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SPACE NUCLEAR SYSTEM
THERMOELECTRIC NaK PUMP
DEVELOPMENT
SUMMARY REPORT

AEC Research and Development Report



Atoms International Division
Rockwell International

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Canoga Park, California 91304

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THERMOELECTRIC NaK PUMP
DEVELOPMENT
SUMMARY REPORT**

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Rockwell International**

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FOREWORD

The work described here was done at the Atomics International Division of Rockwell International Corporation, under the direction of the Space Nuclear Systems Division, a joint AEC-NASA office. Project management was provided by NASA-Lewis Research Center and the AEC-SNAP Project Office.

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ABSTRACT

This report summarizes the engineering, design, fabrication, and test history of the dual-throat thermoelectric NaK development pump, and the engineering and design status of a similar prototype pump intended for use on the 5-kwe Reactor Thermoelectric System. The history of dc pump development and testing on previous SNAP programs is also summarized.

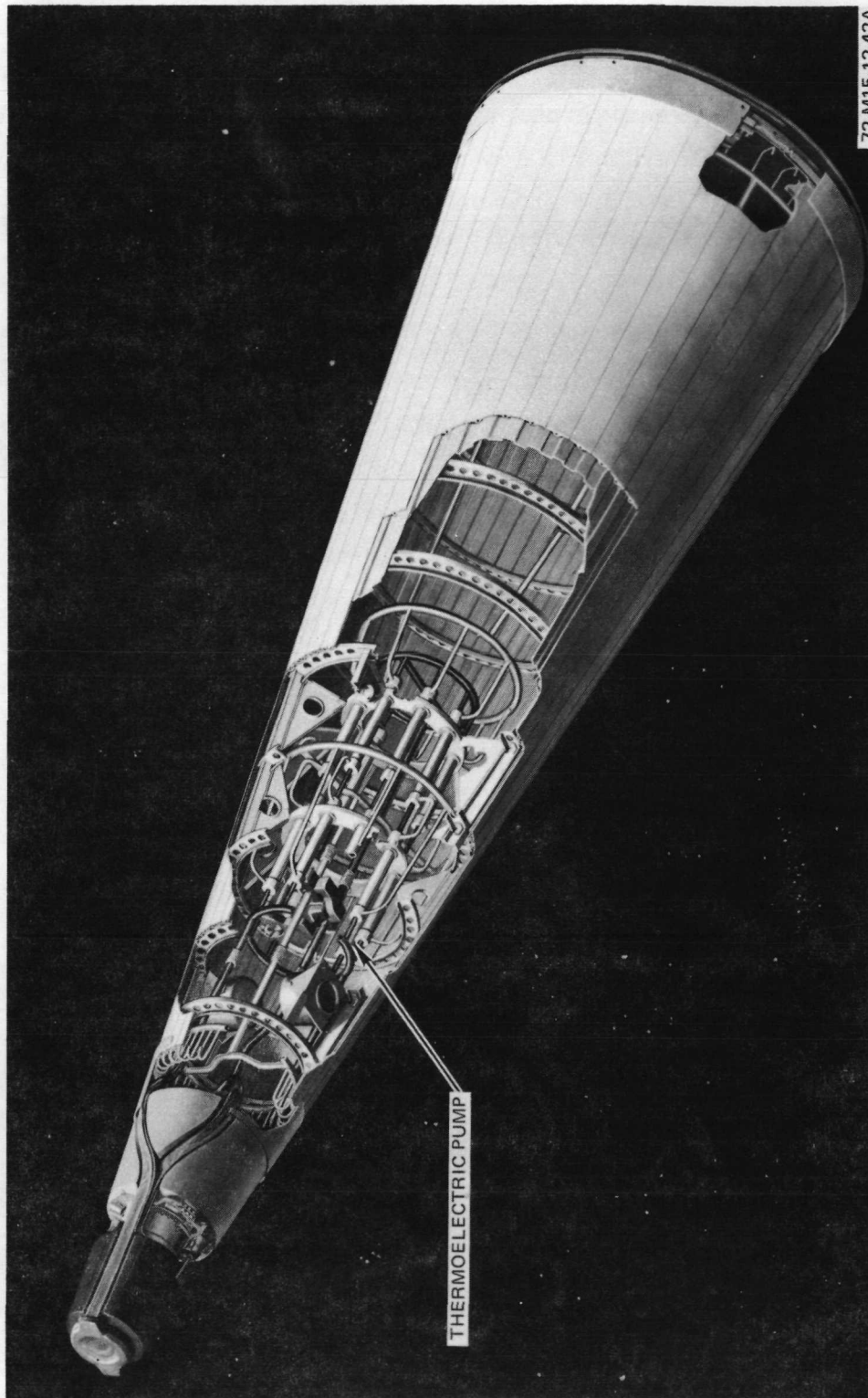
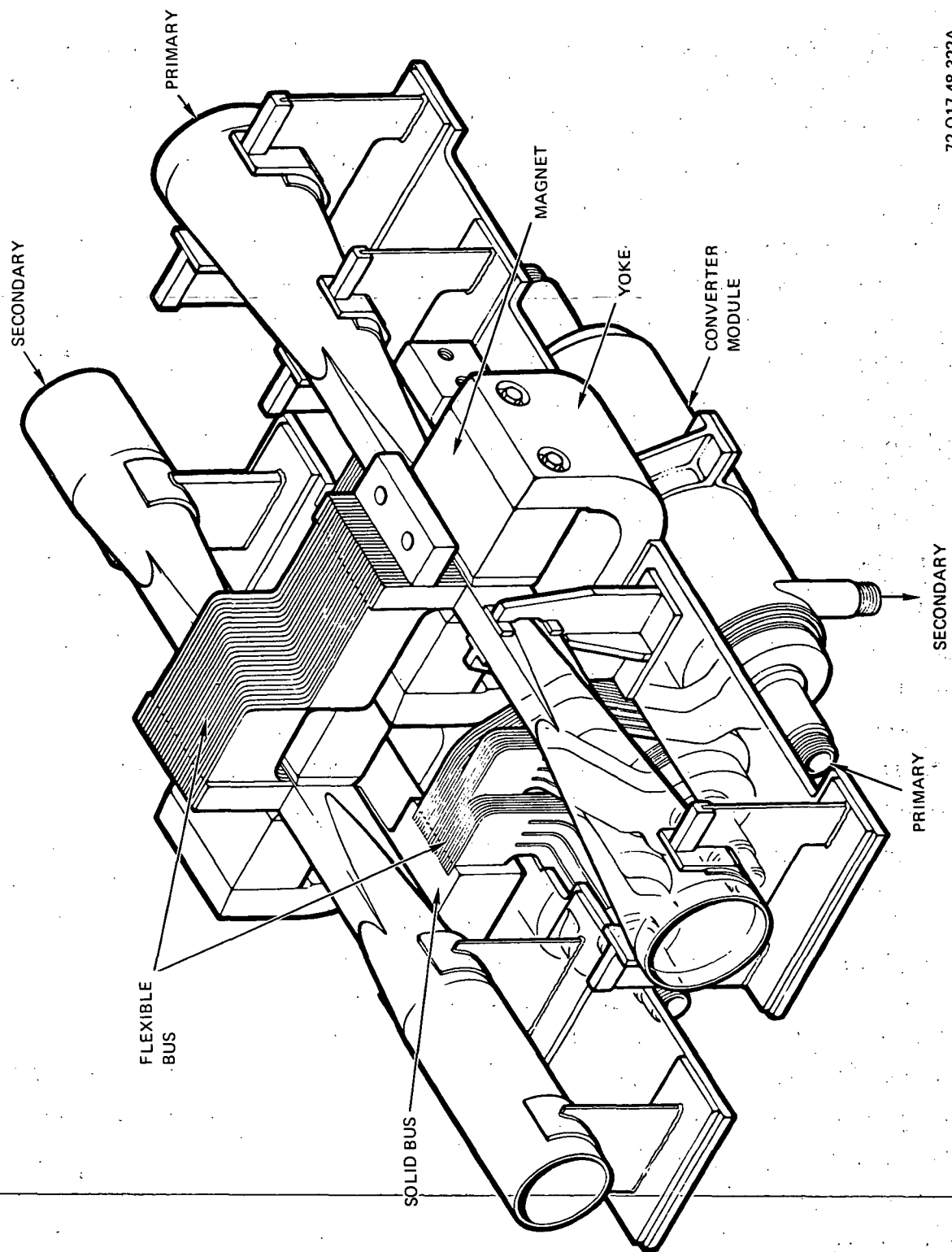


Figure 1. 5-kew Unmanned System

I. INTRODUCTION

A series of compact nuclear reactors and electrical power systems were designed, developed, and tested for the Systems for Nuclear Auxiliary Power (SNAP) Program. The ZrH reactors for these systems were fueled by hydrided zirconium-uranium elements, enclosed within high-temperature corrosion-resistant tubes. Windows in the external beryllium neutron reflector were adjusted by rotating the drums or sliding the segments to regulate the neutron loss from the core, and thus the power output of the reactor. Direct radiating thermoelectric module powered Power Conversion System (PCS's) produced over 500 w of electrical power on the flight-tested SNAP 10A System. Mercury-Rankine cycle turbogenerator PCS's of 3-kwe and 30-kwe power ranges were demonstrated for the SNAP 2 and SNAP 8 systems, respectively. The latest 5-kwe Thermoelectric System was based on the compact tubular thermoelectric PCS. The NaK, used to transfer the heat from the reactor to the PCS, and then from the PCS to the space radiator, was to be circulated by dc conduction-type electromagnetic pumps.

The 5-kwe System is illustrated in Figure 1; the principal components are a nuclear reactor, thermoelectric converter modules, dual-throat thermoelectric pump, heat rejection space radiator, volume accumulator units, interconnecting dynamic liquid-metal heat transfer primary and secondary coolant piping systems, and piping expansion joint units. Thermal energy produced in the nuclear reactor is transferred by liquid metal, NaK (binary eutectic, 22% Na - 78% K alloy), circulated by the dual-throat thermoelectric pump through the reactor and thermoelectric modules of the primary loop, and through the thermoelectric modules and the radiator of the secondary loop. A portion of the coolant from the reactor and from the radiator is circulated through special low-voltage high-current thermoelectric power modules that are an integral part of the pump assembly. These thermoelectric modules provide the electrical power for the pump. The pump is required to provide a coolant flow rate of ~ 5 lb/sec against a 1.1 psi head at 1100° F in the primary loop, and a coolant flow rate of ~ 3 lb/sec against a 1.6 psi head at 600° F in the secondary loop. A conceptual isometric drawing of the prototype pump for the 5-kwe Reactor Thermoelectric System is shown in Figure 2.



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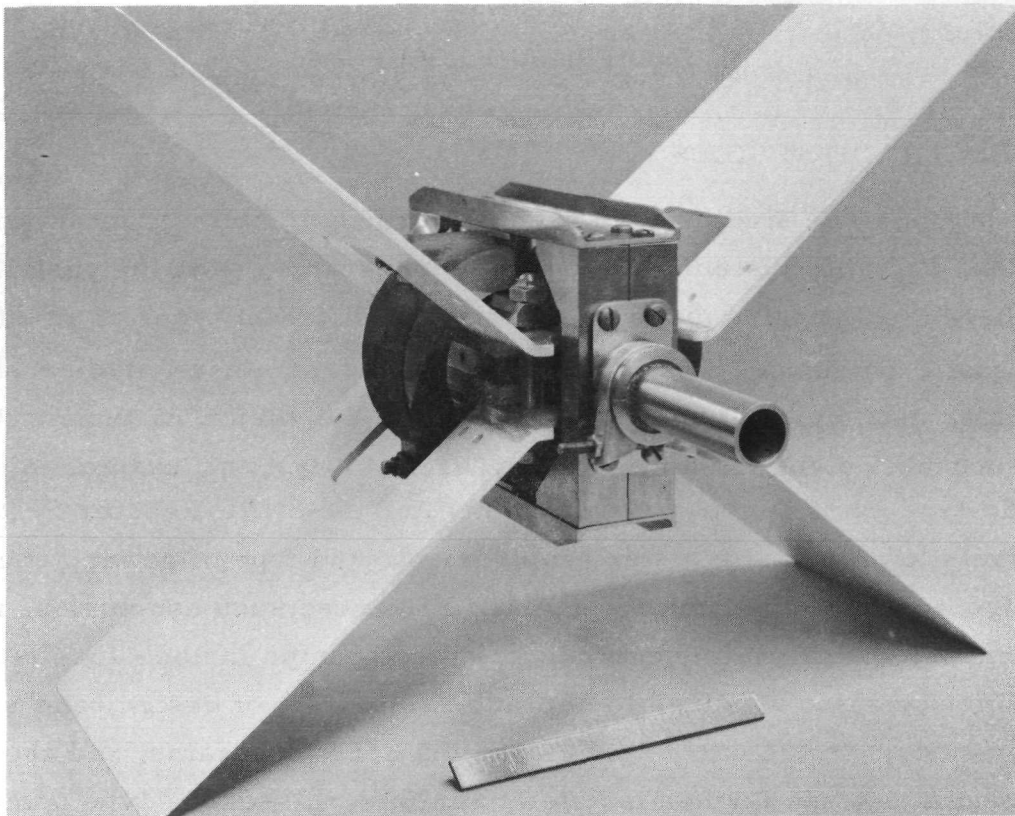
Figure 2. Prototype Thermoelectric Pump Assembly

II. SNAP PRIMARY LOOP PUMPS

A. SYSTEM TRADE STUDIES

A number of trade studies have been performed at Atomics International on pumps and pumping systems for the SNAP programs, over the past 12 years. These studies were made on a variety of different types of ac and dc electromagnetic pumps. The conclusions drawn from these studies have been virtually unanimous (i. e., on the basis of the major criteria considered, such as weight, size, efficiency, reliability, and system integration, the dc-type pump is the optimum choice for the SNAP Reactor Systems). The relatively low hydraulic power requirements and type of power generally available from the SNAP systems certainly influenced such conclusions toward dc type pumps. With a permanent magnet, these pumps include such features as no moving parts, no windings to degrade, simplicity of design, and low fabrication costs. In the early studies and the early programs, the choice of dc permanent pump was further isolated to an integral-source-type pump, in which the power source (thermoelectric elements) was an integral part of the pump, as opposed to a pump using a separate power source. The latter type of pump was in common usage on many liquid metal test loops at Atomics International in the early 1960's. In later trade studies, the optimum choice of pump generally became the separate-source dc pump, as the technology of the compact thermoelectric module program ⁽¹⁾ advanced, and a special module, providing high current and low voltage, was developed. These trade studies are discussed in Sections III and IV of this report.

One exception, in which an ac pumping system was selected over a dc pumping system, was a NASA application for a ZrH Reactor - Brayton Cycle combined system test. ⁽²⁾ Although the dc pumping system was more efficient for this application, several factors, such as the lack of suitable low-voltage high-current power, space for the power conditioning equipment, and higher weight, caused by program redundancy requirements, weighed against it. The hydraulic pumping power requirements were also considerably higher than those of the previous SNAP Program applications.



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Figure 3. SNAP 10A dc Conduction Pump

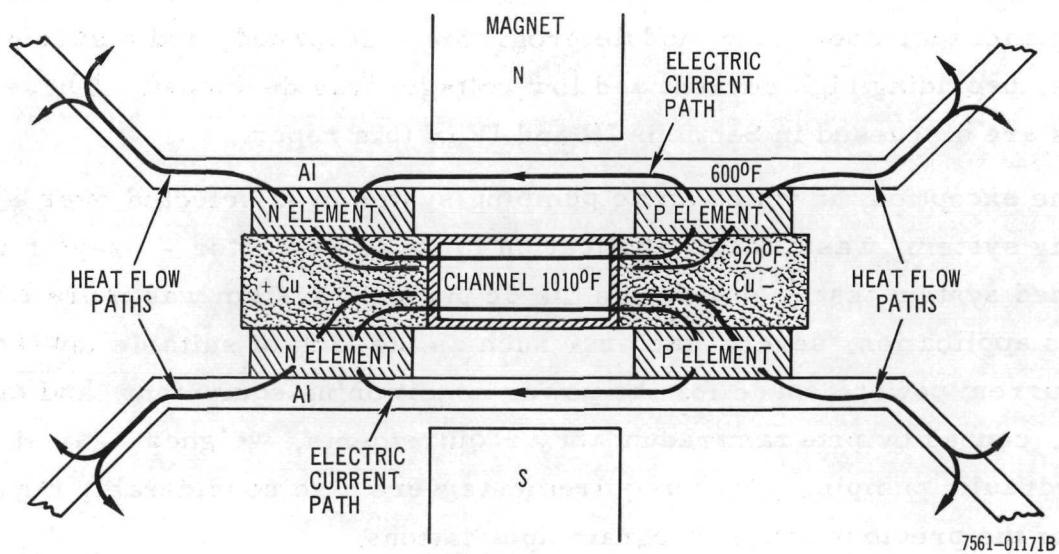


Figure 4. SNAP 10A Thermoelectric Pump Configuration Schematic

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B. PUMP DESIGN AND TESTS

Several types of dc pumps were designed, fabricated, and tested for the SNAP 10A, SNAP 2, and pump technology programs. The key SNAP Program pump design test activities leading to the development of the dual-throat pump are summarized in the following sections.

1. SNAP 10A Thermoelectric Pump

This pump⁽³⁾ was an integral-source dc conduction pump that circulated NaK coolant through the nuclear reactor core and the hot leg of the thermoelectric power converters of the SNAP 10A system. The pump was powered by its own PbTe thermoelectric converter elements, operating at $\sim 300^\circ\text{F}$ hot-to-cold junction temperature differential. The current from the converter, coupled with the field of the permanent magnets, produced ~ 7 w of hydraulic power. The pump was designed to produce a minimum of 13.2 gpm of NaK flow at 1050°F against a head of 1.3 psi.

The rectangular throat section of the SNAP 10A pump (Figures 3 and 4) was formed from Type 316 stainless steel tubing. Copper bus bars, brazed to the throat, also formed the hot leg of the thermoelectric pump power source. Large aluminum fins, coated on the radiative surface with a high-emittance coating, provided the cold sink for the thermoelectric converter. These fins also provided the return current path for the converters. The fins and the thermoelectric elements were mechanically attached to the copper bus bar. Materials to improve thermal and electrical contact were placed at the interface. Alnico-V magnets were mechanically attached to the permeable pole faces, which were electrically insulated from the throat. The structural assembly was designed to withstand the forces encountered during the launch of the SNAP 10A system on the Atlas-Agena.

A total of 41 of these pumps were tested extensively during the development and qualification phases of the SNAP 10A system. In addition to performance mapping, thermal cycling, and launch environment testing, endurance testing, up to 20,000 hr, was conducted on the pump as a component. Two pumps were also included in the 90-day nonnuclear operation tests of two SNAP 10A systems. Another pump operated successfully throughout the

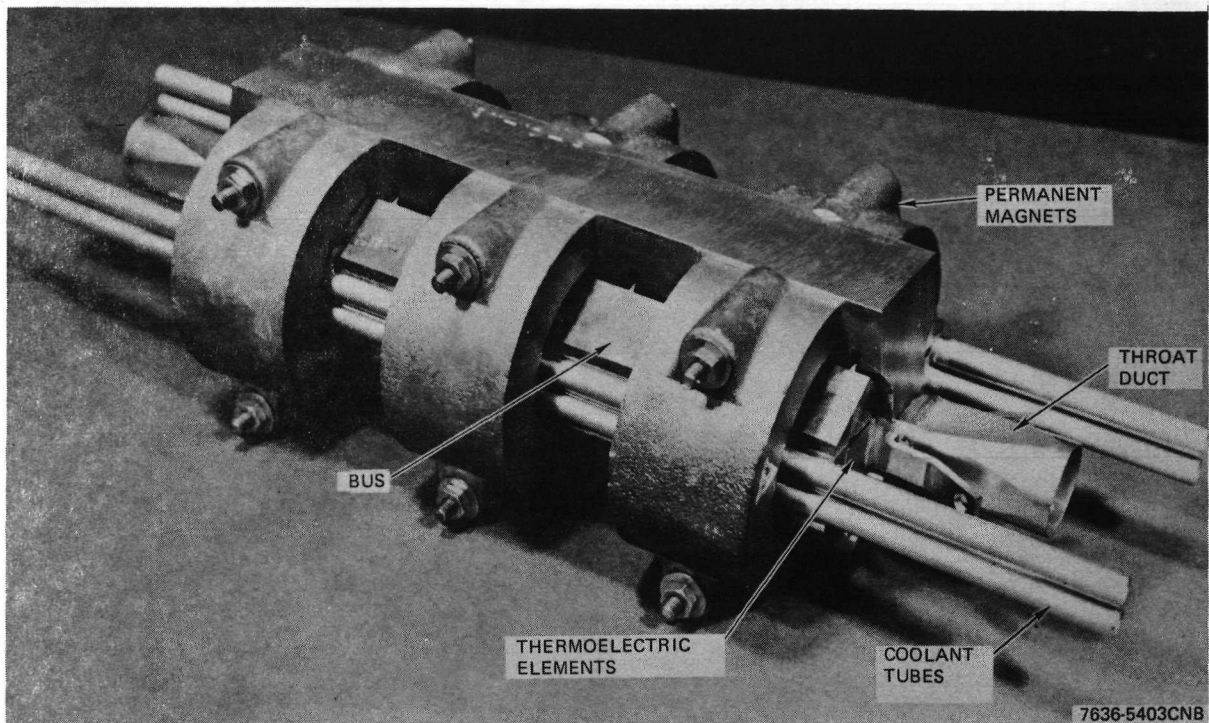


Figure 5. SNAP 2 Pump

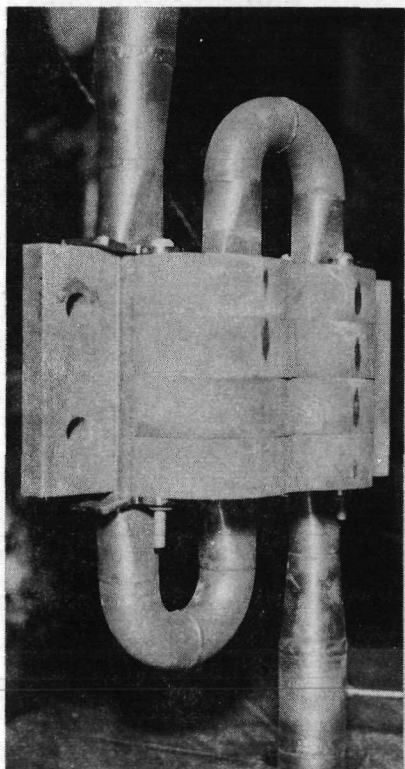


Figure 6. Three-Throat dc Pump

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10,000-hr nuclear ground test of the completed SNAP 10A system. Data received during the 43-day space flight operation of the SNAP 10A (FS-4) indicated that the pump performance exceeded design requirements.

