditions, the total system flow rate would have to be at 14%. The flow increase after opening the freon valve was caused by the temperature decrease of leg 403 and the resulting natural convection. The total system flow rate did not increase, just that of leg 403. Only the flow rate after the valve was opened is significant for evaluation purposes, because in a space environment there would be only a negligible change in flow rate due to the temperature decrease, since natural convection is not present. Unfortunately, the four runs did not produce sufficient data to extrapolate to flight conditions. It should be noted, however, that plugging occurred at rather high temperatures and flow rates. However, this was somewhat off-set by the fact that in the tests, only one leg in the system was cooled and, therefore, acted as a system cold trap. No conclusions were reached on the basis of these results, except that additional low-temperature testing on a full system scale is required. Addition discussion of this test is available in Reference 6.

G. AC INTERFERENCE TEST

With the concept of heating the S10A power system with resistive heaters wrapped around the NaK return lines for ground checkout, an investigation was conducted with the PSM-3 system to determine the magnitude of ac inductive coupling induced in the various sensors.

The approach used to investigate this possible electrical interference was to wrap the two NaK return lines with insulated copper wire and pass current through to generate the number of ampere turns corresponding to the proposed wrap around heater. A four channel Sanborn recorder was used to indicate the magnitude of inductive interference produced.

Instrumentation sensors and recorders investigated were

1) Thermocouples attached to the system (300 points)
2) TE converter power output leads (42 leads)
3) Facility digital data logger
4) Nuclear instrumentation which included
    a) Bendix startup channel
    b) Fission chamber
    c) Amphenol RG-149/M wire

The nuclear instrumentation and wire were placed in the core heater area about 12 in. from the power system. The background counts were supplied by a 5 Curie PuBe source, which provided 2 to 6 counts per sec.

Test runs were conducted at several different current levels for 3 types of inductive circuits on the NaK return lines.

1) Inductive loop up one line and down the second, Figure 62 A.

2) Inductive circuits in the same direction in both lines, Figure 62 B.

3) Cancelling inductive circuits on each line, Figure 62 C.

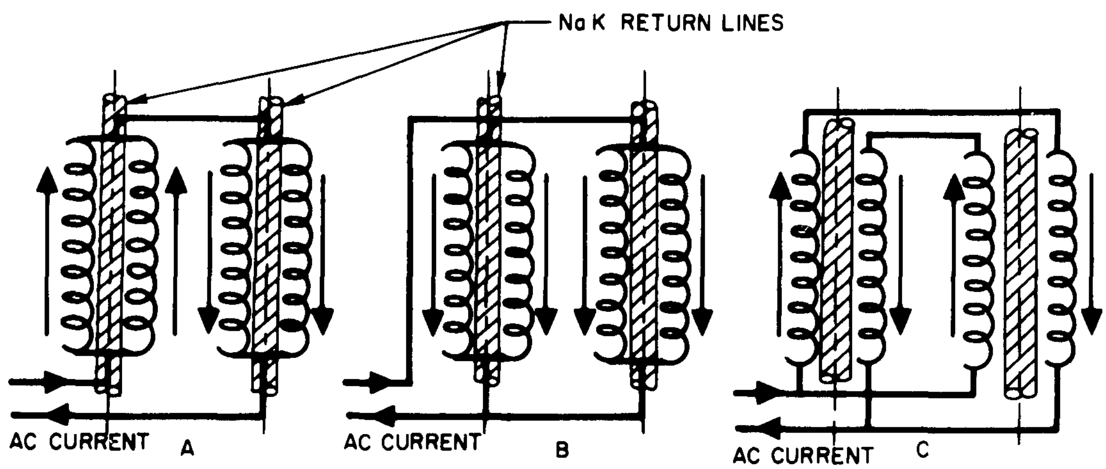

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Figure 62. Three Circuits Used for AC Inductance Test

Single phase current was passed through the coils. The unit was at ambient temperature for the entire test. To determine if flowing NaK would affect the inductive coupling, NaK was circulated through return lines during one phase of this test sequence.

The results of the test follow:

1) There was only a slight difference on sensor interference pickup between the system wired for a complete induction loop (Figure 62A) and the inductive forces in the same direction (Figure 62B). Both methods gave about 25 mv pickup at the sensors in the core area.