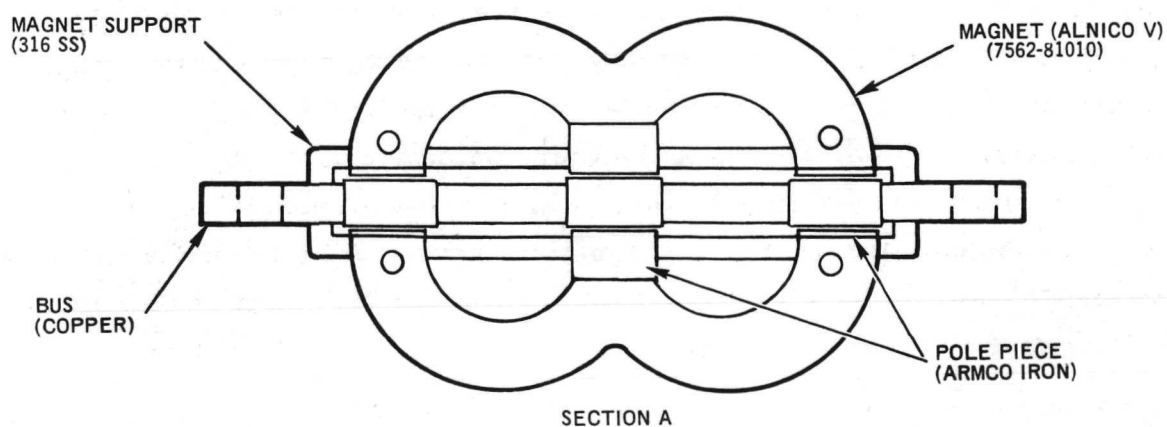
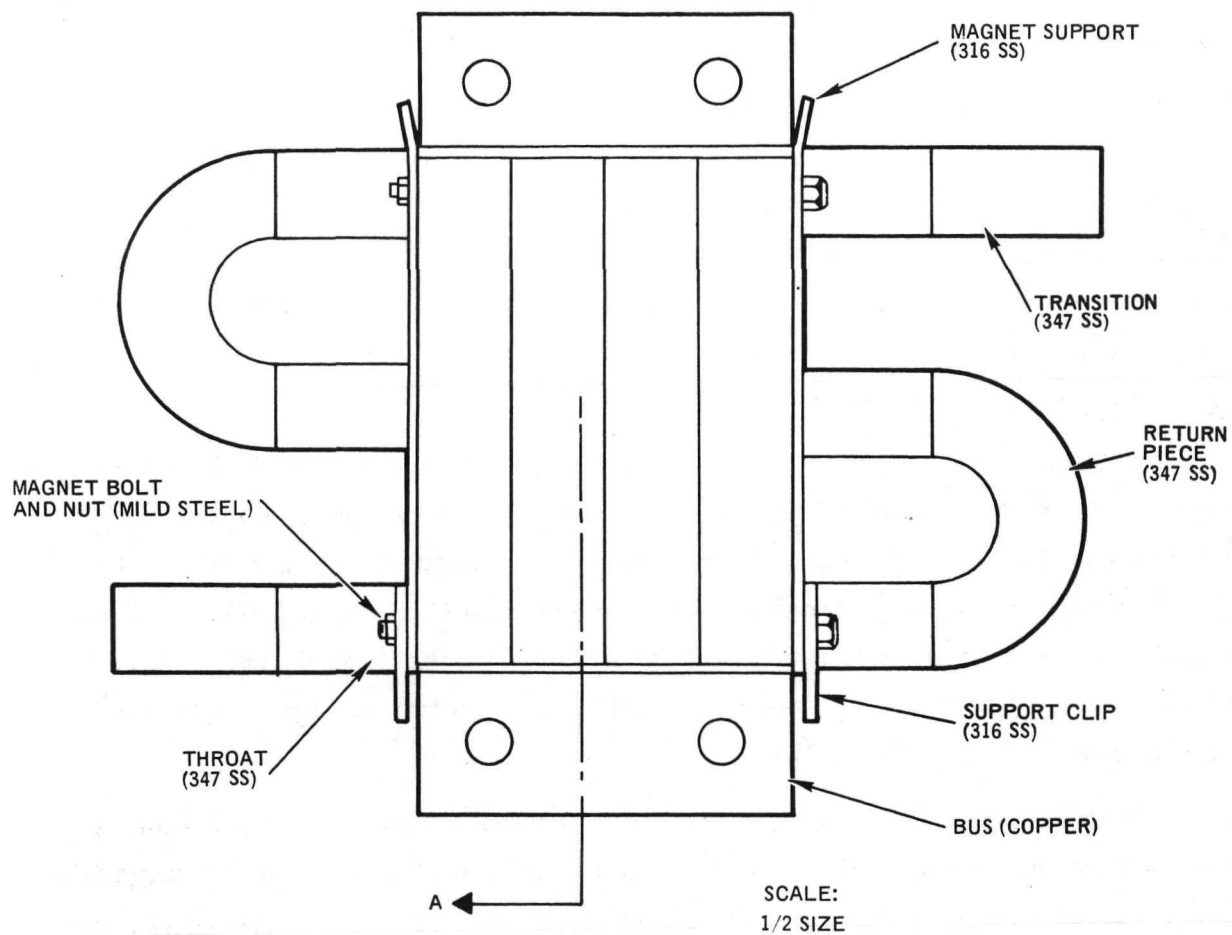
2. SNAP 2 Thermoelectric Pump

The dc conduction pump, Figure 5, designed for the SNAP 2 Mercury-Rankine system,⁽⁴⁾ was a modification of the SNAP 10A pump. The radiator of the SNAP 10A pump was replaced with coolant lines, through which mercury from the PCS was circulated. The mercury provided a uniform cold-leg temperature for the thermoelectric power source, and, in turn, was preheated prior to entry into the mercury boiler.

The original design of the SNAP 2 pump used the same PbTe converter materials as did the SNAP 10A pump. The mercury coolant lines were attached to each end of the return buses. The return buses and the thermoelectric elements were mechanically attached to the copper buses which were brazed to the throat. Because of the $\sim 1000^{\circ}\text{F}$ operational limitation on the PbTe material, the pump was designed to be located on the return side of the NaK coolant ($\sim 1000^{\circ}\text{F}$) to the reactor core.

The SNAP 2 pump design was later revised to use Chromel-constantan as the thermoelectric material. The higher operating temperature capability of these materials permitted the pump to be located on the outlet of the reactor core, which minimized stability problems during reactor-PCS startup. Also, the higher improved physical properties of these materials enabled the pump design to be simplified. The thermoelectric elements were brazed directly to the throat. The copper return buses which contained the coolant lines were brazed directly to the other end of the thermoelectric elements. The return buses were formed as a thin wide plate which passed through slots made in the Armco iron pole pieces of the magnetic circuit. Alnico-V magnets provided the magnetic field. The pump was designed for 1.2 lb/sec flow of NaK at 1200°F against a head of 1.05 psi.

Twelve pumps of this design were built and tested. Of these, four were endurance -tested for 2300 to 7500 hr each; the other ten accumulated a total of 18,000 hr. These tests included simulated reactor and PCS startups, and endurance testing at the design temperature of 1200°F .



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Figure 7. Triple-Pass Pump Schematic

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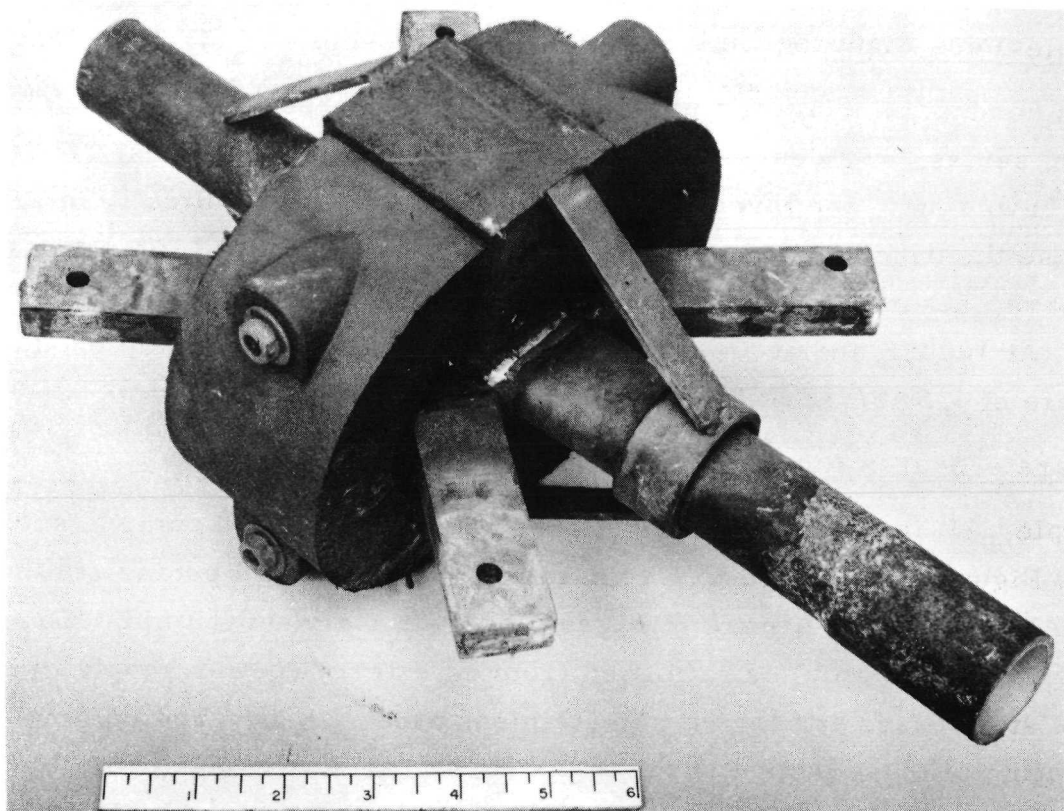
3. Triple-Pass Pump

A dc conduction pump (Figure 6) in which the current flowed through three throats in series, was designed, fabricated, and tested to demonstrate feasibility. In this unit, the three throats were connected hydraulically in series, to increase the head capacity. The three throats were brazed to sections of copper bars, Figure 7. Performance of this unit was within 10% of predicted results. At 1000°F and at an input current of 1000 amp, the pump produced a flow rate of 1.5 lb/sec at 2.4 psi with an efficiency of >24%.

4. Separate-Source Pumps

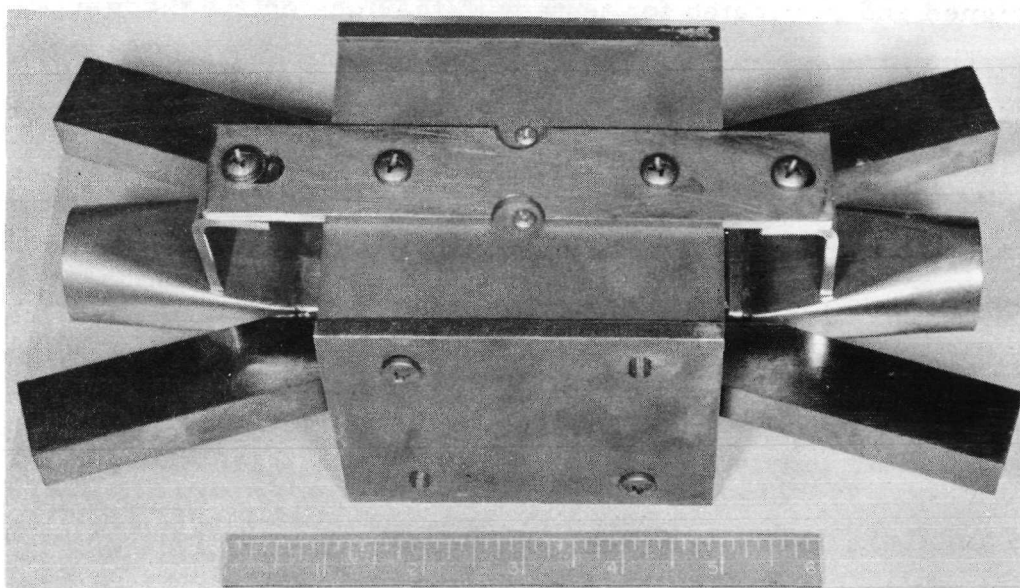
Simple, AI-designed, permanent-magnet, dc conduction pumps, such as shown in Figure 8, are used to circulate NaK, sodium, and potassium in the various AI test loops. Alnico-V magnets provide the magnet field. Controlled current, up to 2000 amp, is furnished from an external power supply to the stainless steel buses attached to the stainless steel throat. The nominal design rating of these pumps is 1.0 to 1.2 lb/sec at 2 psi head, with NaK temperatures up to 1300°F. Over 50 of these units have been used, with over 30,000 total hours of performance on individual pumps.

Two minimum-weight, single-throat, separate-source pumps, Figure 9, were designed and fabricated for tests with thermoelectric module power sources. The throats were made from 0.021-in. thick Hastelloy N sheet, and the inside dimensions were 1.21 by 0.32 by 4.5 in. in length. OFHC copper electrodes, 4.5 in. long, were brazed to the pump throat with NICORO 80 (81.5 Au, 16.5 Cu, 2.0 Ni) brazing alloy. Pump No. 1 used Alnico V as the magnet material, and Armco iron as the magnetic circuit material. Pump No. 2 used Columax (believed to be Alnico V-DG or V-7) magnets and Hiperco 27 as the magnetic circuit material, to achieve a lighter pump. Both pumps achieved comparable performance, such as a flow rate of ~ 1.3 lb/sec at 1.25 psi at 1060°F with 650 amp applied. Both pumps were tested in NaK loops for periods in excess of 300 hr at 1060°F, including a minimum of 5 thermal cycles to ambient. No change in performance or pump integrity was observed as a result of these tests.



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Figure 8. Test Loop Pump

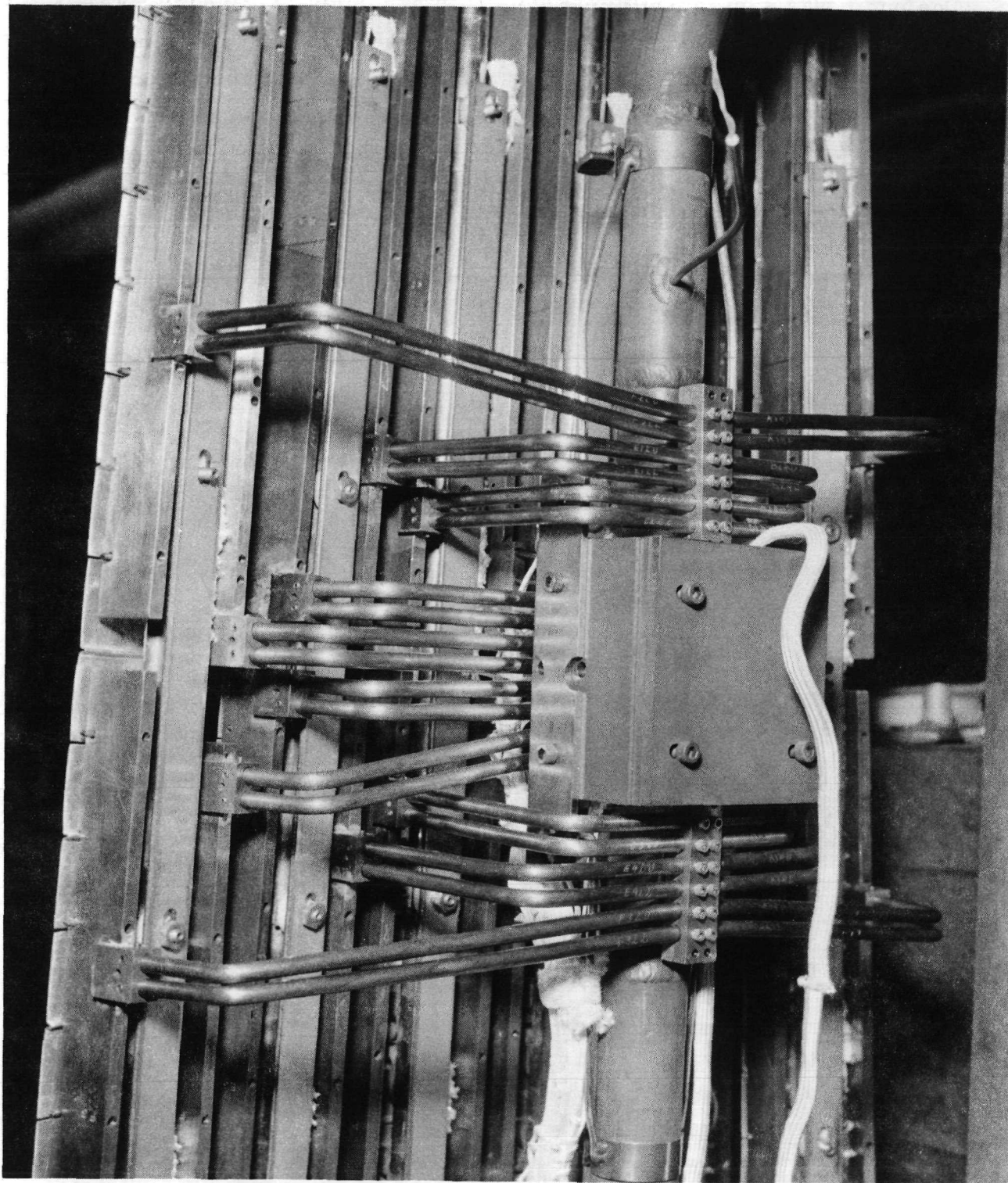


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Figure 9. Separate-Source Pump Assembly

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One pump was subsequently mated with an assembly of six each SNAP 10A direct-radiating thermoelectric modules, and tested for 3 days at module temperatures as high as 1200° F. This proof-of-principle test, conducted in a vacuum chamber, provided a flow rate of 1.7 lb/sec at 1.0 psi with a module assembly input current of 635 amp. Figure 10 shows the test configuration, in which heat was supplied to the modules with electrical cartridge heaters. The pump throat was connected to a NaK loop.



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Figure 10. Test Installation of Thermoelectric Module Assembly —
Separate-Source Pump

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III. DUAL-THROAT THERMOELECTRIC DEVELOPMENT PUMP

A dual-throat dc conduction pump was designed in GFY 1969 for a 25-kwe ZrH Reactor Thermoelectric system which required a 12 to 13 lb/sec flow rate in each of the two loops. This system was designed to use four dual-throat pumps in parallel, to provide the total required hydraulic pumping power. Prior to termination of this program in GFY 1970, sufficient parts were fabricated for two complete pump assemblies (Figure 11), and were put into controlled storage. During GFY 1970, the welding, brazing, and diffusion-bonding processes for this pump were also developed. In the latter half of GFY 1972, the development of these pumps was reinstituted, and assembly of these pumps was completed, as the hydraulic pumping power requirements for the 5-kwe Reactor Thermoelectric System were similar to the expected performance of these development pumps. Table 1 compares the design performance of the two pumping systems. The history of the thermoelectric development pump program is summarized in this section, and of the prototype pump is discussed in Section IV.