2) The interference pickup with the coils wired for cancelling inductive forces (Figure 62C) dropped to 6 mv.

3) Sensors not physically grounded did not indicate any ac pickup. Thermocouple, current and voltage leads on the electrically isolated thermoelectric legs had very little or no inductive pickup.

4) The nuclear instrumentation was unaffected by the inductive coupling. The radiation counts recorded continued to be two to six counts per sec.

5) The KinTel data logger completely rejected the induced ac signal.

A more complete report of this test is published in Reference 9.

VI. TEST PROBLEMS ENCOUNTERED

A. HEATER FAILURES

Failures at the electrical core heater were the greatest problems encountered during the S10A PSM-3 system test. The simulated orbital startup transient test and long-term operation at design conditions could not be conducted owing to the limitations of the core heater.

1. NaK Leaks

Five core heater elements leaked NaK during the S10A PSM-3 system test. These leaks formed at the weld between the solid stainless steel tip and thin-walled inconel sheath of the cartridge heater elements. The differential expansion which occurred during the various heating cycles cracked the metal, allowing NaK to flow into the MgO and lavite electrical insulation around the filament, shorting out the element. The NaK then migrated through the insulation to the exposed end of the heater, where it vaporized in the 2×10^{-5} mm Hg vacuum environment.

To repair these leaks, caps were welded over the exposed ends of the leaking heater elements. Test operation then continued, using the remaining heater elements. Figure 63 shows a capped heater element in the foreground.

The crack itself was not sealed. Therefore, the MgO and lavite in the elements would be exposed to the system NaK, thus remaining a potential source of oxides. None of the oxide plugs which occurred during system testing could be directly attributed to the cracks at the heater elements. The oxide concentration, however, did remain high during most of the test program.

2. Moisture Absorption

The hygroscopic properties of the MgO and lavite electrical insulation caused room moisture to be absorbed by the electrical insulation in the cartridge heater. This moisture would reduce the insulation resistance, thus increasing the possibility of an electrical short. The moisture was baked out of the core heater elements prior to NaK filling by heating the core heater assembly to 700°F with electrical strip heaters banded around the external surface of the heater casing.

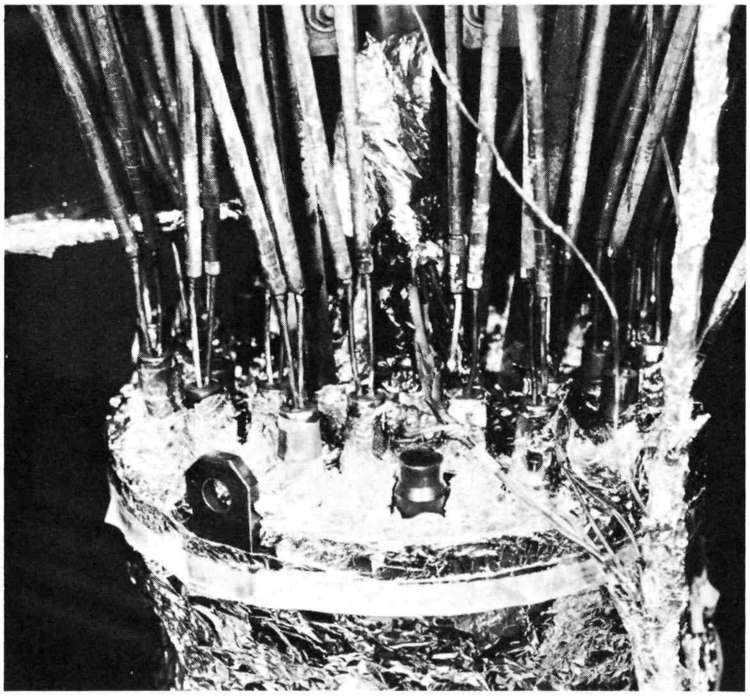

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Figure 63. S10A PSM-3 Core Heater Assembly Showing Capped Heater Element and Melted Heater Leads

The resistance dropped from an average of 150 megohms to 5 megohms, while heating from room temperature to 400°F. The resistance increased to above 100 megohms for all 30 elements while stabilized at this temperature for 12 hr. The resistance then dropped again to 5 megohms when the temperature was raised to 700°F. After 16 hr at this temperature, all the moisture was baked out and the MgO resistance stabilized at infinity.