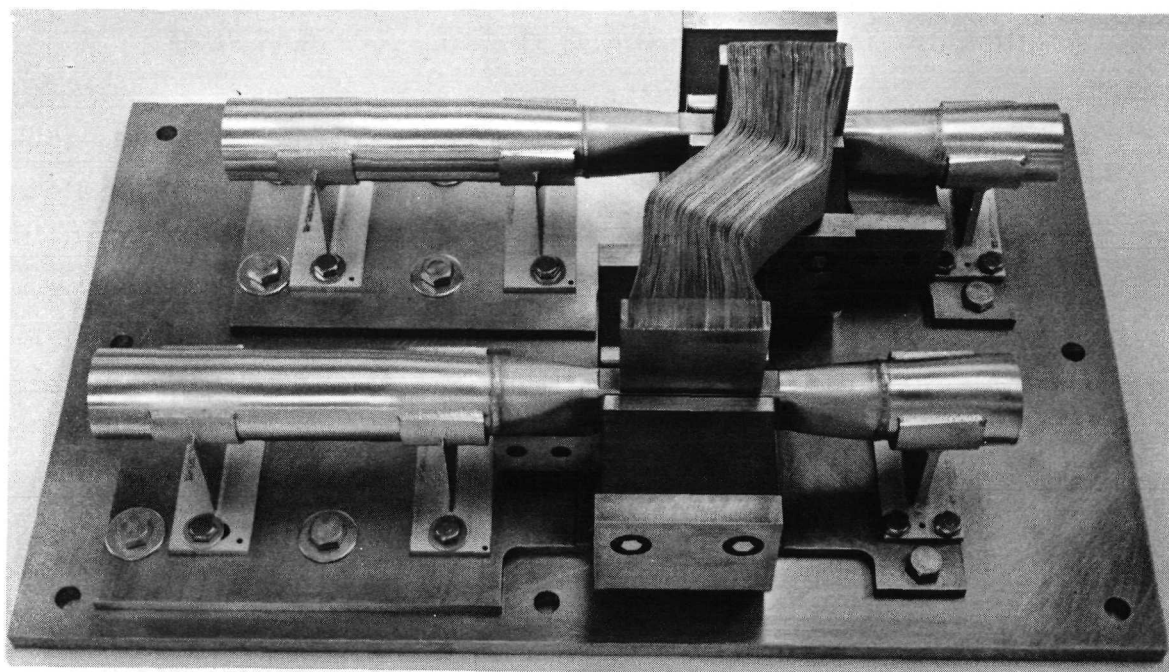
A. DESIGN AND ANALYSIS

1. Parametric Studies

Following the earlier trade studies, which concluded that the dual-throat separate-source pump was the best choice for the 25-kwe ZrH Reactor Thermoelectric system, parametric studies were performed to determine the optimum (minimum weight) size pumps for the system (Table 2), using a technique which was subsequently incorporated into the computer program discussed in the following section. A number of pump geometric parameters were investigated and pump weights were determined for these parameters.

This study was constrained by the criteria that:

- 1) Both throats would be dimensionally identical
- 2) Both throats would utilize identical electric current and magnetic flux
- 3) The pump power supply would be three Westinghouse pump converter modules, connected electrically in parallel.



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Figure 11. Thermoelectric Development Pump

TABLE 1

dc PUMP DESIGN REQUIREMENTS COMPARISON - BOL

	25-kwe System Development Pumps	5-kwe System Prototype Pump
NaK Flow Rate (lb/sec)	3.25/3.10*	4.87/3.01*
Pressure Rise (psi)	2.25/2.10	1.11/1.57
Pump Current (amps)	1800	1728
Flux Density (G)	2325	2505/2000
Voltage (v)	0.189	0.210
Temperature (° F)	1044/663	1059/589
Throat Dimensions (in.)		
Length	2.30	2.30
Height	0.50	0.60
Width	1.00	1.30

*Primary throat/secondary throat

TABLE 2

PUMP GEOMETRIC PARAMETERS

Parameter	Variable Range
Throat Width (in.)	1.0-2.0
Throat Height (in.)	0.3-0.65
Throat Length (in.)	2.0-5.0
Magnetic Flux (G)	1250-2800
Current (amp)	1500-2100

The results of this study provided a pump design with the parameters shown in Table 3.

TABLE 3

DEVELOPMENT PUMP DESIGN PARAMETERS

Parameter	Value
Throat Width (in.)	0.98
Throat Height (in.)	0.50
Throat Length (in.)	2.50
Magnetic Flux (G)	2350
Current (amp)	1800
Throat wall thickness (in.)	0.025

The calculated pump performance for this design is shown in Figure 12. Thermal shunting between the pump throats through the interconnecting bus was calculated at less than 500 watts.

2. Analytical Model

Fundamental equations describing dc thermoelectric pump performance were derived, and an analytical computer model for calculating a minimum-weight, separate-source dc pump system was developed. The basic configuration of a dc conduction pump is shown in Figure 13. The equivalent circuit for this pump is shown in Figure 14.

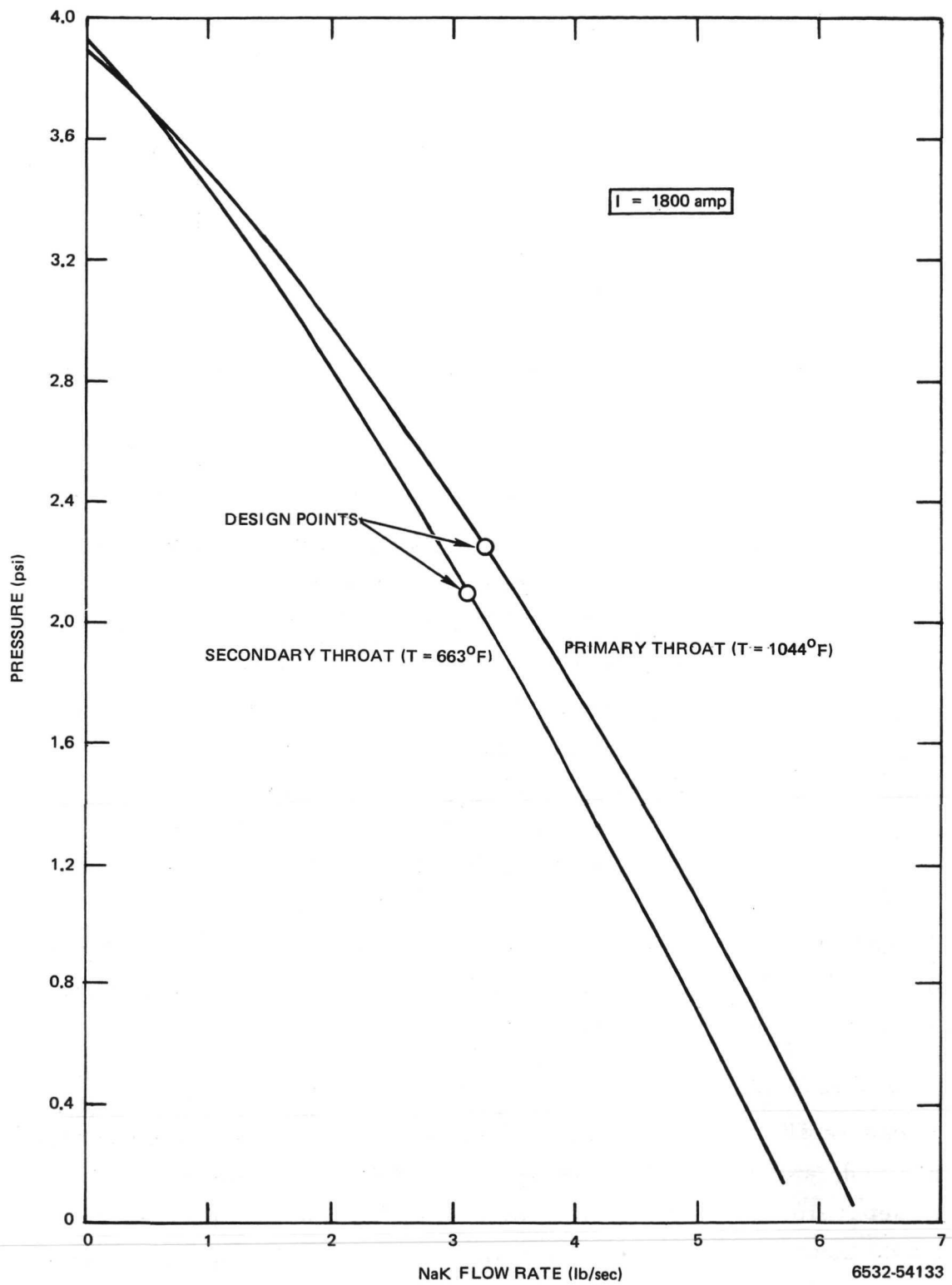
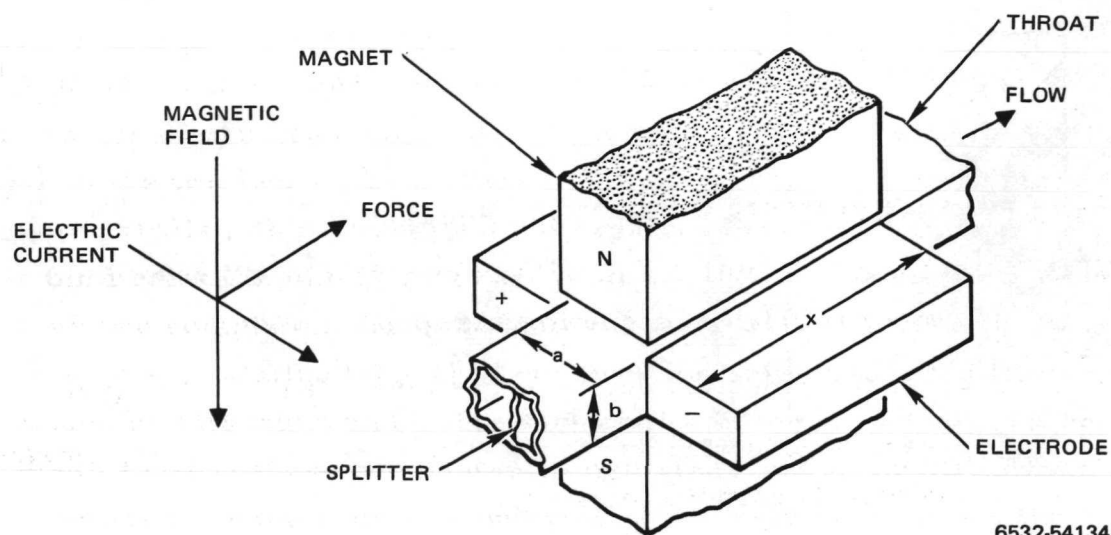
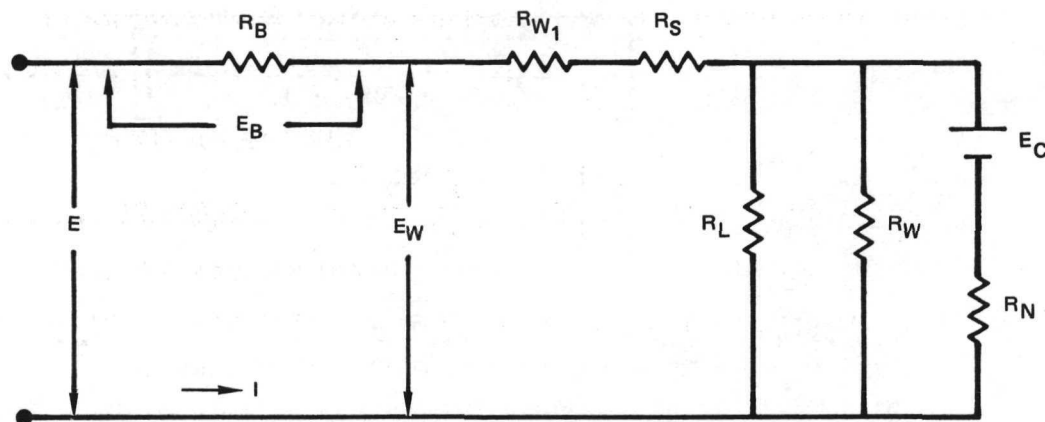


Figure 12. Development Pump Performance



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Figure 13. Basic Configuration of dc Conduction Pump



- I - TOTAL CURRENT (amp)
- E - VOLTAGE APPLIED TO BUS (mv)
- R_B - BUS RESISTANCE (Ω)
- R_{W1} - PERPENDICULAR (TO CURRENT) THROAT WALL RESISTANCE (Ω)
- R_L - BYPASS LEAKAGE CURRENT RESISTANCE (OUTSIDE THROAT) (Ω)
- R_W - PARALLEL (TO CURRENT) THROAT WALL RESISTANCE (Ω)
- R_S - SPLITTER PLATE RESISTANCE (Ω)
- R_N - NaK (IN THROAT) RESISTANCE (Ω)
- E_C - INDUCED BACK emf (mv)
- E_W - VOLTAGE DROP OF THROAT (mv)
- E_B - VOLTAGE DROP OF BUS (mv)

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Figure 14. dc Pump Equivalent Electrical Schematic

The net pressure developed by a dc conduction pump can be expressed as:

$$\Delta P = M_1 G I - M_2 G^2 Q - M_3 G^2 Q - M_4 Q^2, \quad \dots\dots (1)$$

where:

$M_1 G I$ = gross pressure developed by pump (psi)

$M_2 G^2 Q$ = pressure reduction due to back emf developed in the fluid moving through a magnetic field (psi)

$M_3 G^2 Q$ = pressure reduction due to eddy current (end) losses (psi)

$M_4 Q^2$ = pressure reduction due to hydraulic losses in throat, entrance, and exit transitions pieces (psi)

G = magnetic flux density in throat (G)

Q = NaK flow rate (lb/sec)

$$M_1 = 5.714 \times 10^{-7} / b \left[\frac{R_W R_L}{R_W + R_L} / \left(\frac{R_W R_L}{R_W + R_L} + R_N \right) \right], \quad \dots\dots (2)$$

$$M_2 = 3.687 \times 10^{-14} / \left[\rho_N b^2 \left(\frac{R_W R_L}{R_W + R_L} + R_N \right) \right], \quad \dots\dots (3)$$

$$M_3 = 0.959 \times 10^{-14} / (\rho_N b \sigma_N), \quad \dots\dots (4)$$

$$M_4 = \left[K_1 + K_2 (1 - m)^2 + \frac{2 f (a + b) x}{ab} \right] \frac{1.3 \times 10^{-3}}{\rho_N a^2 b^2}, \quad \dots\dots (5)$$

where:

ρ_N = resistivity of NaK (Ω -in.)

σ_N = density of NaK (lb/in.³)

a = throat width (in.)

b = throat height (in.)

- x = throat length (in.)
- K_1 = entrance loss coefficient (dimensionless)
- K_2 = exit loss coefficient (dimensionless)
- m = ratio of throat to pipe size (dimensionless)
- f = friction factor (dimensionless)

The pump weight included the magnets, yoke, pole pieces, throats, NaK, and structural support. The magnet length is determined on the basis of the flux density required and the gap across the throat. Standard equations, supplied by magnet manufacturers, are used to calculate magnet length. The length and width of the throat determine the cross-sectional area of the magnet face, and the overall size of the magnet determines yoke, pole piece, and structural support dimensions and weights.

Calculation of a pump configuration for a particular set of requirements is an iterative process, using many combinations of dimensions, flux density, and currents, to find the best design (minimum pump weight, minimum pump system weight, maximum efficiency, etc.). For the development pump, which had two throats of identical dimensions connected in series electrically, this required separate calculations of the respective throat temperatures, as M_1 , M_2 , M_3 , and M_4 are all temperature dependent. It was obvious that these calculations could best be performed by a computer, so an analytical computer model was established.

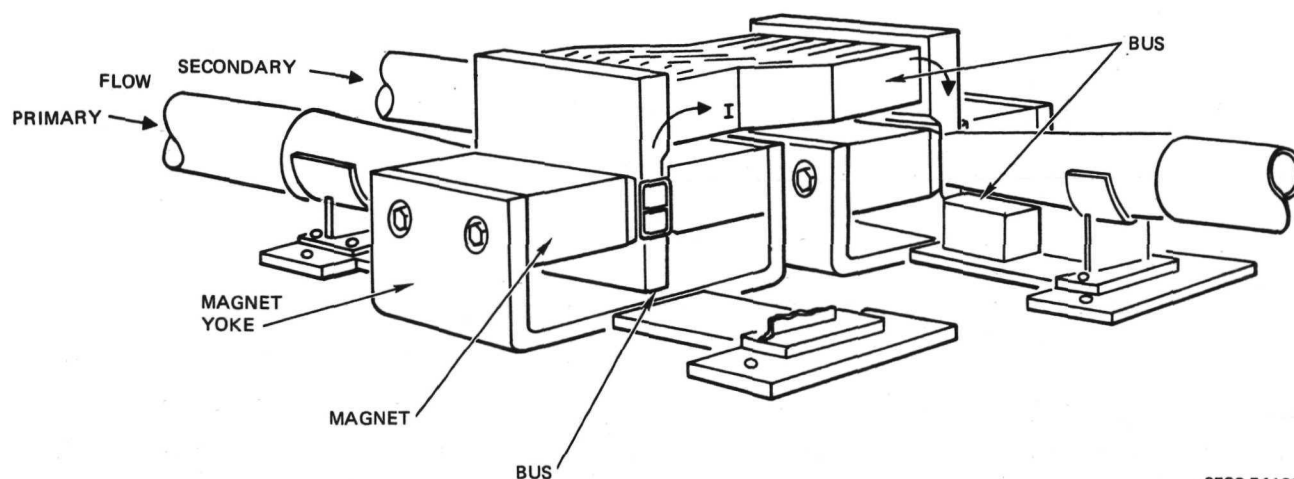
This code is discussed in greater detail in Reference 5.

3. Design Description

The configuration of the development pump was as shown in Figure 15. The principal dimensions are listed in Table 4.

The materials of construction are as follows:

Throats, diffusers, supports	Type 316 stainless steel
Magnets	Alnico V-7
Bus	OFHC Copper
Yoke	Armco Iron
Pole Pieces	Hiperco 27



6532-54136

Figure 15. Dual-Throat NaK Pump Assembly

TABLE 4

DEVELOPMENT PUMP THROAT DIMENSIONS

Throat Width (in.)	0.98
Throat Height (in.)	0.50
Throat Length (rectangular section) (in.)	3.00
Bus Length on Throat (in.)	2.30
Bus Width on Throat (in.)	0.55
Throat Wall Thickness (in.)	0.030
Splitter Length (in.)	3.00
Splitter Thickness (in.)	0.20

The surface of the pole piece facing the throats was coated with alumina to provide electrical isolation, and the flexible bus was covered with low-emissivity gold-molybdenum foil to reduce heat transfer from the bus to the magnets and to the surrounding environs.

4. Stress Analysis

Three areas of the development pump design were evaluated to the requirements of the ASME Section III Nuclear Code and the High Temperature Code Case 1331-5. The areas studied included the copper bus - stainless steel braze joint, the throat flexible supports, and the stainless steel throat. The throat bus braze joint study indicated that the cyclic life of this joint would exceed 50 thermal cycles. However, because of uncertainties in the property data for the materials at this joint, this study recommended thermal cyclic tests to establish such limits. Several such tests were started prior to program close-out, and are reported in Section III-C. Studies of the flexible throat support and of the throat indicated that both would withstand 50 thermal cycles and the expected operating stresses with adequate design margin.

Prior to installation of the development pump into the NaK test loop, a structural evaluation of the thermal loads on the pump was performed. This study indicated that the NaK inlet lines to the pump required restraints, except in the axial direction (direction of NaK flow), and that the brackets following the pump throats be firmly attached, so that their support base could not move axially. All other portions of the loops in the vicinity of the development pump were supported in a flexible manner, from either spring hangers or nonrigid floor-mounted supports. Installation of the pump in the test loop was performed with these restrictions.

B. CRITICAL FABRICATION PROCESSES

The critical fabrication areas of the development pump assembly were the pump throat with its splitter plate, and the formation and attachment of the flexible interthroat bus assembly to the throats.

1. Throat With Splitter Plate

The throat assembly is a welded assembly of the center section (with a rectangular pumping section and partial transitions to the circular inlet and outlet pipes) and the two transition ends, as shown in Figure 16. The center section is made from a circular tube which is progressively reworked, with

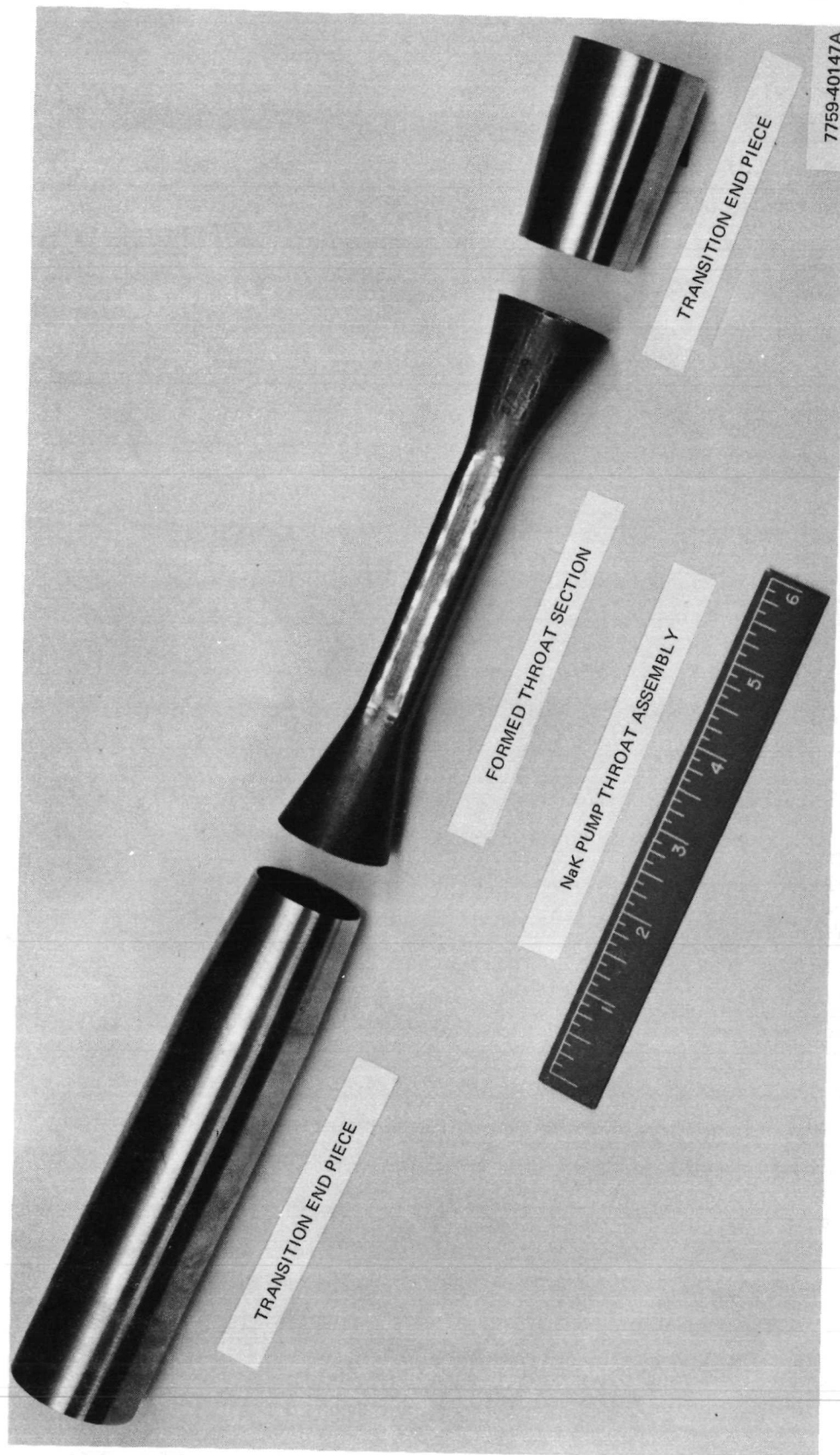


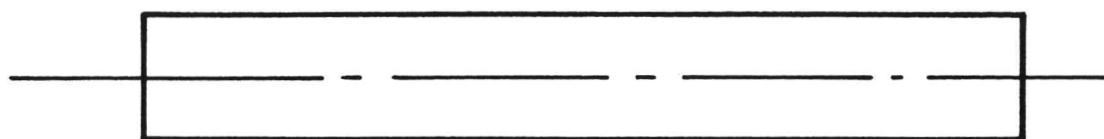
Figure 16. Fabrication of Typical Throat Section

minimum material stretching, to the final configuration, as shown schematically in Figure 17. The welding of the splitter plate to support the thin side walls, and the machining of the walls to the final thickness, is shown schematically in Figure 18.