3. Leads Melting and Shorting

Prior to test operation, the core heater elements were modified. The operation of a similar heater assembly in another vacuum environment caused many of the heater lead wires to overheat and melt the lead wire solder joints. These joints on S10A PSM-3 were removed and replaced with a nickel weld. Also, 2 in. of lead wire adjacent to the heater element were left uninsulated and painted with a black paint to dissipate a maximum amount of heat.

Two failures resulted from a current overload at the heater variable transformer, burning out the fuses in the supply. These failures occurred when the core outlet temperature was above 900°F.

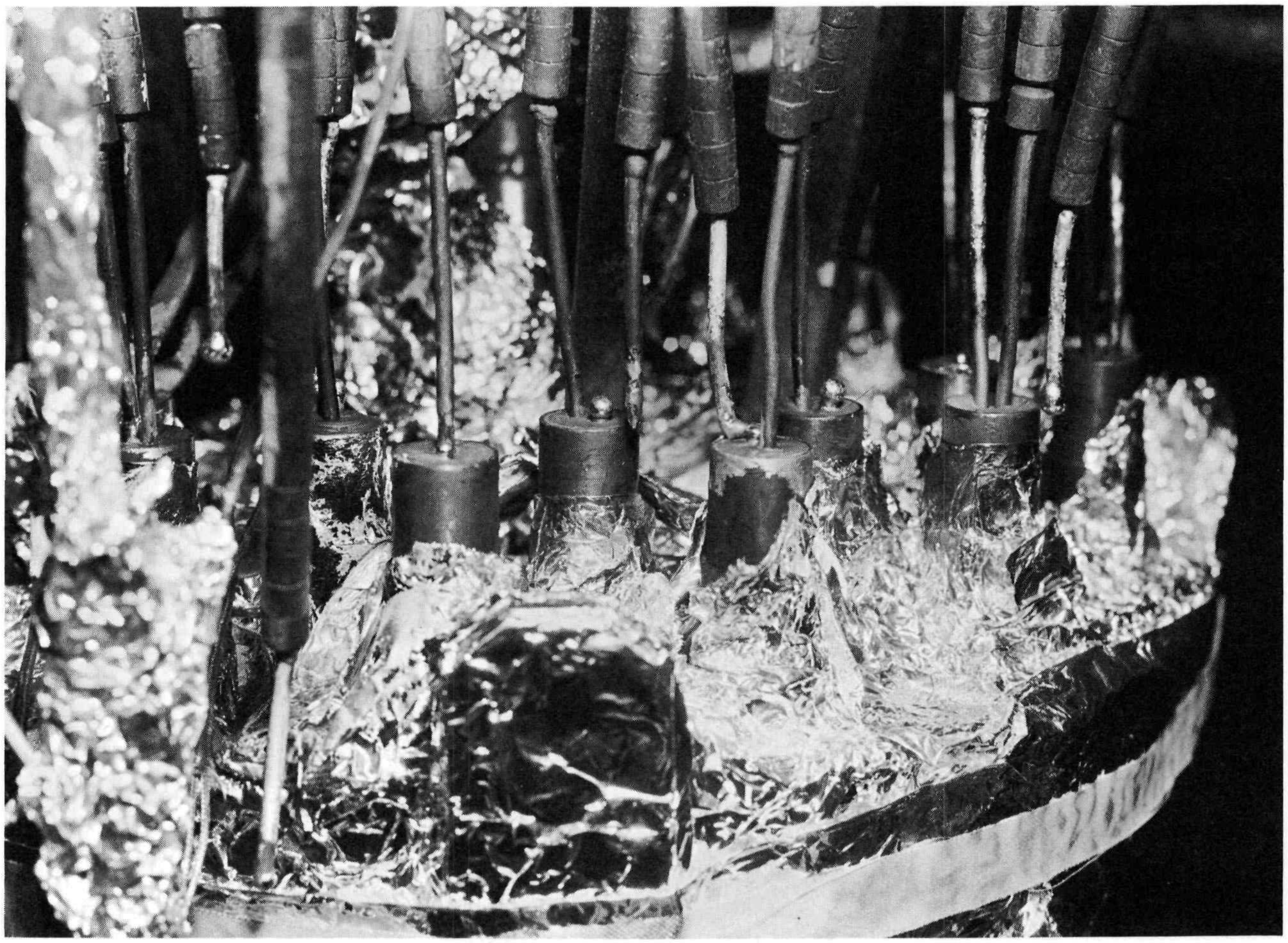

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Figure 64. PSM-3 Core Heater Showing Melted Heater Leads

The second of these two failures caused nine heater lead wires to melt directly adjacent to the heater elements (Figure 64). The nickel lead wires on the core heater were replaced with 3/16 in.–copper tubing to improve the electrical conductivity, heat conduction and heat rejection surface area.