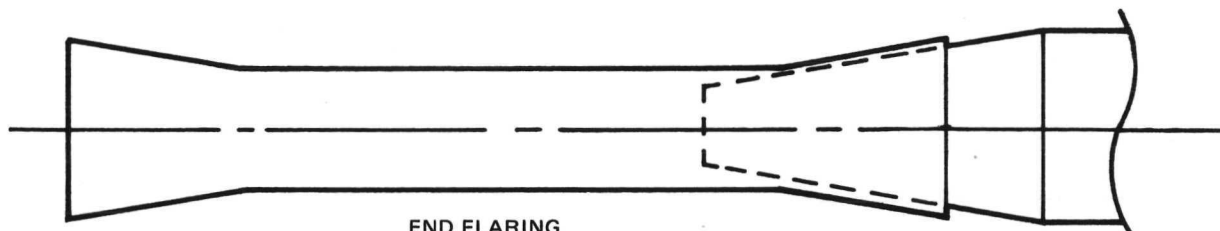
Extensive efforts were required to develop an acceptable method of welding the splitter plate within the throat. The initial attempt to electron beam weld the blind splitter from the outside of the throat (Figure 19) failed to consistently produce welds which were free from "built-in cracks" in the high-stress junction between the splitter and the throat walls. The problem was traceable to an inaccuracy in locating the splitter plate within the throat, and controlling the electron beam during the welding. The final method was to slit the throat walls, insert the splitter through the slit, and TIG weld the visible splitter to the wall (Figure 20). Because the splitter is visible during the weld setup, it was possible to locate and control the weld head accurately enough to repeatedly produce structurally acceptable welds.

2. Flexible Bus Fabrication and Brazing

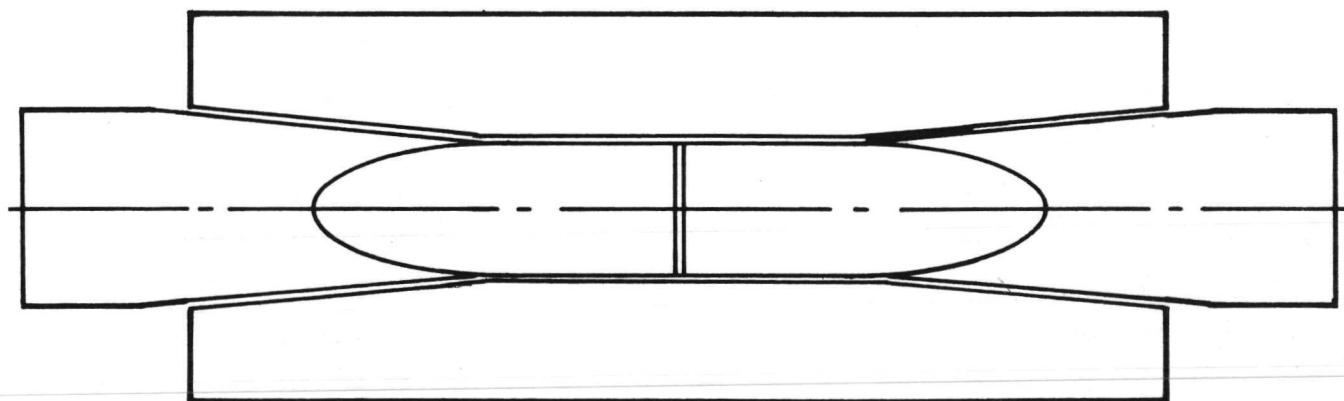
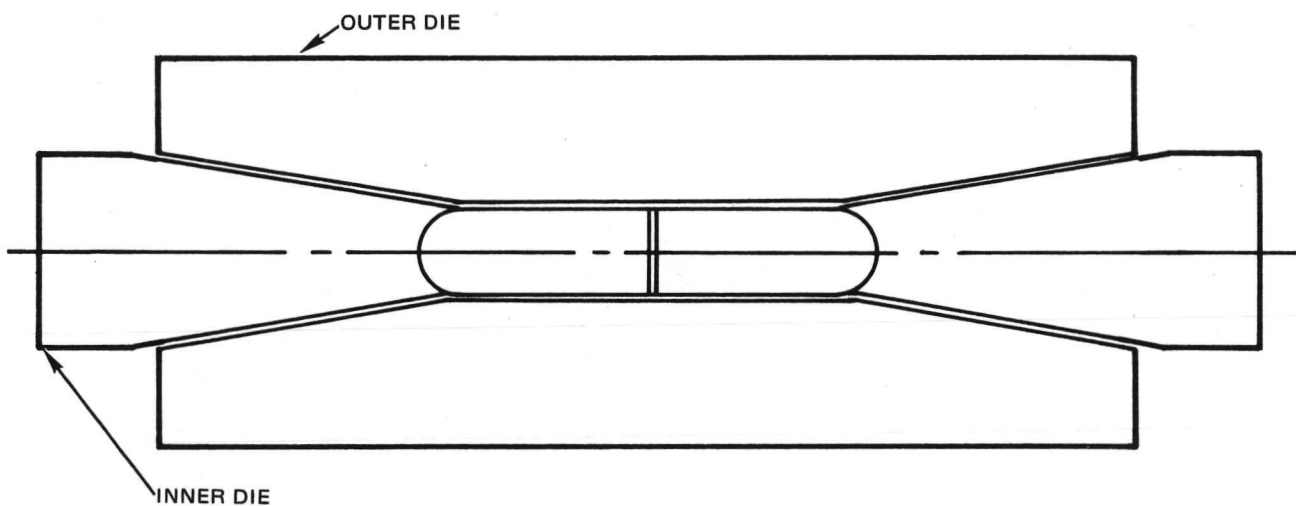
The flexible bus, to absorb the differential expansion between it and the two throat locations, is made up of multiple, jogged, thin copper strips. After some initial trials to form the bus assembly by brazing the strip ends to end spacers, a diffusion bonding technique of bus assembly fabrication was developed. As shown schematically in Figure 21, the ends of the multiple strips are diffusion bonded, under heat and temperature in vacuum, to the end spacers to form solid ends. Subsequently, these solid ends are machined to the final dimensions, and brazed to the two throats simultaneously with the solid copper input and return buses. The setup for this brazing operation is shown on Figure 22. This diffusion-bonding method eliminated the need to select a second high-temperature braze material with slightly higher brazing temperature to form the bus assembly. The earlier problems of voids being created in the flexible bus-to-throat bond joint by the wicking action of the interstrip braze was also eliminated. The excellent metallurgical joint between the components of the flexible bus, and between the bus and the throat, is shown on Figure 23.



STRAIGHT TUBE

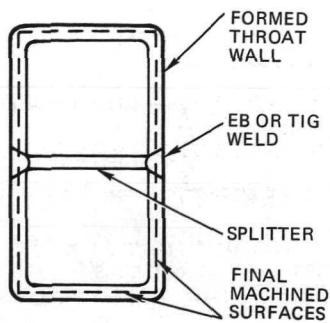


END FLARING



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Figure 17. Forming Throat Center Section



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Figure 18. Throat Splitter Welding and Final Machining

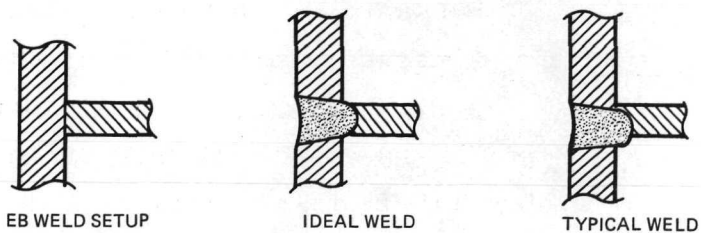
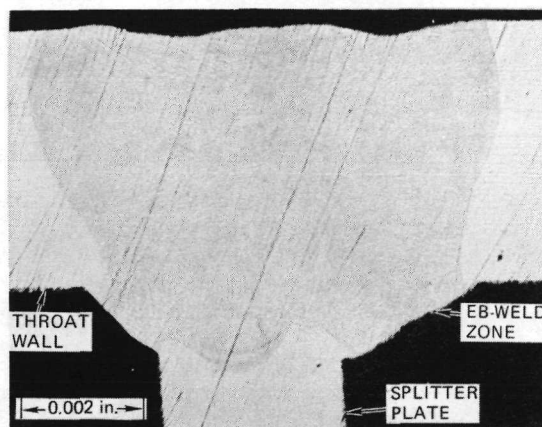


Figure 19. EB Welding of Splitter Plate



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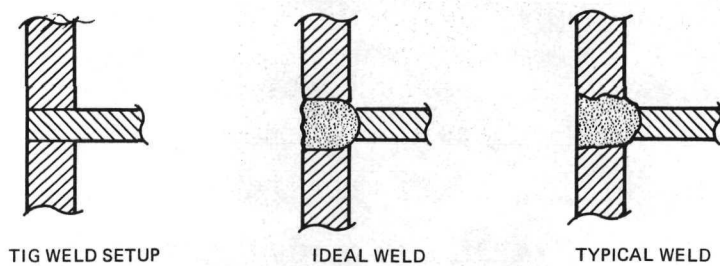
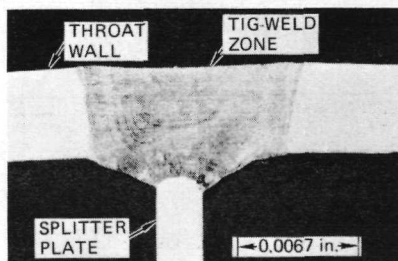
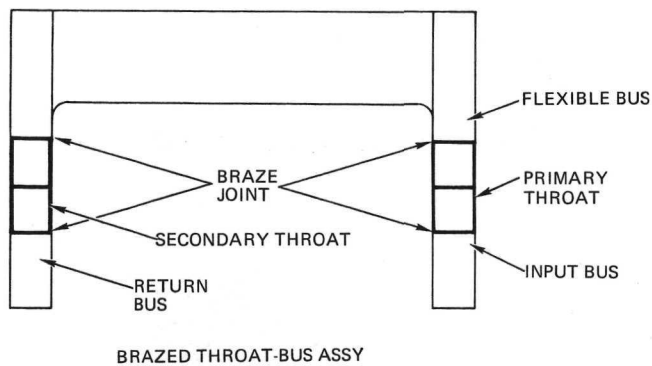
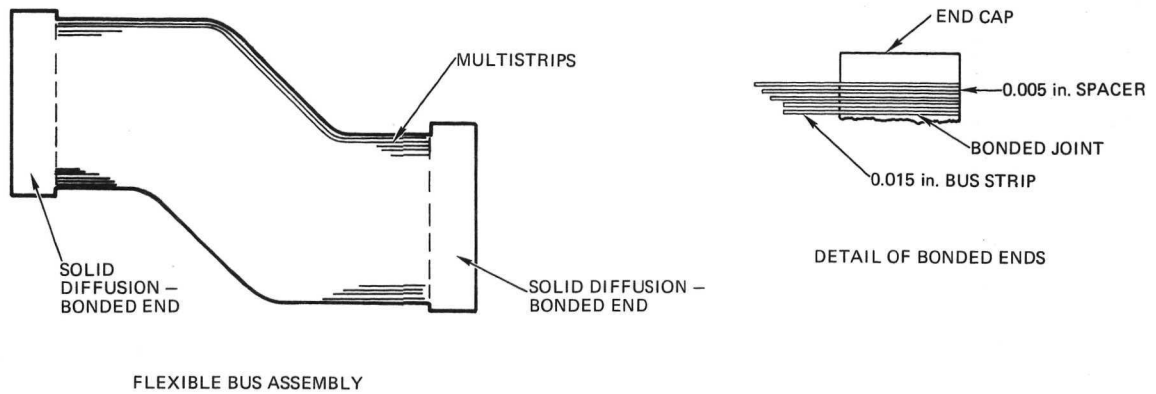


Figure 20. TIG Welding of Splitter Plate



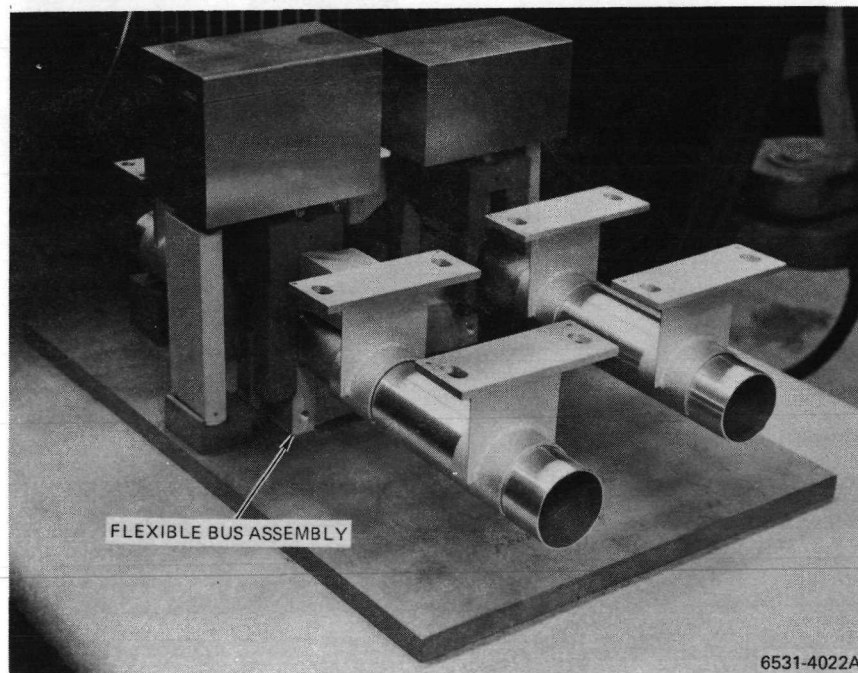
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Figure 21. Diffusion-Bonded Flexible Bus



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Figure 22. Bus-to-Throat Brazing Setup

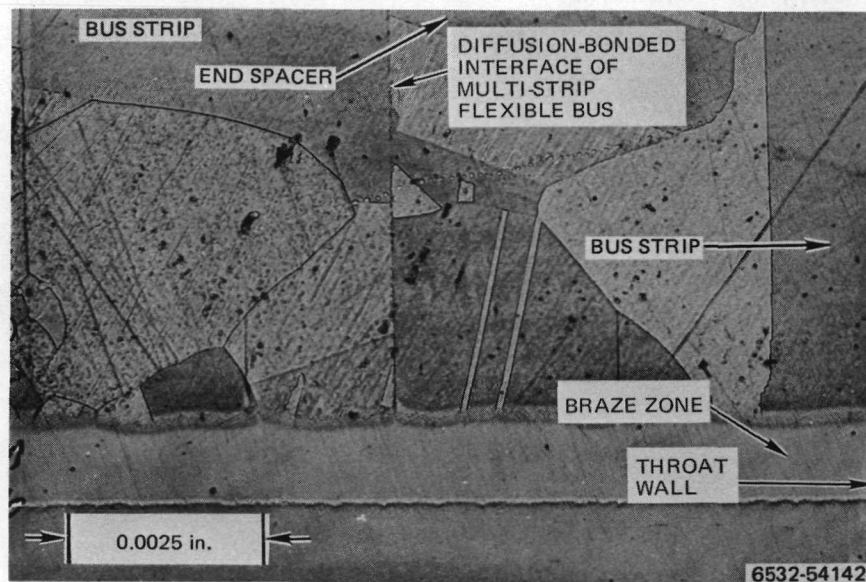


Figure 23. Flexible Copper Bus to Stainless Steel Throat Braze Joint

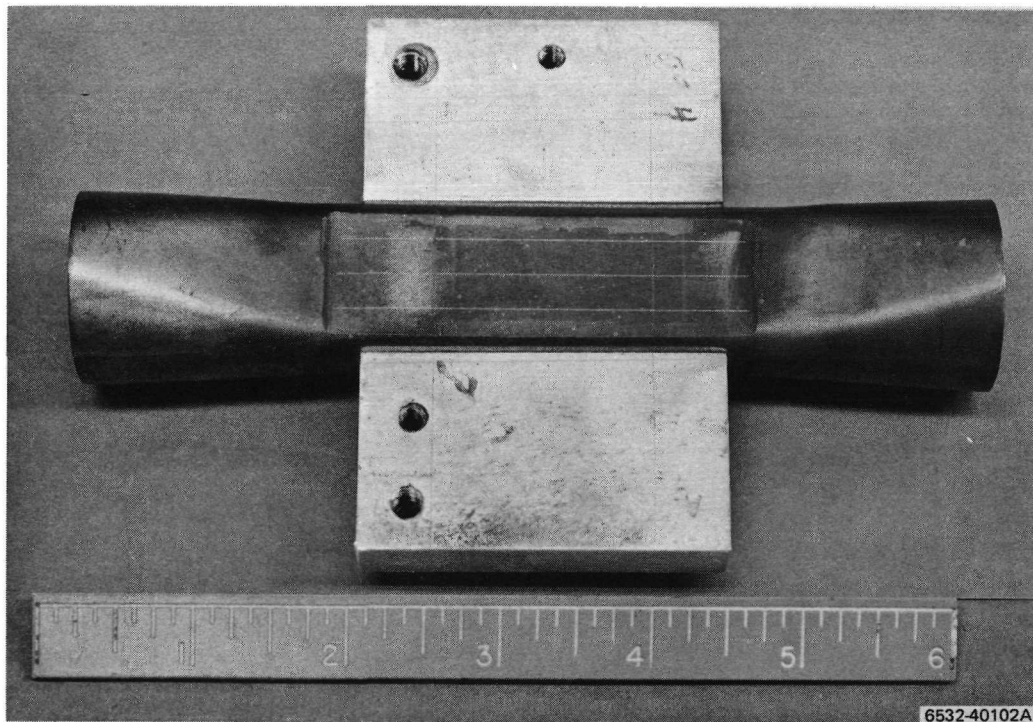


Figure 24. Pump Throat Assembly No. 004

TABLE 5

THERMAL CYCLE PROGRAM FOR
SEMI-PROTOTYPE THROAT SPECIMENS
(Nicoro 80 Braze Alloy)

	S/N 001	S/N 002	S/N 003	S/N 004
Nominal Wall Thickness (mils)	15	25	25	25
Splitter Plate	Yes	Yes	No	No
Peak Temperature (°F)	1100	1100	1200	1200
Ambient (Nominal) (°F)	100	100	100	100
Number of Cycles	50	50	50	50

C. BUS-THROAT VERIFICATION TESTS

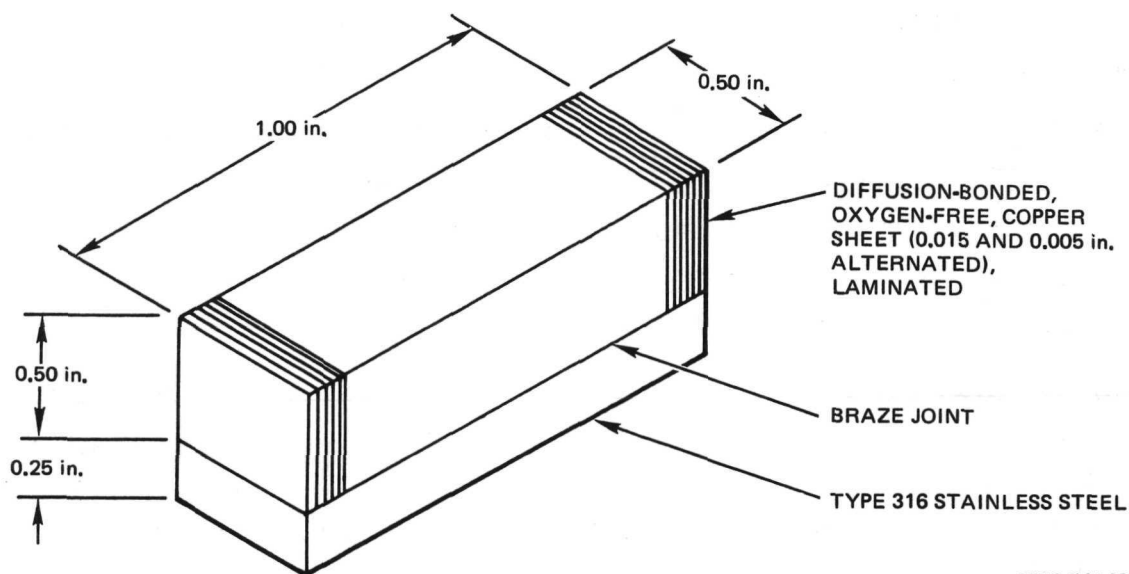
A test program was conducted to establish braze joint lifetime for the bus-throat interface. These tests included:

- 1) Thermal cycle testing of the semi-prototype throat assemblies (Figure 24) between 1100 or 1200° F and ambient, to identify any tendency toward thermal ratcheting or other loss of pump throat dimensional stability, electrical conductivity, or mechanical strength, particularly in the braze regions (see Table 5).
- 2) Thermal aging of brazed joint diffusion couple specimens (Figure 25), at temperatures of 1100 to 1600° F and times of 60 to 960 hr (see Table 6), to identify any tendency toward diffusion-related loss in long-time joint strength and integrity (e. g. , through embrittlement and/or void formation), including experimental verification of diffusion rates of critical braze constituents — the high (1600° F) test temperature permitted accelerated testing.