Heater lead wires melted and shorted two more times due to NaK leaks at the heater elements. The first leak, which occurred at 600°F, caused electrical arcing with subsequent melting of 12 lead wires. Thermocouples attached to three other core heater lead wires at this time indicated a maximum temperature of 312°F. When the second heater element leaked NaK, the individual element circuit breakers tripped sequentially over a 48 hr period, because of electrical arcing at the heater elements.

A detailed investigation of the heaters which arced in the PSM-3 test and another similar test disclosed that an electrical conduction path developed at the surface of the electrical insulation. The MgO apparently sublimed or dis-associated in some way at the high temperature and low pressure, to leave an electrical conduction path. Upon application of a minimum voltage, this thin surface layer would conduct, causing an electrical arc with subsequent melting of the lead wires. An ohmmeter check between these same arcing leads, however, would not give a low resistance reading. Evidently the arcing which occurred must act similar to a capacitance discharge.

B. NaK LEAKS IN CONVERTER

Three NaK leaks developed in the converter tubes during the PSM-3 test program. The first leak occurred at the upper manifold weld of converter tube 435 as was described in Section V-A. The temperature differential between tubes due to the oxide plugged condition of tube 435 caused this tube to fracture.

NaK leaks developed at two other tubes in the converter, 404 and 433. These pin hole leaks were discovered near the top manifold after about 50 days of system operation at NaK temperature to 800°F. The NaK extruded through these holes to form tiny rosettes of oxidized NaK. Repair was accomplished by draining the NaK from the tubing and welding the pin holes shut. The leak at tube 404 was at the back surface of the tube; repair required removal of the shield casing and cutting a hole through the converter shell.

C. TEST EQUIPMENT FAILURE

1. Heater Powerstat

The blowing of fuses on the core heater variable transformer, mentioned in Section VI-A-3, was due to overloading the transformer. The core heater system was designed for a maximum output of 33 kw at 120 vac line to neutral. This was thought to be adequate; the excessive system heat losses, however, required 40 kw to reach the design temperature. A simple rewiring of the core heater circuit from wye to delta permitted obtaining this power, but it over-loaded the current capacity of the variable transformer. The current rating for each line was 135a, but the load required 175a to reach 40 kw when wired in delta.

2. Pump Power Supply

One emergency shutdown occurred because the system pump power supply failed (at 470°F system temperature) because control transformer brushes on the power supply shorted and melted. The core heater was turned off immediately to prevent overheating the stagnant NaK in the core. The control transformer was repaired and testing continued.

The 500a current restriction of the original pump power supply limited the NaK flow to 10 gpm. A new power supply of twice the current capacity was installed late in test program but the design operating conditions could not be attained at that time due to limitations of the core heater.

D. CALIBRATION PROBLEMS

1. Thermocouples

System Test Unit personnel installed all thermocouples. No acceptance tests or calibrations were made on the sensors prior to their installation. In addition, the chromel-alumel thermocouple wire was supplied from seven different sources. As a result, the accuracy of temperature measurements was not known but suspected to be as bad as ±1% of the reading.

The data logger and other thermocouple read-out equipment were calibrated and adjusted to within the manufacturers' specification on the average of once every two months. The specified accuracies of all the instrumentation are listed in the Instrumentation List in the Appendix.

2. NaK Differential Pressure Transducers

The two differential pressure transducers were calibrated with gas pressure prior to loading the system with NaK. The valving at the transducers was designed to permit periodic calibration of the transducer with the system filled with NaK. This would be accomplished by closing a valve on one side of the transducers and varying the NaK system pressure by manipulating the gas pressure against the expansion compensator bellows.

This calibration procedure was attempted on two occasions. This method was unsuccessful, however, owing to a very small leakage through the loading line valves. Each time a calibration was attempted, the two expansion compensator bellows fully collapsed.

3. Flowmeter Calibration

The three permanent-magnet-type NaK flowmeters were calibrated with NaK flowing in a separate test loop.

The flowmeters were calibrated at NaK temperatures from ambient to 1000°F. Also, the magnet pole face temperature was increased to determine the effect of magnet temperature on flowmeter signal output.

The output for each of the flowmeters was linear at about 1.2 mv per gpm. An increase in pole face temperature from 190°F to 580°F reduced the signal about 5%.

During power system assembly, the magnets were removed from the NaK tube section. If the units were reassembled with a slightly different geometrical orientation, the previous calibration would have been nullified.

This may have occurred and could account for some of the excessively large heat losses calculated for the heat balance reported in Section V-B. No way was known to recheck the calibration of the flowmeters after installation onto the system.

VII. CONCLUSION

A. The detection of several serious problems that would have severely affected the ground test schedule had they been initially encountered during the ground testing of a flight system, one of the most significant contributions of the PSM-3 system tests to the overall SNAP 10A schedule and objectives, was discussed in the previous section of this report. Because they were discovered on PSM-3, design modifications have been incorporated to preclude their occurrence on future ground tests.

B. Because of failures noted in the previous section of this report, some of the PSM-3 test objectives were not met. Operation at the design core outlet temperature of 936°F was maintained for a total of approximately 70 hr, rather than the goal of 1000 hr. Simulated orbital startup was also deleted from the tests. These departures from the specified test plan were caused primarily by failure of the core heater rather than a prototype flight hardware item.

C. The core heater design was inadequate.

D. The NaK loading cart design was inadequate.

E. In general, considering the test limitations, the SNAP 10A PSM-3 test vehicle met its design goals. The following table summarizes the system design points and test results.

TABLE IV
SYSTEM DESIGN POINTS AND TEST RESULTS

	Design Point	Test Result*
Heat input to converter, kw	27.9	27.9
Heat rejected by radiator, kw	27.32	27.16
Heat radiated from the NaK lines and structure to the radiator, kw	2.0	4.0
Heat transfer through TE elements, kw	25.32	23.16

*Test results converted to design conditions of 960°F core outlet temperature and 12.0 gpm NaK flow rate.

TABLE IV

SYSTEM DESIGN POINTS AND TEST RESULTS (CONTINUED)

	Design Point	Test Result*
Conductance per element, watts/°F	0.031	0.027
Temperature difference across TE element, °F	262.0	279.0
Open circuit voltage, volts	57.5	59.64
Electrical power, watts	585.0	534.0
Carnot efficiency (ηc), %	19.8	21.3
Overall efficiency (ηo), %	2.1	1.91
Device efficiency ($\eta o/\eta c$ x 100), %	10.67	8.98
Total system pressure drop, psi	1.0	0.96
Heat barrier heat loss, watts	40.0	33.0

*Test results converted to design conditions of 960°F core outlet temperature and 12.0 gpm NaK flow rate.

F. The manual data reduction techniques employed were inadequate.

VIII. RECOMMENDATIONS

A. NaK LOADING CART

The NaK loading cart used for filling PSM-3 was unsatisfactory for the job demanded. All loading carts for future SNAP 10A systems will require improvements in the following areas.

1) Design the loading cart heater and pump to be capable of raising the NaK temperature of the system to 850°F at a flow of 14 gpm.

2) Provide a cold trap capable of reducing the oxide plugging temperature to below 20°F which can be utilized at flowing NaK temperatures to 850°F.

3) Provide a plugging indicator to ensure that the oxide concentration is equal to or below the design operating level.

4) Provide drain tank and fill tank with sufficient capacity for two complete changes of NaK inventory in the power system and fill lines without recharging of the loading cart fill tank.

B. CORE HEATER REDESIGN

A redesign of the core heater is required for all future nonnuclear SNAP 10A system tests. The core heater elements must be fabricated with materials of similar thermal expansion to prevent cracking as occurred at the tip of the PSM-3 heater elements.

The electrical shorting which apparently occurred as a result of vaporization of the MgO and lavite electrical insulation could be prevented by encapsulating the electrical insulation. Some method of avoiding the dissociating of insulation into the vacuum environment where the leads pass into the MgO is required.