Candidate brazes were Nicoro 80 (Western Gold & Platinum, 81.5 Au - 16.5 Cu - 2 Ni, solidus — 1670° F, liquidus — 1697° F) and Gemco (Western Gold & Platinum, 88 Cu - 12 Ge, solidus — 1508° F, liquidus — 1769° F). Nicoro 80 was the primary braze candidate, and Gemco was the backup braze candidate. The throat assemblies were all brazed with Nicoro 80. The results of these tests are summarized in the following sections.

1. Thermal Cyclic Tests

A total of 50 thermal cycles were performed on two throat assemblies at 1100° F and two assemblies at 1200° F. The peak cycling rates did not exceed 15° F/min. Pre- and post-test dimensional measurements were made on each throat assembly, and resistance across each throat was measured at the end of every 5 thermal cycles (at operating temperature and at ambient). There were no significant changes in electrical resistance, dimensions, or appearance of the specimens, as a result of these tests.



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Figure 25. Schematic for Diffusion Couple Test Specimens

TABLE 6

THERMAL AGING PROGRAM FOR
DIFFUSION COUPLE TEST SPECIMENS
(Nicoro 80 and Gemco Braze Alloys)

Temperature (° F)	Time (hr)			
	60	240	960	Spares
1600	1	1(1)	1	1
1400		1(1)	1	1(1)
1200		1(1)	1	2
1100			1	2

() Gemco Braze

2. Thermal Aging Tests

The diffusion couple test specimens were vacuum encapsulated in Pyrex tubes, and placed on test at 1100, 1200, 1400, and 1600°F, per Table 6. At the end of the aging period, each specimen was visually examined, removed from the capsule, and sectioned for microscopic examination of the as-polished and the etched brazement. Micrographs of the pre- and post-test Nicoro 80 brazements showed them to be sound, with good wetting of both base metals, and no Kirkendall void development in the braze region, through 960 hr at 1600°F. Electron microprobe analyses showed no detectable diffusion of the gold into the stainless steel, but appreciable gold diffusion into the copper, as would be expected. From the microprobe data obtained on gold diffusing into copper, a set of curves (Figure 26) were generated, showing gold penetration at temperature between 1050 and 1600°F. Performance of this braze joint under mission conditions is expected to be excellent.

Micrographs of the (alternate) as-fabricated Gemco (88 Cu - 12 Ge) brazements showed limited braze-region porosity, mostly at the braze-to-copper interface, and a new phase at the braze-to-stainless interface. Electron microprobe analyses showed this phase to be germanium-rich. During thermal aging at 1600°F for 240 hr, most of the dissolved germanium in the braze region diffused into the copper base metal, but not into the stainless steel, and there was no apparent movement of germanium into or out of the new phase at the braze-to-stainless interface, nor did the grain size or appearance of this new phase change. There was no appearance change in the braze region of the thermally aged specimens, even at 1600°F — a slight surprise, considering an initial brazement solidus of 1508°F. Physical performance of this braze joint under mission conditions could be satisfactory; but mechanical performance cannot be predicted without further mechanical testing, because of the extent of the new phase at the stainless-to-braze interface.

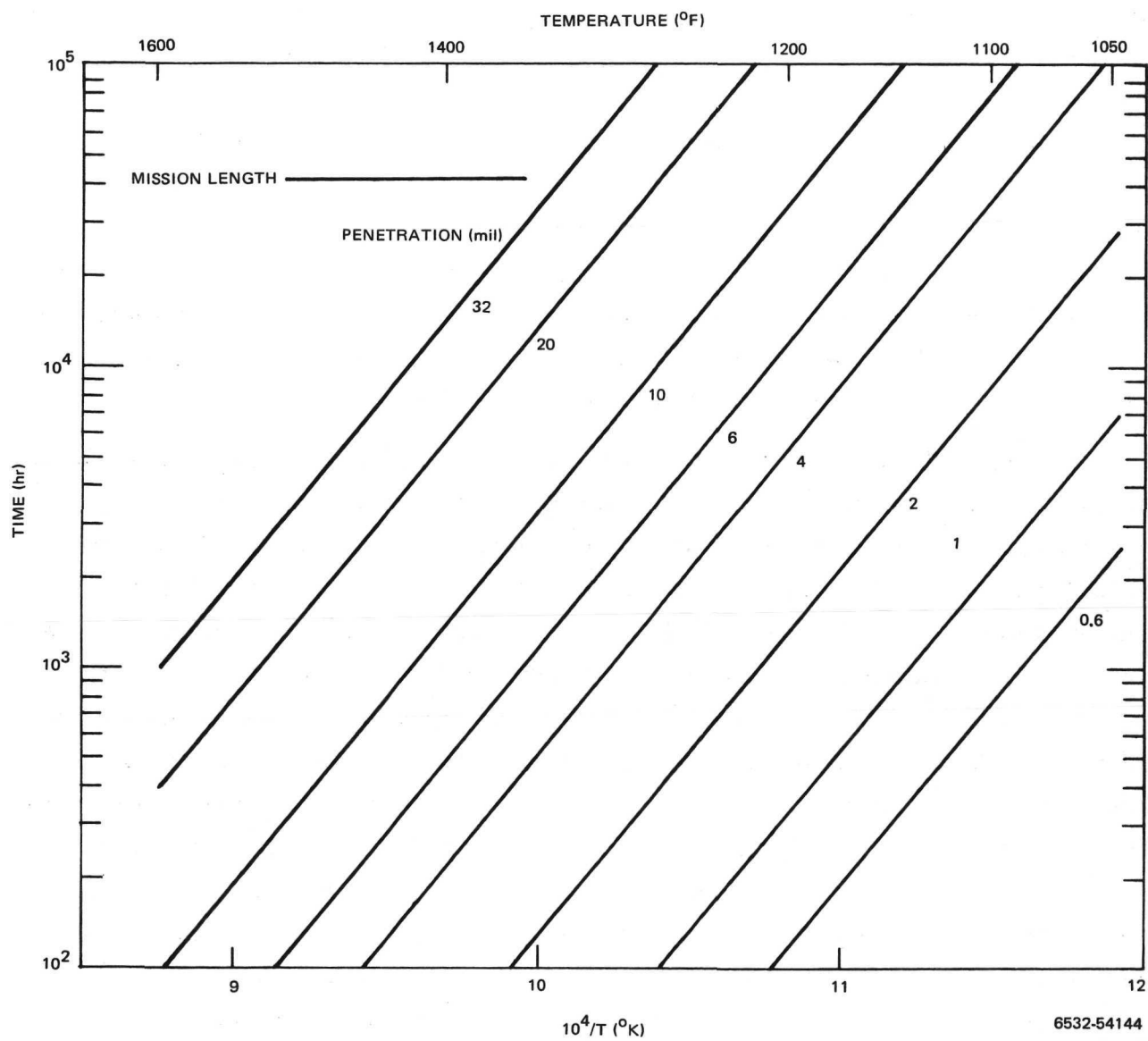


Figure 26. Predicted Penetration of Gold Into Copper

D. PUMP PERFORMANCE TESTS

1. Test Description

a. Test Facility

Testing of the development pump was performed in the power converter assemblies (PCA) NaK test loop installation in Building 023, Santa Susana. Table 7 lists the overall performance characteristics of this loop and Figure 27 presents a flow schematic for the major loop components. Figures 28 and 29 show the PCA loop, without and with thermal insulation, prior to the test loop modifications. This loop was designed to provide minimum thermally induced stresses on a rigidly supported test item.

b. Test Installation

The development pump was installed in the PCA loops, as shown in Figures 30 and 31, with the pump rigidly supported to the vacuum chamber cover. The piping was supported in a flexible manner to permit axial movement in the direction of NaK flow, and rigid support in the other directions. In the foreground of Figure 30 is shown the vacuum chamber, cover, and dc pump power supply, with the pump installed in the loops. The uninsulated portions of the loop in Figure 31 show the modifications made to the loop for the test. Figure 32 shows the thermocouples and voltage taps installed on the pump and immediately adjacent to it. Additional instrumentation included the voltage taps located on opposite sides of the piping close to the throat for measuring flow, and the immersion thermocouples and pressure sensors shown in Figure 33. Current was measured with a calibrated current shunt installed in the current bus to the external dc power supply, and flow was measured with the loop EM flowmeters. All data except the vacuum chamber pressure were obtained with a digital data logger, capable of a maximum rate of ~ 4 data points/sec. These data were acquired on punched tape, and input to a time-share computer program which converted the signals into engineering units and computed selected performance parameters, such as flow, pressure, power, efficiency, etc.

TABLE 7
PCA TEST LOOP CHARACTERISTICS

	Supply Loop	Rejection Loop
Maximum Operating Temperature (° F)	1300	800
Heater Power (kw)	300	150
Heat Rejection (at 550° F) (kw)	--	250
Flow (gpm)	50	50
Operating Pressure (psig)	30	30
Transient Capability		
Rate of Temperature Increase (° F/min)	30	15
Rate of Temperature Decrease (° F/min)	60	30

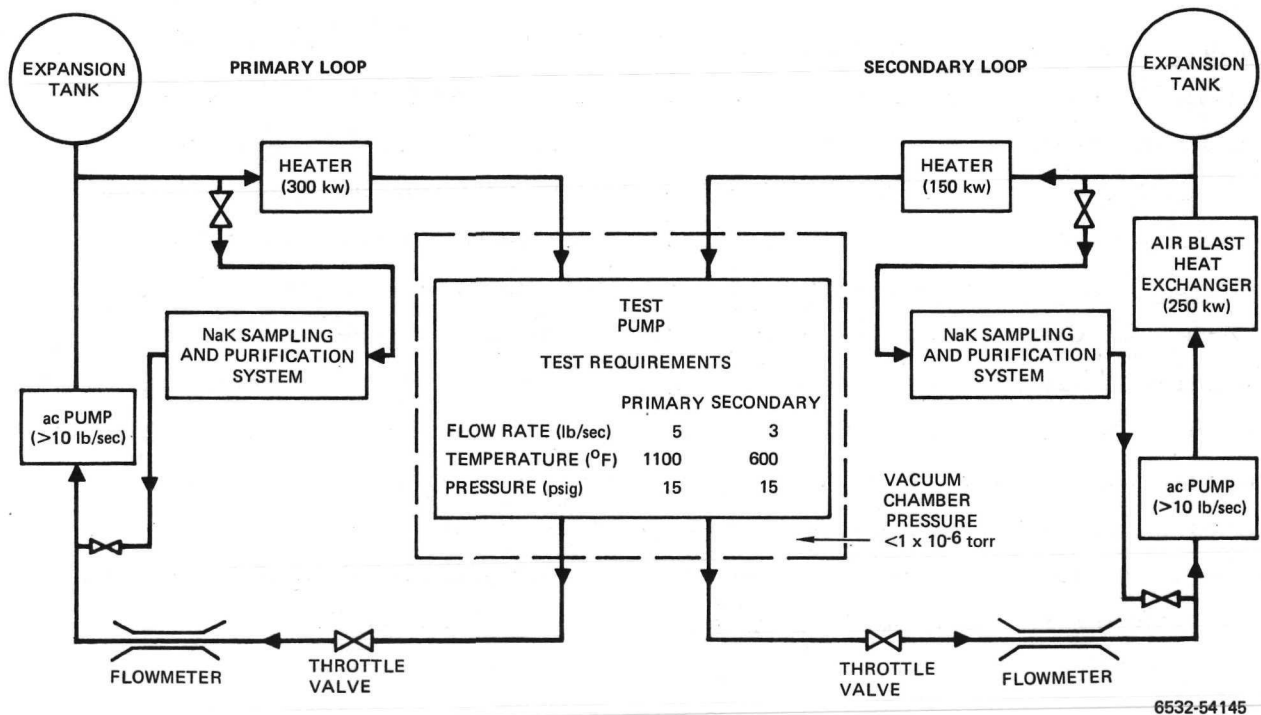


Figure 27. Flow Schematic - Pump Test Loop

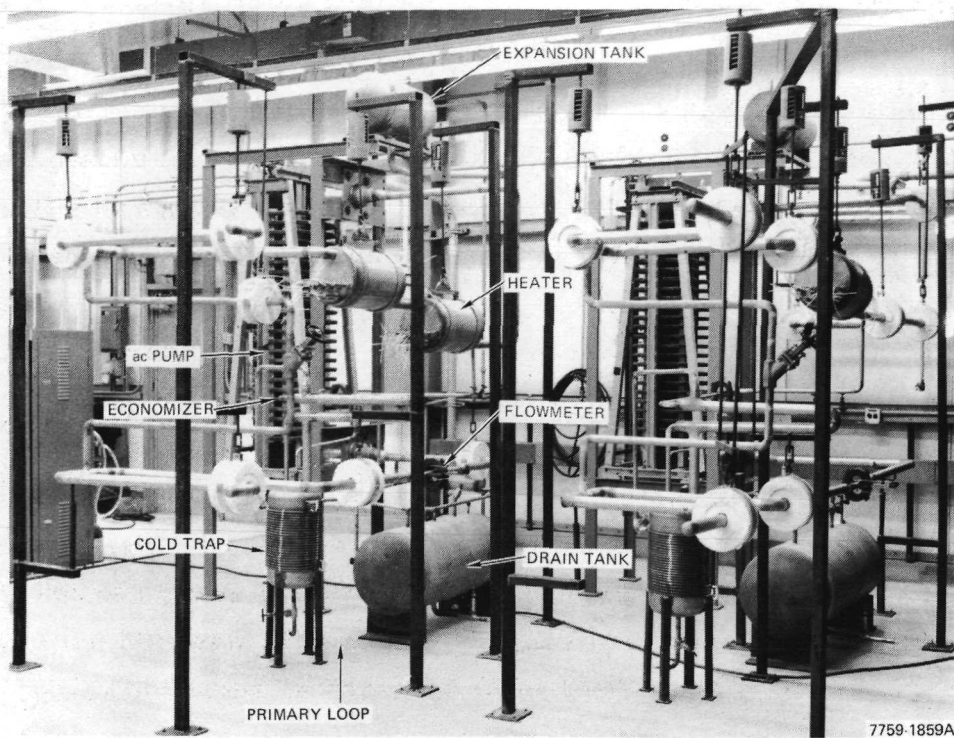
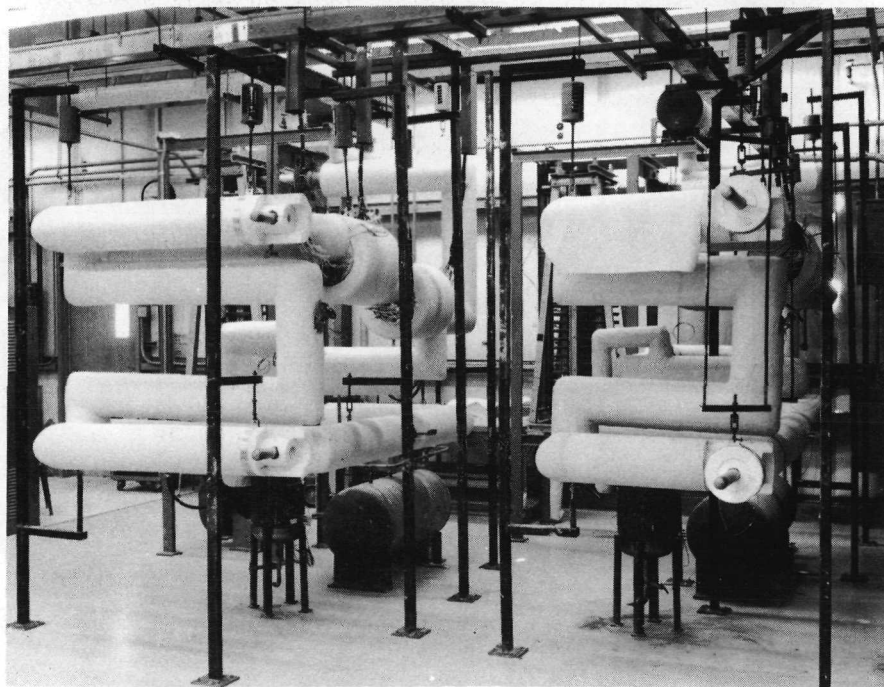
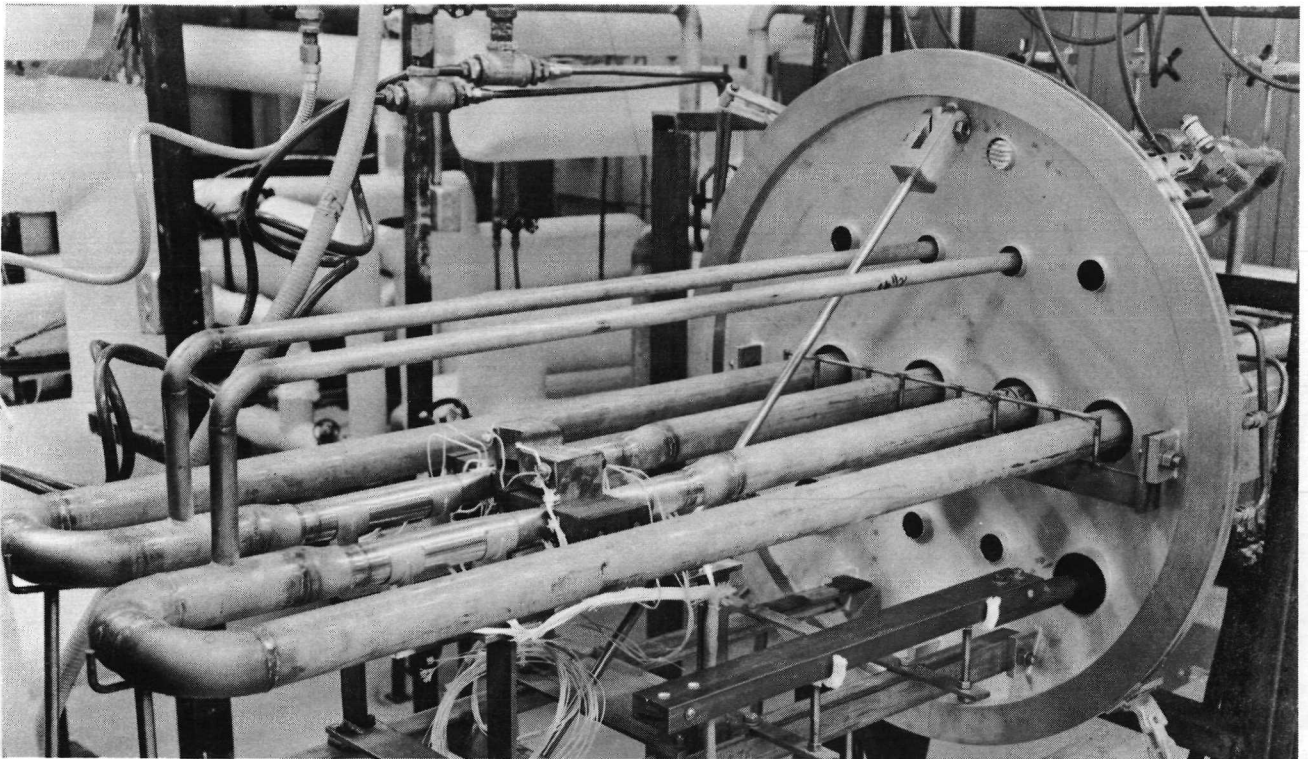


Figure 28. PCA Test Loop Without Thermal Insulation



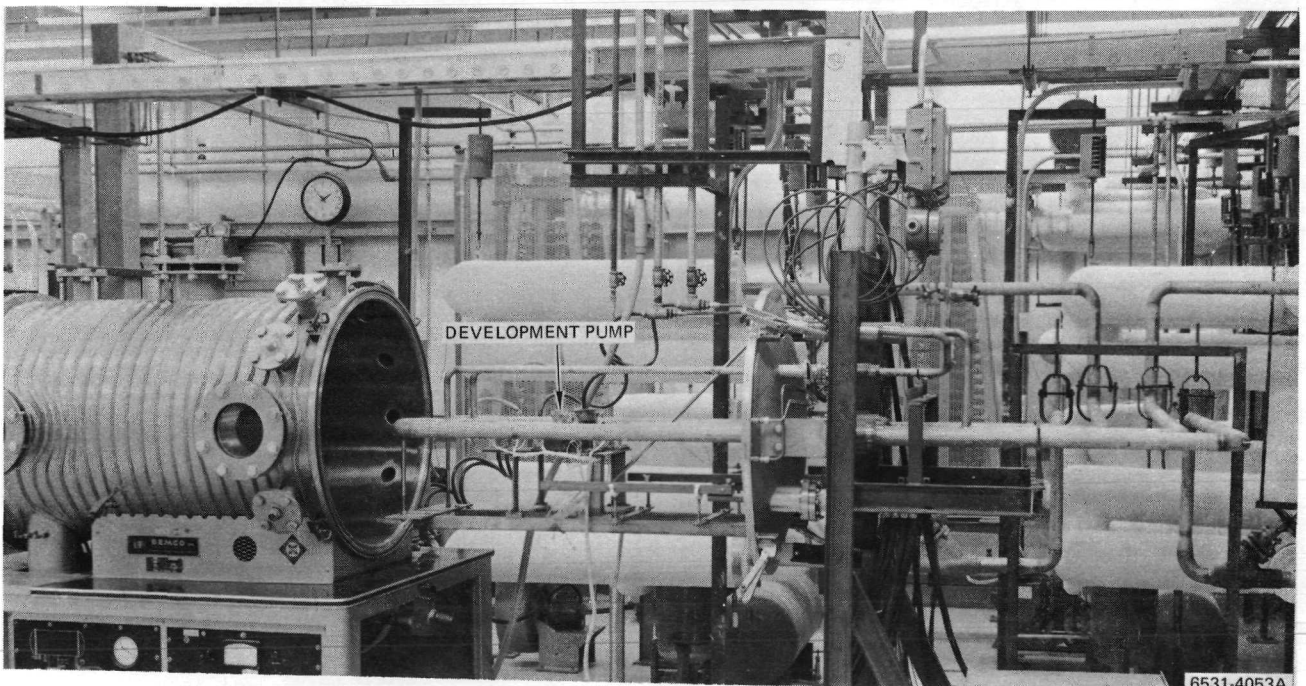
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Figure 29. PCA Test Loop With Thermal Insulation

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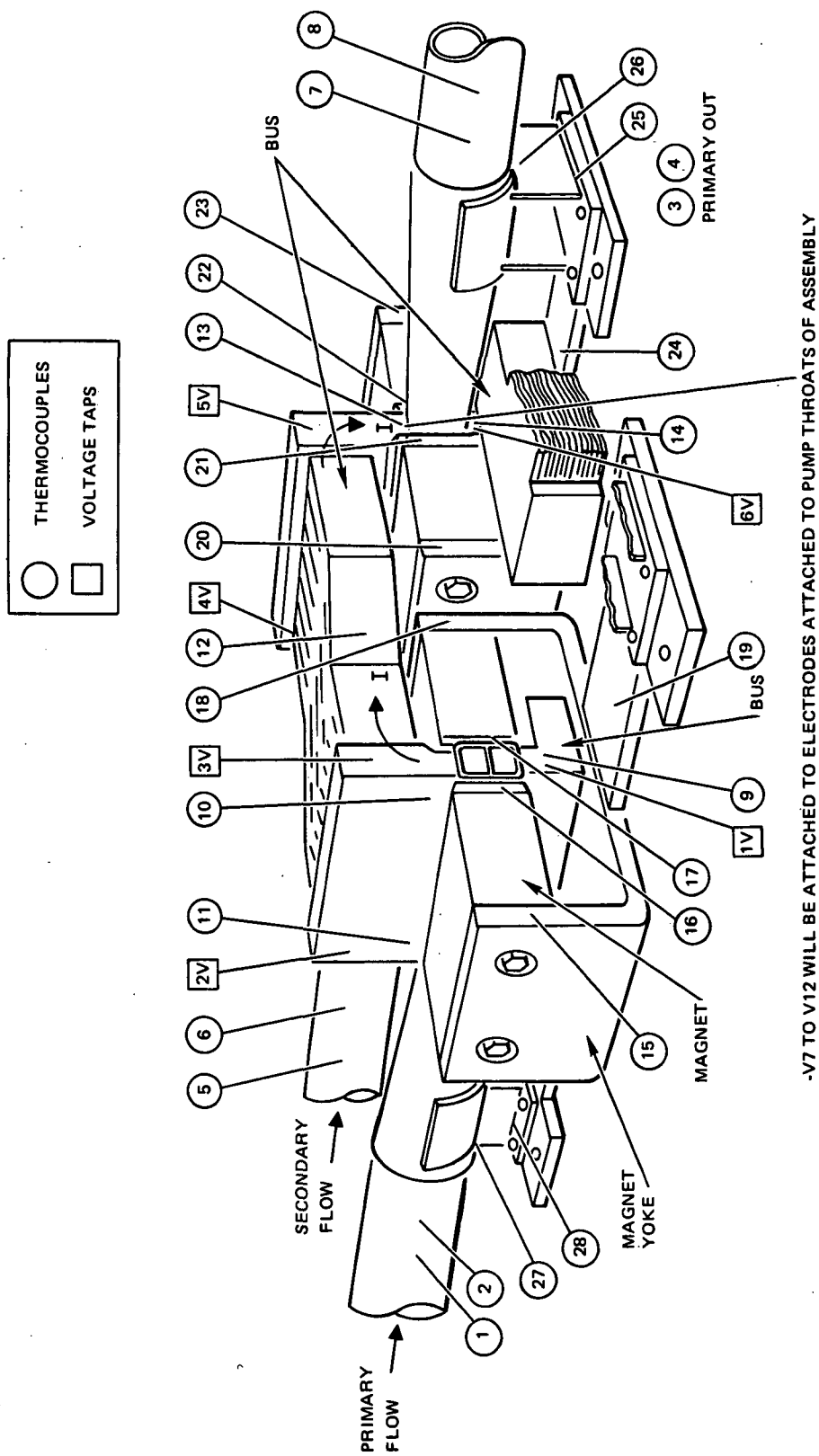
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Figure 30. Development Pump Test Installation — Closeup View



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Figure 31. Development Pump Test Installation — Overall View



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Figure 32. Development Pump Test Instrumentation

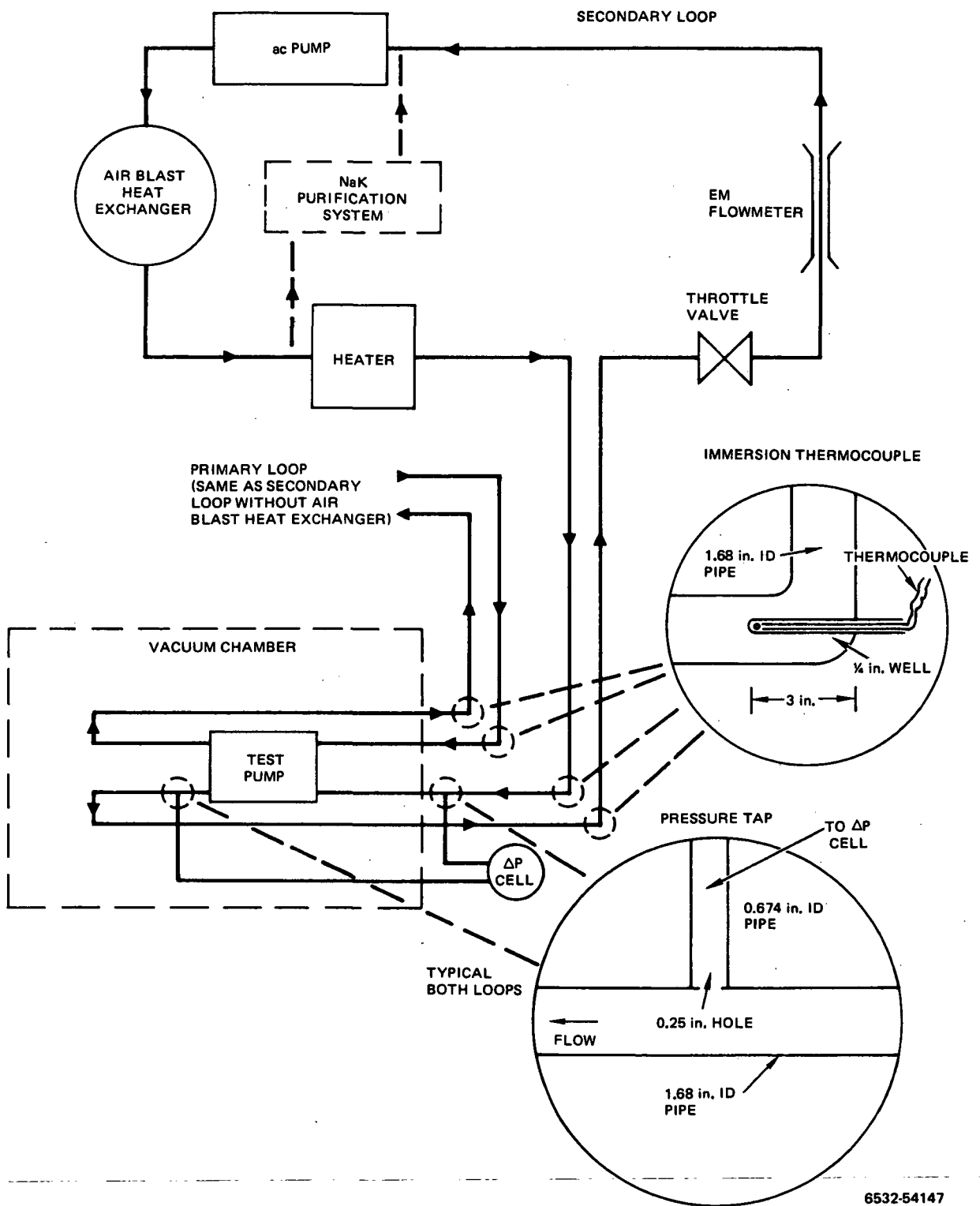


Figure 33. Pressure, Flow, and NaK Temperature Instrumentation

c. Test Procedure

(1) Phase I

The development pump was installed into the test loop, and all instrumentation used to acquire performance data was calibrated. The differential pressure (ΔP) cells were calibrated in place with an inert gas, using a mercury manometer. The loops were filled with NaK, flow was started, the vacuum chamber was sealed, and a pressure of $< 1 \times 10^{-5}$ torr was obtained within the chamber. The primary and secondary test loops were circulated at 600 and 500° F, respectively, until the oxygen concentrations of each were reduced below 10 ppm. Performance data (temperatures, throat developed pressure, flow rates, voltage, and pump input current) were acquired at selected flow rates and currents at ambient temperature, at off-design conditions, and at nominal development pump (1050/660° F) and prototype pump (1110/600° F) design temperatures (Table 8). Over 550 hr of testing was performed at primary loop temperatures exceeding 1000° F, including 10 thermal cycles between 1110/600° F and ambient temperature. Selected performance tests were repeated at the end of the test to detect degradation in pump performance that may have occurred. Additional data was acquired at ambient temperature with several values of magnetic flux in each throat, and with zero flux, to better characterize the pump computer model and to explain the differences between empirical pump performance and predicted performance. At the conclusion of the test, the loops were drained, the pump was removed from the loop, cleaned, and packaged for storage.

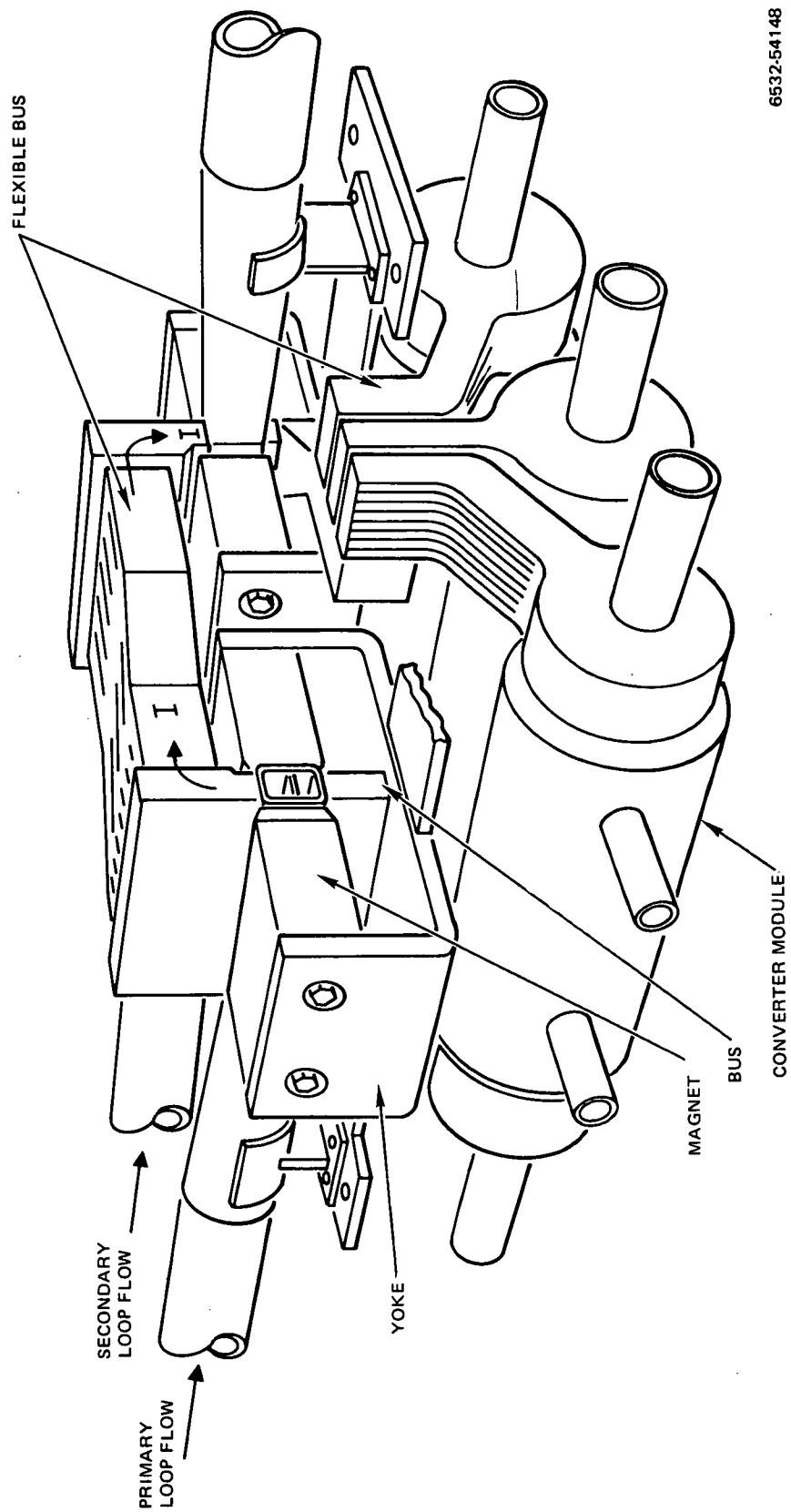
(2) Phase II

The second phase of this test program was to have been a test of the combined development pump - thermoelectric module assembly, Figure 34, in the same vacuum chamber as the first phase tests, but program close-out intervened. Performance of this test would have required additional modification to the NaK test facility, so that the flow rate and temperature of each pump throat and each (hot and cold) side of the thermoelectric modules could be controlled independently. A flow schematic of the loops for this test installation is shown in Figure 35. Performance data, consisting of flow rates, temperatures,

TABLE 8

TEST MATRIX - DEVELOPMENT PUMP

Temperature (°F)		Current (amp)	Flow Rate (lb/sec)
Primary	Secondary		
75	75	30, 60, 90, 120	0, 0.1, 0.2, 0.3, 0.4
75	75	0, 400, 800, 1200, 1600, 1800	0, 1, 2, 3, 4, 5
500	300	700	0, 1, 2
700	400	1100	0, 1, 2, 3
900	550	1500	0, 1, 2, 3,
1050	650	0, 400, 800, 1200, 1600, 1800	0, 1, 2, 3, 4, 5
1110	600	0, 400, 800, 1200, 1600, 1800	0, 1, 2, 3, 4, 5
	Ten thermal cycles to 100°F at 1000 amp and 3 lb/sec		
	Steady-state testing at 1600 amp and 3 lb/sec		
1110	600	0, 400, 800, 1200, 1600, 1800	0, 1, 2, 3, 4, 5
75	75	0, 400, 800, 1200, 1600, 1800	0, 1, 2, 3, 4, 5
75	75	Zero flux and low flux performance	



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Figure 34. Thermoelectric Development Pump Assembly

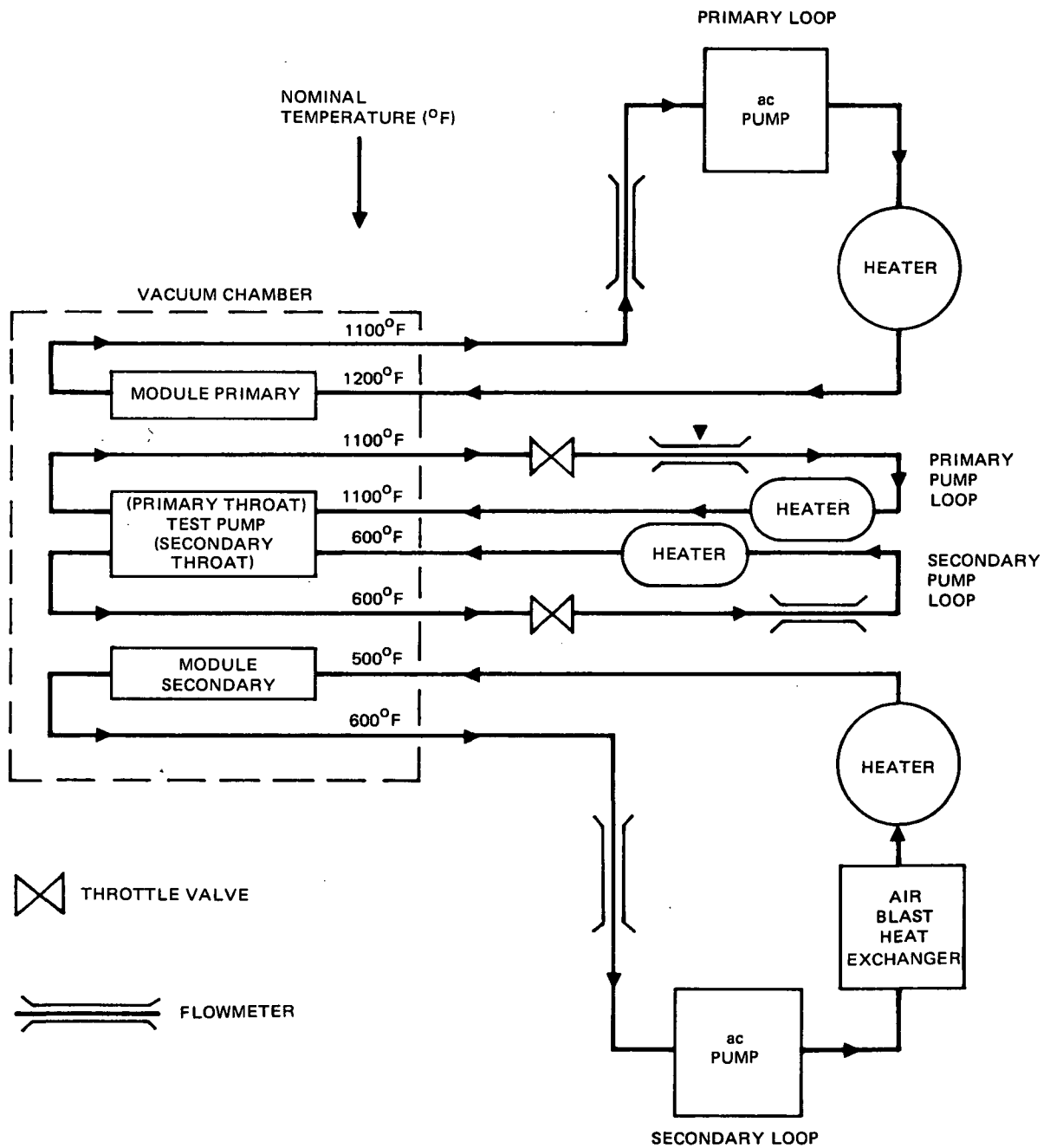


Figure 35. Pump Assembly Test Loop Installation

pressures, and current, was to have been acquired at thermoelectric converter hot-to-cold side temperature differentials from 60 to 600° F, as the peak hot-side converter temperature was raised to 1200° F and the peak cold-side converter temperature was raised to 600° F, at several values of pump flow. Steady-state testing for a period of 2500 to 5000 hr was scheduled at a primary throat temperature of 1100° F, a secondary throat temperature of 500° F, primary side module inlet/outlet NaK temperatures of 1200/1100° F, and secondary side module inlet/outlet NaK temperatures of 500/600° F. The pump assembly was to have been cycled from these temperatures to ambient a minimum of 10 times during this test (5 cycles at the start, and 5 cycles at the end). Performance mapping at off-design temperature and flow conditions was to be performed, to provide data for current system transient studies. Finally, data were to have been acquired with a simulated battery power supply providing current in the range of 10 to 200 amp across the throats, to determine startup characteristics and power requirements. Current through the throats would be determined from the voltage drop across the flexible bus between the throats.