A highly reflective thermal insulation should be installed on the outer surface of the core heater casing to reduce the excessively high heat losses calculated for the S10A PSM-3 core heater. Improved thermocouple installation techniques at the core inlet and exit nozzles will aid in better defining the actual magnitude of heat loss at the core heater.

C. USE OF HIGH TEMPERATURE, NON-OUTGASSING COMPONENTS

All surfaces of PSM-3 discolored badly during the system test. Most of these discolorations were caused by outgassing substances from the binder used in the lead wire insulation. The lacquer impregnation used in the TC wire plated onto all surfaces of the power system and vacuum vessel where it burned or left a deposit.

The resulting discoloration of the power system could not be tolerated on a flight system. Care must be exercised in future systems to avoid installing any wire or other components which could contaminate the structure. Likewise, any test support equipment installed in the test chamber must be similarly selected for a minimum of outgassing substances.

D. ADEQUATE SAFETY FACTORS IN TEST EQUIPMENT

Three of the major difficulties encountered during the system test program were due to failures of the test equipment.

The first piece of equipment to malfunction was the NaK loading cart. The recommended modifications were discussed previously.

Next the system pump dc power supply failed primarily, because it was underdesigned. The design flow of 12 gpm could not be obtained with the original 500a power supply, so the unit was continually operated near its maximum output. Had a larger power supply with an ample safety factor been used during the entire program, this failure would likely have not occurred.

The core heater electrical circuit was designed for a 33 kw output. A minimum of 30.5 kw was known to be needed. This provides only about an 8% safety margin, which proved insufficient because of excessive heat losses at the core heater.

It is recommended that the power supplies purchased for all future SNAP 10A system tests include at least 25% excess capacity.

E. NaK CAPILLARY LINES

When the unit was highly contaminated with NaK oxide, the 1/4 in.-capillary lines to the pressure transducers permanently oxide plugged, while the 3/8 in.-

lines could be flushed clean. On the basis of this experience, it is recommended that no NaK tubing smaller than 3/8 in. be used where danger of a NaK oxide plug exists.

F. TESTING

The data reduction and evaluation of future tests must be computerized to reduce the delay time between the test and the evaluation of the test and eliminate the necessity of manually reducing large quantities of data.

Because of the inconclusive data obtained from the tests on NaK plugging, additional testing is required. On subsequent system tests, provisions should be made for good low temperature simulation of the space environment.

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APPENDIX A
FLOW DISTRIBUTION – GRAVITY EFFECT

Writing the Bernoulli equation, including friction losses, across the converter on earth, we have

$$\frac{K_i \rho_i V_i^2}{2g} + (\Delta\rho)_i h = \Delta P \quad , \qquad \ldots\text{(A-1)}$$

where

$\frac{K_i \rho_i V_i^2}{2g}$ = frictional loss from the converter inlet to outlet along the i^{th} converter tube

$(\Delta\rho)_i$ = NaK density difference between the i^{th} converter tube and the return line

h = converter height

ΔP = total converter pressure drop

$\Delta\rho$ = a constant for the 10 flow paths in a converter quadrant

Writing the total pressure drop in terms of average properties for the converter quadrant,

$$\Delta P = \overline{\frac{K\rho V^2}{2g}} + \overline{\Delta\rho}\, h \quad . \qquad \ldots\text{(A-2)}$$

Equating Equations A-1 and A-2 and solving for K_i,

$$\overline{\frac{K\rho V^2}{2g}} + (\overline{\Delta\rho})h = \frac{K_i \rho_i V_i^2}{2g} + (\Delta\rho)_i h \quad ; \qquad \ldots\text{(A-3)}$$

$$K_i = \frac{2g}{\rho_i V_i^2}\left[\overline{\frac{K\rho V^2}{2g}} + (\overline{\Delta\rho})h - (\Delta\rho)_i h\right] \quad . \qquad \ldots\text{(A-4)}$$

In space where there are no gravity effects,

$$\Delta P_S = \frac{K_{iS}\rho_{iS}V_{iS}^2}{2g} \quad , \qquad \ldots (A\text{-}5)$$

where the subscript "S" refers to space conditions, and

$$\Delta P_S = \overline{\frac{K_S\rho_S V_S^2}{2g}} \quad . \qquad \ldots (A\text{-}6)$$

Assuming that

$$K_{iS} = K_i \ , \qquad \rho_{iS} = \rho_i \ , \quad \text{and}$$

$$\overline{\frac{K_S\rho_S V_S^2}{2g}} = \overline{\frac{K\rho V^2}{2g}} \quad , \qquad \ldots (A\text{-}7)$$

we find that

$$\frac{K_i\rho_i V_{iS}^2}{2g} = \overline{\frac{K\rho V^2}{2g}} \quad . \qquad \ldots (A\text{-}8)$$

Solving for V_{iS},

$$V_{iS} = \sqrt{\frac{\overline{K\rho V^2}/2g}{K_i\rho_i/2g}} \quad . \qquad \ldots (A\text{-}9)$$

Substituting Equation A-4 for K_i,

$$V_{iS} = \sqrt{\frac{\overline{\frac{K\rho V^2}{2g}}}{\frac{1}{V_i^2}\left[\overline{\frac{K\rho V^2}{2g}} + (\overline{\Delta\rho})h - (\Delta\rho)_i h\right]}} \quad . \qquad \ldots (A\text{-}10)$$

Rearranging,

$$\frac{V_{iS}}{V_i} = \sqrt{\frac{1}{1 + \frac{[(\overline{\Delta\rho})h - (\Delta\rho_i)h]}{\frac{\overline{K\rho V^2}}{2g}}}} \quad , \qquad \ldots \text{(A-11)}$$

and

$$\frac{Q_{iS}}{Q_i} = \sqrt{\frac{1}{1 + \frac{(\overline{\Delta\rho} - \Delta\rho_i)h}{\Delta P_f}}} \quad , \qquad \ldots \text{(A-12)}$$

where Q is the volumetric flow rate and $\Delta P_f = \overline{K\rho V^2}/2g$. It can be seen that if the density of a particular leg is less than the average, the flow rate in space, through that particular leg, will be greater than it was on the ground and the converse is true. Also, rather large density departures from the average density would have to occur before the NaK velocity in a particular tube would be appreciably different in space from what it was on the ground. The temperatures measured during the PSM-3 tests resulted in NaK densities that, when used in Equation A-12, yielded flow rate differences of nominally two percent. The flow rate difference is therefore considerably less than the accuracy obtained in predicting the flow rate on the earth and can therefore reasonably be neglected.

APPENDIX B
INSTRUMENTATION LIST

A. DIGITAL DATA LOGGER (KinTel)

1) Operation

a) Automatically scans and logs 400 input signals at the rate of one point per sec, or

b) Will continuously monitor and indicate any single point upon demand.

2) Signal Input

a) 0-5v dc

b) 0-10 mv dc

c) 0-23 mv dc (chromel-alumel thermocouple, 0-1200°F)

3) Output

a) Visual indication on digital voltmeter

b) Typed out in engineering units with an electric typewriter, readout units on typewriter are as follows:

i) 5v dc input reads 5.000

ii) 10 mv dc input reads 10.00

iii) 1200°F input reads 1200.

c) Punched paper tape (digital) for computer processing

4) Overall system accuracy: ±1% of full scale

B. MULTI-RANGE DC ELECTRONIC VOLTMETER (METRONIX MODEL 301)

1. Use: Backup to data logger for dc voltage signals

2. Wired to a 100 point selector switch

3. Ranges:

a) 0-10/30/100/300 mv dc

b) 0-1/3/10/30/100/300 v dc

4. Instrument accuracy ±3% of full scale for each range

C. TEMPERATURE INDICATOR (Leeds & Northrup Model Speedomax "B")

1. Use: Backup to data logger
2. Wired to a 40-point selector switch
3. Range: 0-1000°F chromel-alumel thermocouples
4. Instrument accuracy: ±1/2% of full scale

D. SINGLE PEN MILLIVOLT RECORDER (2 ea. Westronics Model S 5/M and 1 ea. Varian Model G11A)

1. Uses: Three units recorded the NaK flow rate indicated by the three permanent magnet flowmeters
2. Range: 0-10 mv dc
3. Accuracy of both models: ±5% of full scale

E. PERMANENT MAGNET FLOWMETER (3 each AI Drawing No. L137-20001)

1. Use: Indicated NaK flow rate at both converter inlet lines and one of the two converter outlet lines
2. Each unit calibrated individually in separate calibration loop
3. Output:
   a) About 1.2 mv/gpm
   b) 5% loss of output when pole face temperature rises from 190° to 590°F
4. Accuracy: ±4% of reading if geometry is undisturbed