The thermoelectric pump modules that were to be used on this pump assembly were designated TEM 14B, which was a modified version of the TEM 14A modules that had been tested for over 30,000 hr (see Reference 3 for module design and test information) at Westinghouse.

2. Test Results

The results of the Phase I tests conducted on the thermoelectric development pump are summarized in the following paragraphs.

In general, the performance of the development pump was somewhat better than originally predicted. Figure 36 shows the measured pressure-flow characteristics of each throat at a primary throat temperature of 1050° F and a secondary throat temperature of 600° F vs the predicted values at these temperatures. The computer code of Reference 5 was employed to provide these predictions, and it used throat flux densities of 2325 G, throat wall thicknesses of 0.025 in., a throat length of 2.5 in. and a throat exit hydraulic loss coefficient of 0.2 in each throat.

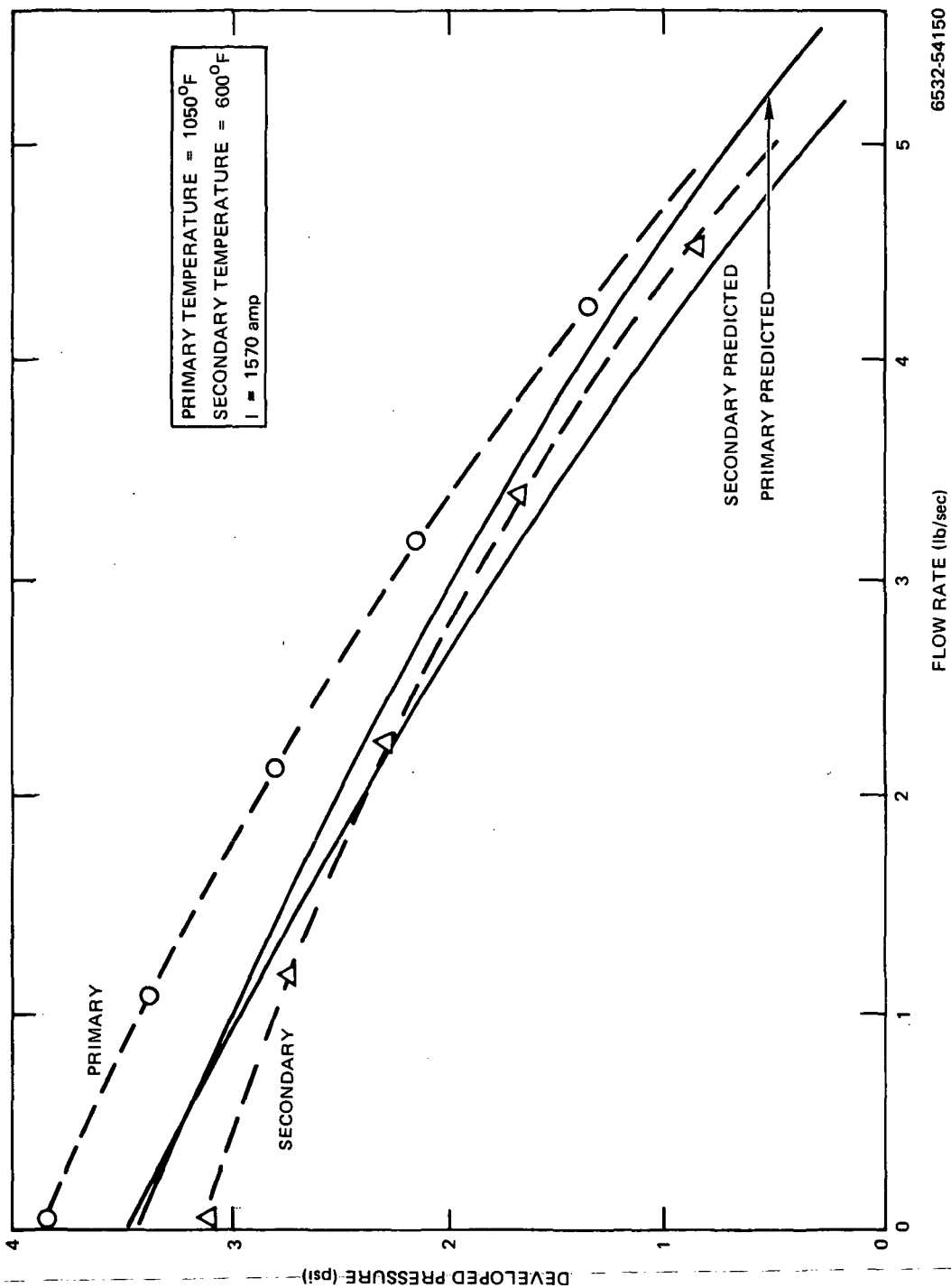


Figure 36. Development Pump -- Original Prediction vs Empirical Performance

Dimensional measurements on the throat showed that the bus length along the throat was 2.3 in. , and the throat wall thicknesses were ~ 0.030 in. These changes in dimensions affected the pump performance in opposite ways. The increased wall thickness resulted in more current being shunted around the NaK in the throat, but the shortened bus resulted in less leakage current passing through the NaK at the ends of the throat in the region beyond the magnetic field. Since the latter effect is beneficial and predominates, the ratio of effective current to total current applied across the throat was higher than predicted.

Post-test throat magnetic flux measurements and throat hydraulic pressure loss measurements provided additional data for adjusting the computer model to fit the empirical test results. The ambient temperature magnetic flux density in the primary throat had degraded $\sim 3\%$ (2630 to 2550 G), and that of the secondary throat had degraded by $\sim 15\%$ (2630 to 2250G) during the test. Since there were no measured changes in secondary throat performance during the tests, it was concluded that this change occurred prior to acquisition of the initial data at operating temperature. The cause of the secondary throat flux degradation was either due to handling during test installation or, more probably, due to the high current flowing through the throats, which, in the secondary throat, established a field that opposed the field of the permanent magnets, and resulted in some permanent demagnetization in this throat. This effect also further reduces the flux density during the time current is flowing, resulting in an effective throat flux density lower than that measured in the secondary throat at the conclusion of the test. The direction of current flow through the primary throat establishes a magnetic field that should reinforce the permanent magnets, but apparently causes no increase in the effective flux density when current is flowing.

Hydraulic pressure loss measurements, made across the throats with the magnets removed, showed that these losses were greater than predicted, and that the primary throat losses were greater than the secondary throat losses. The reasons for this became fairly obvious during post-test examination of the NaK diffusers, and the transition sections at the ends of the diffusers. The cone angle in the diffusers was $\sim 50\%$ larger than that used in the original analytical model, and the transition welds showed considerable drop through,

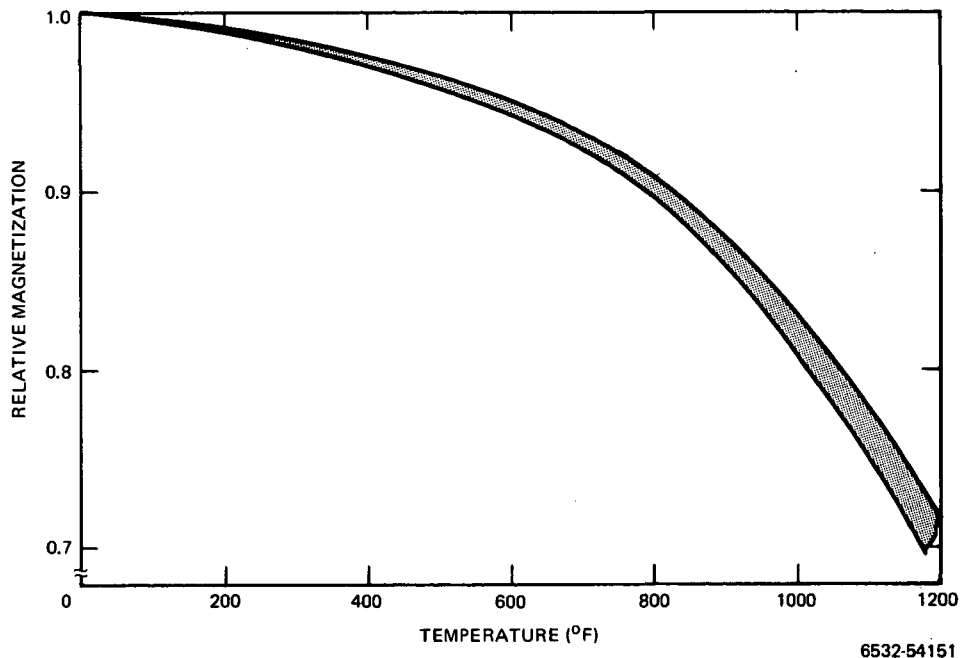


Figure 37. Relative Magnetization vs Temperature
(Alnico V-7) (Reversible effect)

TABLE 9

DEVELOPMENT PUMP COMPUTER MODEL CHANGES

	Primary	Secondary	Was for Both (Original Code)
Flux Density			
Ambient	2600	2050*	2450
Operating Temperature	2300	1875*	2325
Exit Loss Coefficient	0.6	0.45	0.20
End Leakage Resistance Term	$20 \rho_N/b$	$20 \rho_N/b$	$2.5 \rho_N/b$
Throat Wall Thickness (in.)	0.030	0.030	0.025

*Effective flux densities

some misalignment, and general roughness. The weld drop through and roughness was greater in the primary side than in the secondary side. The exit transitions are within 2 in. of the upstream pressure taps (Figure 33), and local turbulence could have resulted in additional measured differences between the two throats. The loss of magnetic flux due to temperature appeared to be ~ 2 to 3% greater than predicted (Figure 37) but this may have been due to insufficient yoke cross section.

From an analysis of the test data the factors shown in Table 9 were changed in the computer model.

Close agreement between predicted results and experimental results was then obtained, throughout the temperature range from ambient to 1100° F. Figure 38 shows the agreement obtained between predicted and measured test results at a primary throat temperature of 1110° F and a secondary throat temperature of 600° F. Figure 39 shows similar agreement at 100° F. Figure 40 shows the zero flow pressure developed by each throat, as a function of current at 100° F. The effective flux density in the secondary throat is decreasing at higher currents, showing > 10% reduction at 1600 amp over that measured at ambient temperature with no current (2050 vs 2250 G).

Figure 41 shows the performance characteristics of the primary throat as a function of throat magnetic flux density. The lowest curve shows the performance characteristics of the primary throat, using soft iron in place of the magnets. When placed on the secondary throat, a negative pressure was produced. This verifies the establishment of a magnetic field in the throats by the flowing current. Figure 42 shows the pressure developed, and the flow rate for each throat, as a function of operating time at primary/secondary throat temperatures of 1110/600° F, respectively, with constant loop hydraulic losses and constant pump input current. There was no discernible change in performance of the secondary throat for the duration of the test, and a 2 to 3% change in both the flow and pressure developed by the primary throat at a fixed loop hydraulic configuration. This could be accounted for by the change in magnetic flux density that occurred in the primary throat (2630 to 2550 G) during the test.

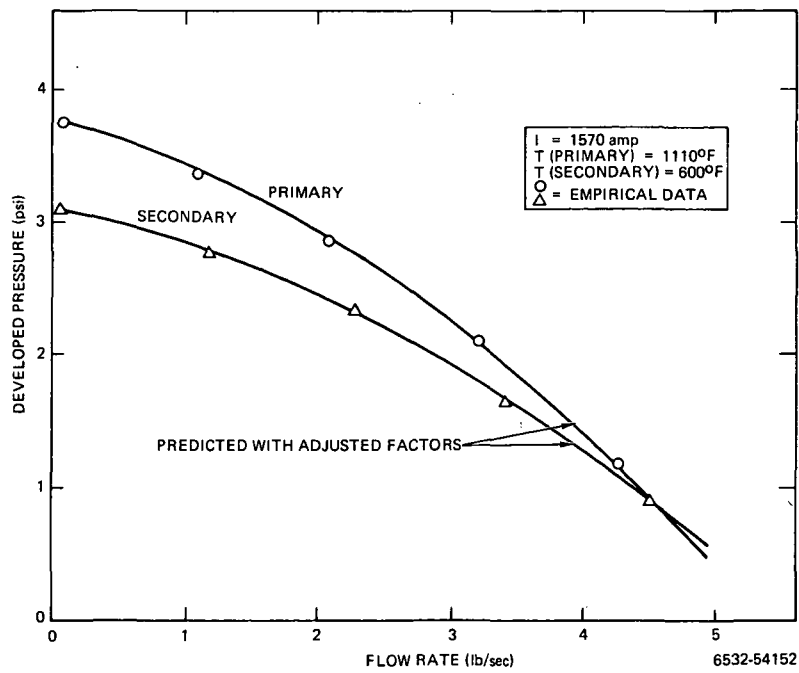


Figure 38. Development Pump - Present Prediction vs Empirical Performance

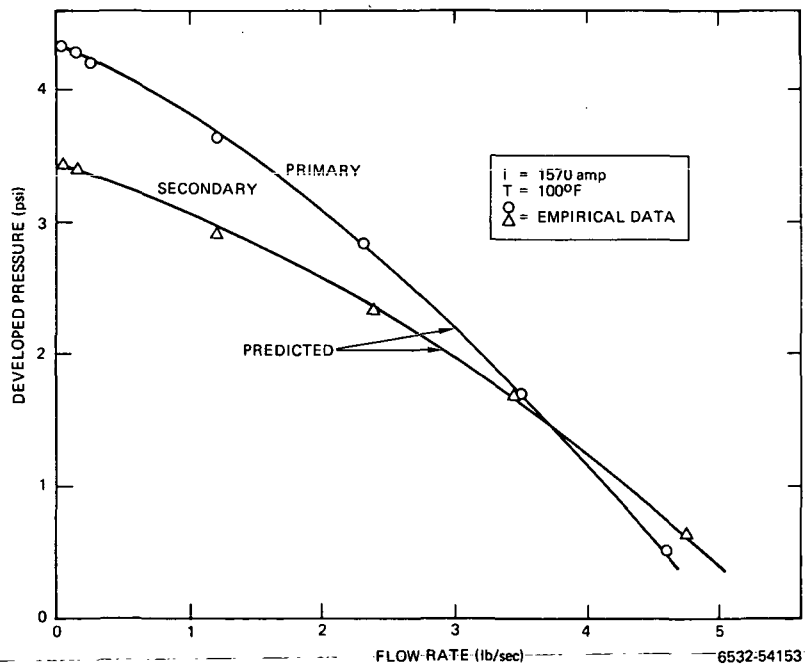


Figure 39. Development Pump - Predicted vs Empirical Performance at Ambient

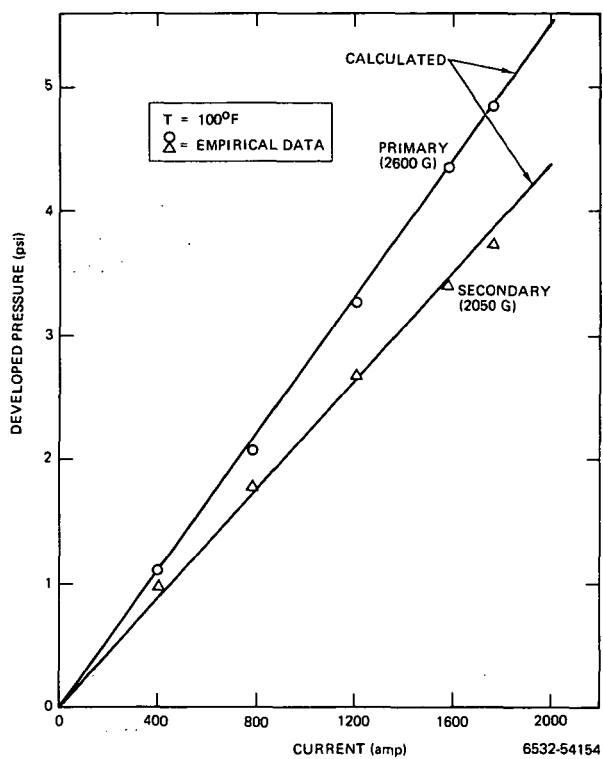
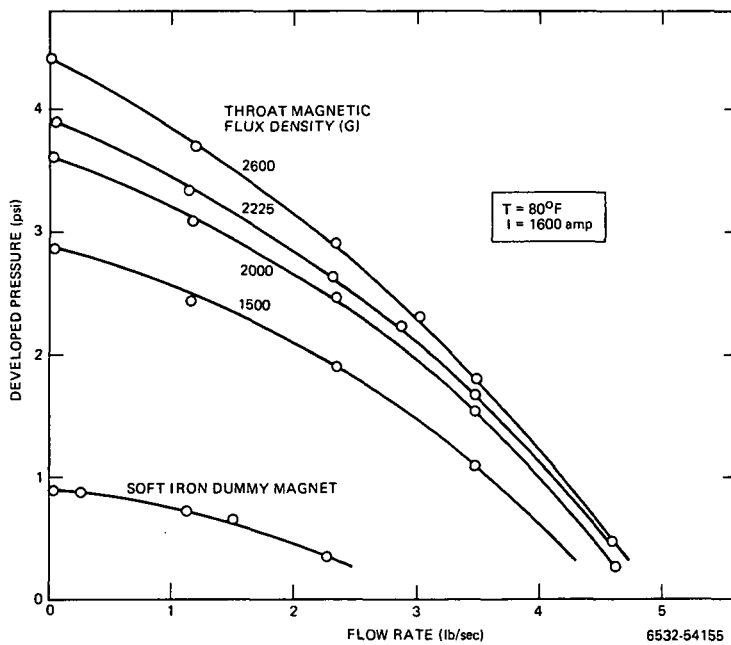


Figure 40. Development Pump – ΔP vs I at Zero Flow

Figure 41. Primary Throat Performance as a Function of Flux Density



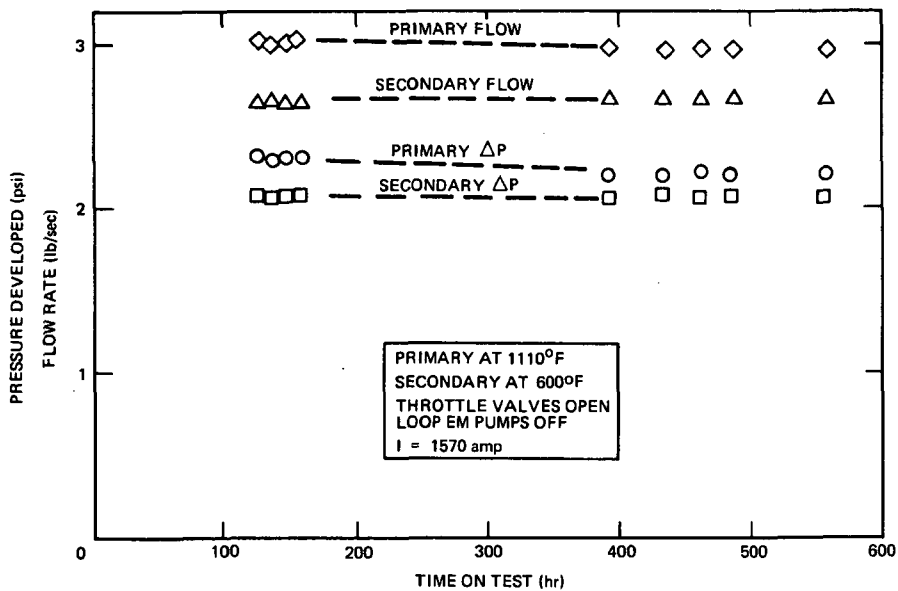
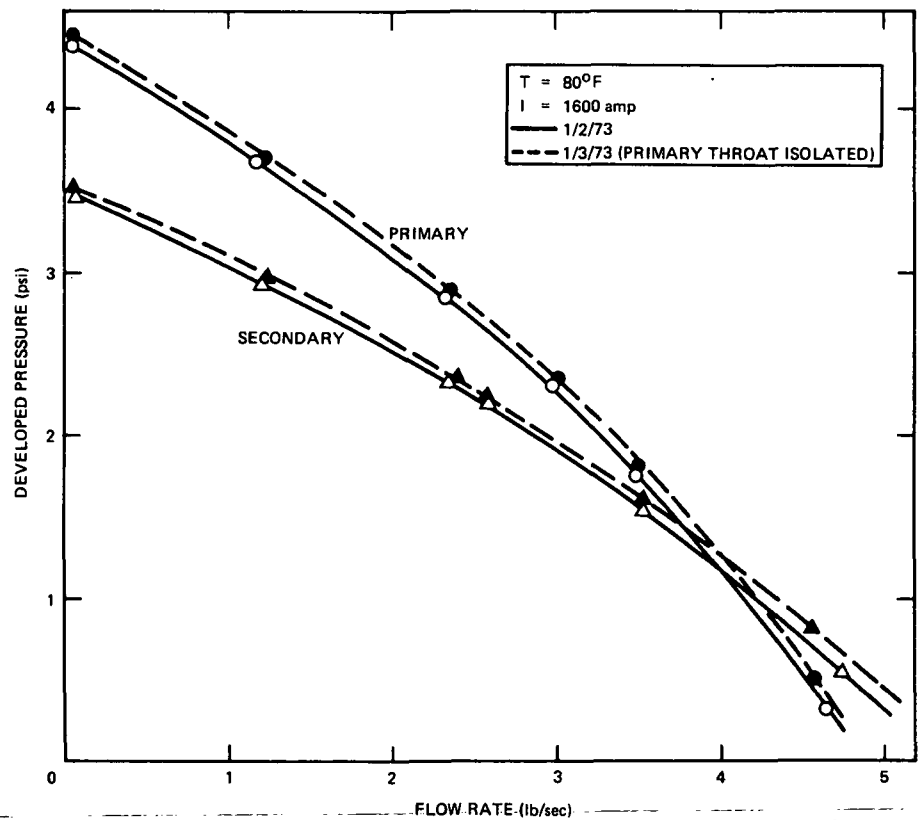


Figure 42.
Development Pump -
Pressure and Flow
Rate vs Test Time

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Figure 43.
Development Pump
Performance with
Electrical Isolation



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It was demonstrated, at the conclusion of the test, that not all of the current applied to the pump assembly was passing through the throats. The current buses are metallurgically bonded to the throats, and the throats are welded to support members that are mechanically connected to a common structure. Figure 43 shows a pressure vs flow data obtained with the pump assembly as installed, and then with the primary throat electrically isolated from the common structure. An increase in performance, equivalent to $\sim 2\%$ increase in applied current, was effected. The shunt used to measure current was located outside of the vacuum chamber, and measured the total current supplied. All test data were corrected to show that the actual current across the throats was 2% less during the test, which accounts for most of the previous performance data being shown at 1570 amp, rather than at 1600 amp.