F. TEMPERATURE RECORDER-CONTROLLER (Leeds and Northrup Model PAT 60)

1. Use: Controlled power input to electrical core heater
2. Continuously recorded core heater outlet temperature with a single pen
3. Control either manual or automatic using the core heater outlet thermocouple

4. Input: Thermocouple chromel-alumel (type K)

5. Range: 0-1200°F

6. Accuracy: ±1/2% of full scale

G. DIFFERENTIAL PRESSURE TRANSDUCER (2 each Statham Model PM 80TC)

1. Use: Measured NaK pressure differential across power system pump and across one quadrant of the converter tubes

2. Operating principle: Diaphragm movement actuated resistive, balanced, complete unbonded strain gage bridge

3. Powered by Transistorized Strain Gage Amplifier (Statham Model CA9-0)

   a) Power required: 28v dc at 35 ma

   b) Frequency: 10 kc

4. Range: 0-1.5 psi

5. Output to data logger;0-5v dc from amplifier

6. Accuracy: ±1% of full scale

H. ABSOLUTE PRESSURE TRANSDUCER (2 ea. Pace Engineering Model P21A)

1. Use: Measured the gas pressure in the power system expansion compensators

2. Operating principle: Variable magnetic reluctance induced by position of the magnetic stainless steel diaphragm

3. Powered by Carrier-Demodulator (Pace Model CD10)

   a) Power required: 28v dc at 0.2a

   b) Carrier frequency: 3.4 kc

4. Range: 0-50 psia

5. Output to data logger: 0-5v dc from carrier demodulator

6. Accuracy: ±3/4% of full scale

I. VOLTMETER (General Electric)

1. Use: Indicated phase-to-neutral voltage of core heater circuit
2. Connected in series with a 3 position selector switch to monitor voltage for each phase
3. Range: 0-150 vac
4. Accuracy: ±1% of full scale

J. WATTMETER (General Electric)

1. Use: Indicated power input to core heaters
2. Input: 3 phase, 4 wire, 60 cycle, 120 vac line to neutral
3. Range: 0-65 kw
4. Accuracy: ±1% of full scale

K. WATTMETER (General Electric)

1. Use: Indicated power input to radiant heaters
2. Input: 3 phase, 4 wire, 60 cycle, 120 vac line to neutral
3. Range: 0-16 kw
4. Accuracy: ±1% of full scale

L. TURBINE FLOWMETER (3 ea. Potter Model 1/2 - 0135)

1. Use: Measured water flow rate to each section of the vacuum vessel
2. Operating principle: Propeller in flowing stream translates liquid velocity to a dc voltage signal (The output signal is fed through a frequency to dc converter)
3. Range: 0.6 to 10 gpm
4. Output to data logger: 0-5v dc
5. Accuracy: ±1/2%

M. THERMOCOUPLE GAGE CONTROL BOX (3 ea. Consolidated Vacuum Corporation Model GTC-105)

1. Use: Monitored vacuum pressures at several locations on the vacuum pumping system

2. Automatic trip point actuated safety interlock circuits on vacuum pumping system

3. Operating principle: Output of thermoelectric junction is proportional to heat conducted away by gas molecules in thermocouple gage tube

4. Range: 1 to 1000 x 10^{-3} Torr

5. Accuracy: ±1 x 10^{-3} Torr at lowest reading to ±100 x 10^{-3} Torr at highest reading.

N. IONIZATION GAGE CONTROL BOX (Consolidated Vacuum Corporation Model GIC 110)

1. Use: Measured vacuum pressures inside vacuum chamber

2. Operating principle: Current conducted between filament and plate is proportional to density of gas molecules in ion gage tube

3. Input power: 100 ma at 115 vac

4. Range: 2 x 10^{-9} to 1 x $10^{-8}/10^{-7}/10^{-6}/10^{-5}/10^{-4}/10^{-3}$ Torr

5. Output to data logger: 0-10 mv

6. Accuracy: ±5% of full scale reading for each range

O. CURRENT SHUNT (40 ea. Janco Catalog No. 8300-50)

1. Use: Measured current output of TE modules

2. Range: 0-50 a

3. Output to data logger: 0-50 mv

4. Accuracy: 0.3% of full scale