An examination of the voltage drop data obtained across the flexible bus showed that this bus could be used as a shunt for determining the current being passed through the throats, with an accuracy of about ± 30 amp. The voltage taps located on the throat in the fringe flux region can be used to indicate the flow, provided the current is known, as this flow signal is very sensitive to current. The absolute accuracy of the flow measurement is probably in the order of 6 to 8%. Calibration of these sensors against instruments with known accuracies, as was done in this test, is required in order to achieve these accuracies.

3. Post-Test Examination

At the conclusion of the test, an examination of the pump assembly and the vacuum chamber internals was conducted, to help determine the cause of the performance degradation in the primary throat, and to determine the cause of the rise in peak magnet operating temperatures (from 740 to 780°F). The inside of the vacuum chamber, the piping, and the structure within the vacuum chamber were found to be covered with vapor-deposited coatings of various colors. Also, some of the gold-molybdenum foil covering the primary piping had loosened, exposing this piping. The change in surface emissivities due to these effects explains the rise in magnet temperatures.

A significant amount of copper (1000 times greater than expected) was found in this coating, causing some concern as to its source. It would have required operating temperatures $\sim 300^{\circ}\text{F}$ higher than measured to produce the amount of copper detected in the coating, unless the copper was transported through the gas phase as CuO , with the oxygen being supplied by in-leakage of air. Another experiment was performed in a similar environment (untrapped oil-diffusion-pumped chamber), with a single throat containing $\sim 20\text{ in.}^2$ of exposed copper surface at 1200°F for 1730 hr. An examination of a stainless steel surface, maintained at $650^{\circ}\text{F} \sim 8\text{ in.}$ from the throat, revealed 10 to 20 times as much copper as expected. The mechanism of transport was not definitely established, at the time this program was closed out.

The magnetic flux densities within each throat were remeasured at the conclusion of the test, and the transition pieces between the pump and the test facility plumbing were removed and examined, as discussed previously. The vacuum chamber internals and the pump were cleaned, and the pump was packaged for storage.

4. Recommended Design Modifications

Design changes that should improve the performance of the development pump include the following:

- 1) Provide a smaller cone angle in the transition between the rectangular throat and the round system piping (reduce from 18 to 12° , if possible)
- 2) Reduce the misalignment, weld drop-through, and surface roughness within the throats and diffusers
- 3) Increase the yoke cross section. The computer model utilizes a yoke cross section equivalent to $\sim 11/19$ that of the magnet cross section. If this had been done in this pump, the yoke thickness would have been 0.7 in. throughout, instead of 0.6 in. at the center and 0.5 in. at the ends which contact the magnets. The degradation in the throat flux density and the high magnet temperature sensitivity was possibly caused by this deficiency.

- 4) Electrically isolate the throat supports, to eliminate stray current paths between the primary and secondary throats
- 5) The interaction between the current-induced magnetic fields and the permanent magnets should be carefully evaluated, to obtain minimum interference effects.

IV. PROTOTYPE THERMOELECTRIC PUMP

A. DESIGN REQUIREMENTS

The objective of the prototype thermoelectric pump design was to provide the minimum weight pumping system (pump + power source + heat rejection system) that would satisfy 5-kwe reactor system pumping requirements. These are as shown in Table 10.

TABLE 10
5-kwe SYSTEM PUMPING REQUIREMENTS

	BOL*	EOL*
Primary Loop		
Flow (lb/sec)	4.87	4.83
Pressure Drop (psi) [†]	1.11	1.09
Temperature (° F)	1059	1105
Secondary Loop		
Flow (lb/sec)	3.01	2.94
Pressure Drop (psi) [†]	1.57	1.50
Temperature (° F)	589	611

*BOL — Beginning of life; EOL — End of life

†A 15% design margin is incorporated into these pressure drop requirements.

The operating life of the system is 5 years, with the temperatures increasing uniformly from the BOL temperatures to the EOL temperatures of Table 10 during this period. The pump shall be capable of providing from 1 to 100% of design flow in the primary loop with an external power source, and there shall be a continuous progressive relationship between applied electrical current and flow rate. Voltage taps shall be located on the throats in the fringe flux region, and will be used to measure flow.

The pump must be capable of withstanding the 5-kwe Reactor Thermoelectric System environmental requirements, as follows:

	Pressure (psig)	Temperature (° F)
Primary Throat	-15 to +50	50 to 150
	30	70 to 1100
	32 (5 year)	1050 to 1150
Secondary Throat	-15 to +50	50 to 150
	30	70 to 700
	20 (5 year)	550 to 650
Thermal Cycles	100 thermal cycles between operating temperatures and 70° F	
Radiation (Total)		
Fast Neutrons (> 0.1 MeV)		1×10^{14} nvt
Gamma		5×10^9 rad

The configurational limits of the pump assembly were established, in concert with overall 5-kwe Reactor Thermoelectric System layout studies. The dual-throat pump assembly was located as close to the reactor and the center-line of the cone as the available space allowed. Once an overall size of 21 in. by 13 in. by 10 in. became established, any significant increase in size of either length (21 in.) or width (13 in.) would have necessitated changes in the system design layout.

B. PUMP CONCEPT TRADE STUDIES

Early in the conceptual design phase of the 5-kwe Reactor Thermoelectric System Program, a trade study was performed to evaluate a number of types of pumping systems considered for use in the program. This trade study provided an evaluation of two basic methods of providing system requirements. These were: (1) ac pump systems vs dc pumping systems, on the basis of best of each type for this general application, and (2) an evaluation of three variations of dc pumping systems (dual-throat, single-throat, and multipass pump configurations).

Factors which were considered in this trade study evaluation are listed in Table 11.

TABLE 11
TRADE STUDY EVALUATION FACTORS

Factor	Desired Characteristics
Pump System Weight*	Minimum
Pump Weight and Size	Minimum
Reliability	Maximum
Power	Minimum, matched to pump
Current	Minimum (dc pumps)
Costs and Schedule	Minimum
Performance Predictability	High accuracy
Fabrication Process Development	State of the art
Startup	Low power and power supply weight

*Includes pump, power supply, power conversion equipment, interconnecting wiring, structure, and all equipment associated with heat supply and heat rejection for pump power supply.

These evaluations were performed for a two-loop system, with one loop at $\sim 1100^{\circ}\text{F}$, the other loop at $\sim 600^{\circ}\text{F}$, and hydraulic pumping power requirements of $\sim 30\text{ w/loop}$. The power source available to these systems consisted of either the regular thermoelectric power modules which would require inversion for the ac pumps and voltage reduction for dc pumps, or a special low-voltage thermoelectric power module (TEM 14A) that had been developed for ZrH reactor thermoelectric systems for dc pumps. The results of these evaluations are summarized in Table 12 for the three dc-type systems, and in Table 13 for the ac vs dc systems. The dual-throat dc pump concept (Figure 2) is clearly superior to the single-throat (Figure 44) and the multipass (Figure 45) concepts, on a weight basis, and would probably sustain lower fabrication costs, also. The dc pump concepts are all superior to an ac-type pump for this system, for the same reasons as discussed in Section III (i. e., cost, reliability, weight, etc.).

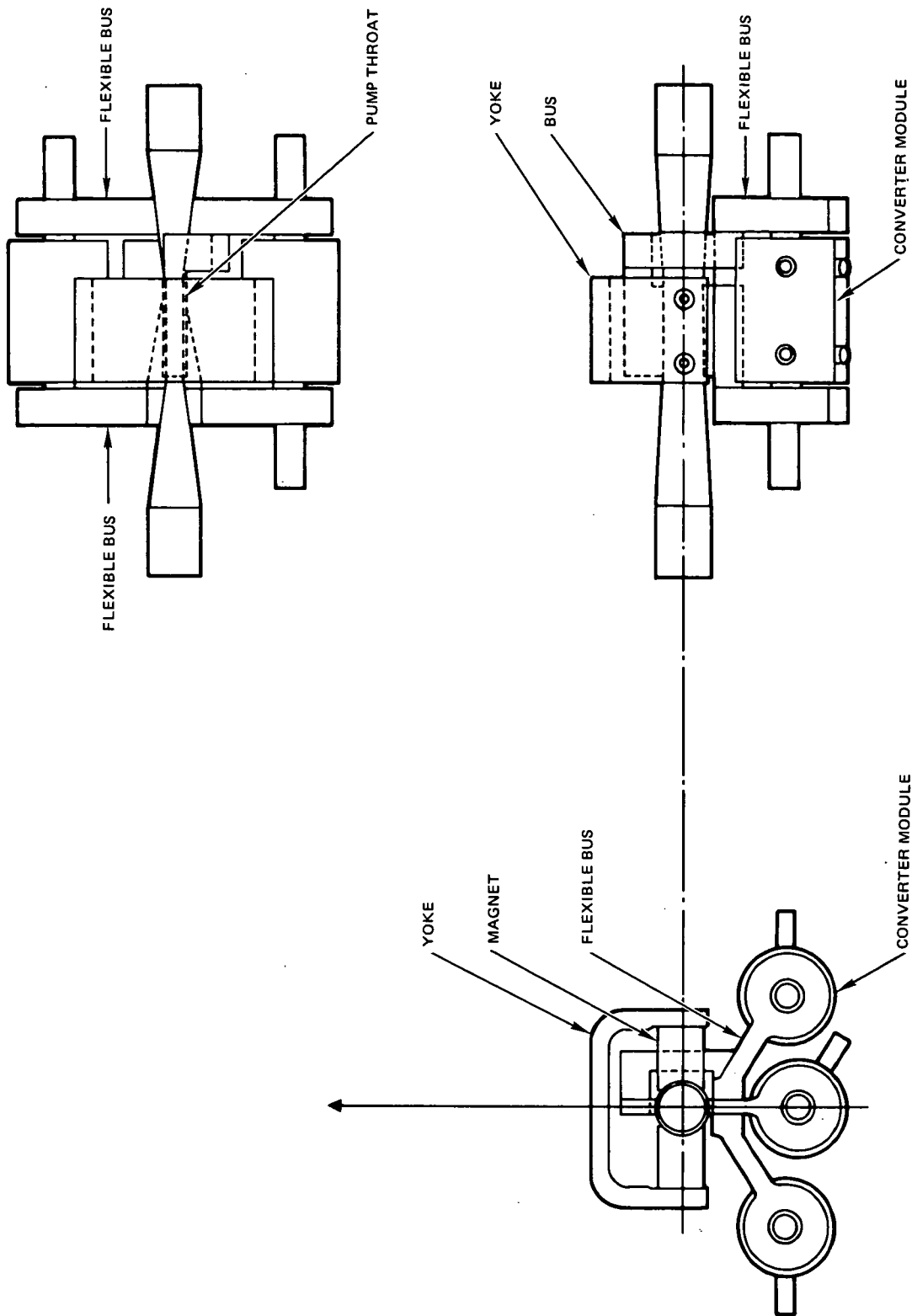
TABLE 12
COMPARISON OF dc PUMPS

Parameter	Single Throat			Multipass	
	Dual Throat	Primary Loop	Secondary Loop	Primary Loop	Secondary Loop
Voltage (V)	0.204	0.136	0.094	0.169	0.129
Current (amps)	2000	1875	2121	1537	1574
Power In (W)	407	448		463	
Hydraulic Power (W)	65	59		59	
Overall Efficiency (%)	16.0	13.2		12.7	
Total Bus Length (In.)	25	36		50	
Bus Efficiency (%)	67	60		67	
Shunt Heat Loss (W)	700	Nil		Nil	
Thermoelectric (Con- verter Efficiency (%)	2.6	2.0		2.0	
Weight (lb)					
Pump	69	46	38	63	45
Thermoelectric Converter	24	17	17	17	17
Heat Supply and Rejection	<u>125</u>	<u>179</u>		<u>185</u>	
Total Pump System	218	297		327	
Configuration	Fig. 2	Fig. 44		Fig. 45	

TABLE 13

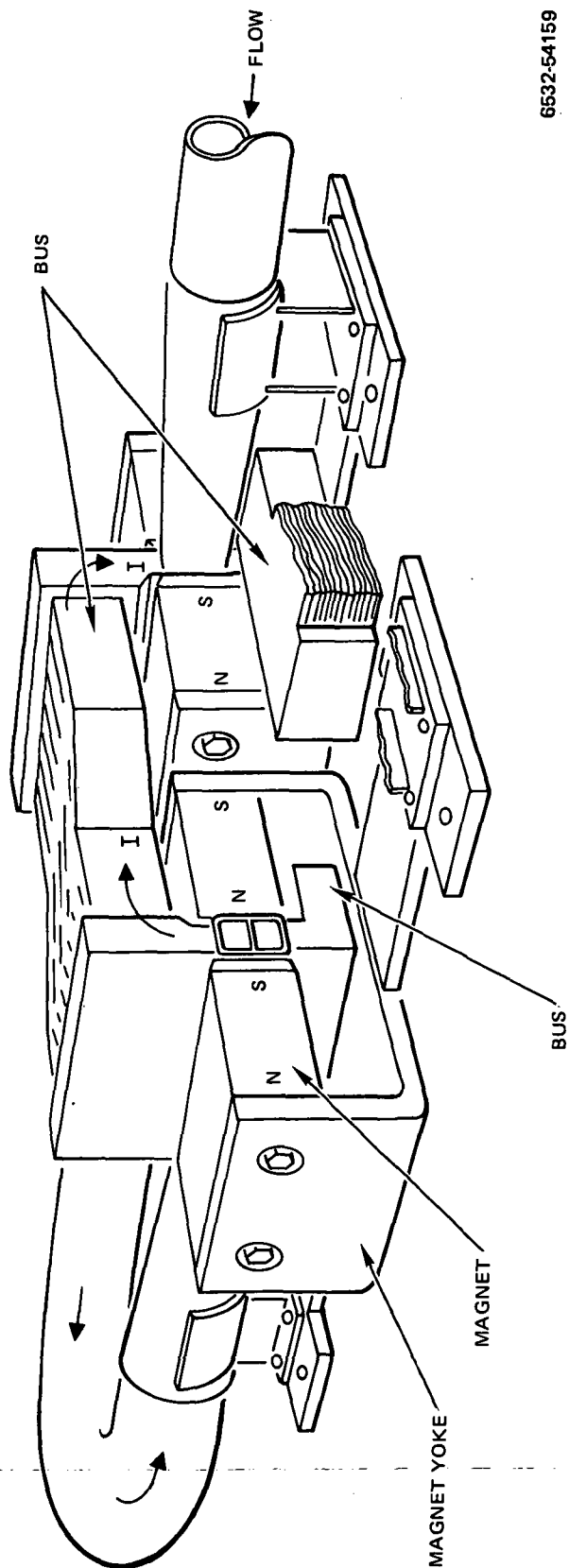
COMPARISON OF ac vs dc PUMPS – THERMOELECTRIC POWER SUPPLY
(Two-loop system – 60 w hydraulic power)

Parameter	dc – Dual Throat		ac	
Efficiency (%)	Pump	14.7	Pump	6
	Converter	2.6	Inverter	85
			Converter	5.9
	System	0.38	System	0.31
Weight (lb)	Pump	69	Pump (2 each)	100
	Converter,	149	Inverter (2 each)	20
	Heat Supply and		Converter,	208
	Rejection		Heat Supply	
	System	218	and Rejection	
Converter Power (w)		407		1170
Startup Requirements	Requires only dc battery, but very inefficient. Minimum battery voltage ~ 50 times more than necessary		Probably less battery weight. Higher voltage needs provide more flexibility in startup design.	
Reliability	Higher than ac		$R_T \times R_C \times R_{IN} \times R_W$	
	$R_{TB} \times R_C$		R_T = Throat	
	R_{TB} = Throat and Bus Joint		R_C = Converter	
	R_C = Converter		R_{IN} = Inverter	
			R_W = Windings	
Cost and Schedules	Lower costs, shorter schedule to obtain empirical data		No fabrication or development effort performed yet	
Fabrication Process	More advanced – similar type pumps previously used on SNAP program		No ac pumps fabricated for this required range	
Performance Predictability	Good agreement demonstrated at lower flows and pressures (~ 10 w hydraulic power)		Less accurate, due to more variables	



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Figure 44. Single-Throat Pump



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Figure 45. Multipass Dual-Throat NaK Pump Assembly (One each per loop)

C. PUMP DESIGN STUDIES

1. Configuration

The configuration selected for the prototype pump assembly, Figure 2, incorporates many of the same features as the developmental thermoelectric pump assembly. The power modules are located as close as practical to the pump throats, to keep electrical power losses low. The buses between the throats, and between the pump module and the throat, are fabricated of multiple, separated, strips of copper, to provide flexibility, and to minimize thermal stresses. A thermal reflective barrier covers the flexible bus between throats, to reduce magnet temperatures and the amount of thermal energy that escapes the pump assembly and is ultimately shunted to the radiator. The direction of current flow (module to primary throat to secondary throat, etc.) is such that the magnetic field established by the current does not interfere with the magnetic field across the primary throat. The present configuration causes some magnetic field losses in the secondary throat; but, since the hydraulic pumping requirements are lower in that loop, these losses can be tolerated. The transition between the rectangular throat and the round system piping is made as uniformly and smoothly as possible, and with an angle ($\sim 12^\circ$) that keeps the transition piece length within reason and does not provide intolerable entrance and exit hydraulic losses. All joints in the electrical circuit between the ends of pump power modules are of the metallurgical type (welded, brazed, or diffusion bonded). The wall thickness of throats (0.028 in.) and pipe transitions (0.025 in.) is greater than that of the system piping (0.020 in.).

2. Stress Analysis

Structural analysis of the prototype pump assembly (Figure 2) has thus far been confined to the primary throat and flexible strut, because, in the two throats, it has the highest operating temperature and the greatest temperature differential between throat and support plate. The primary throat operates at a maximum temperature of 1105°F , as compared to 610°F for the secondary throat. The primary throat has an operating temperature difference between it and its support plate of $\sim 500^\circ\text{F}$, resulting in a significant relative thermal growth. The flex strut must handle this relative growth, while supporting the

TABLE 14
SUMMARY OF DESIGN MARGINS

Location	Design Margins				Launch-Low Temperature (NaK pressure due to acceleration)	
	Operational-High Temperature			Primary		Secondary
	Load-Controlled Limits (Primary)	Strain and Deformation- Controlled Limits (Secondary)				
		Creep-Fatigue Damage Factor (must be <1.0)	Buckling Instability			
Pump Throat	+1.70	0.25, <1.0	NA	+3.7	-	
Splitter	+ .06	0.25, <1.0	NA	+4.0	+2.2	
Wall						
Strut						
Flex Member	+3.20	0.75, <1.0	+0.29	NA	NA	

throat against torsion and lateral loads. The secondary throat operates at approximately the same temperature as the support plate, resulting in a negligible relative thermal growth.

This analysis of the primary pump throat and flex strut indicates that launch and operating stresses are within the requirements of the ASME Boiler Pressure and Vessel Code, Section III, and the High Temperature Code Case 1331-5. The high-temperature (1105°F) and long-duration ($\sim 5 \times 10^4$ hr) operating requirements of the primary pump unit make it susceptible to creep-fatigue failure; therefore, creep-fatigue evaluations, per the High Temperature Code Case 1331-5, were also performed. A summary of the design margins on the primary pump throat and flexible strut is shown in Table 14.

3. Thermal Analysis

A finite element thermal analysis program was written to model the prototype pump assembly. This model was prepared to provide steady-state thermal conditions, and, with a minimum of additional effort, to also provide transient thermal profiles. Thus far, only steady-state thermal profiles had been obtained. The boundary conditions for this study were as shown in Table 15. A summary of the results is shown in Table 16.

Figure 46 is a cross-sectional view of the pump assembly, showing nodal temperatures. The results of this analysis show temperature profiles similar to those calculated and measured for the development pump.

D. PROTOTYPE DESIGN

1. Description

The configuration of the prototype pump assembly is as shown in Figure 2, and on the referenced layout drawing.⁽⁶⁾ The materials of construction, and the typical dimensions of each throat, are shown in Figure 47. The overall dimensions are 21 in. (direction of NaK flow) by 13 in. (direction of magnetic flux) by 10 in.

2. Design Optimization

The prototype pump size and power requirements were determined with the dc pump computer code,⁽⁵⁾ using the design performance requirements of Section IV-A as inputs with the following constraints and assumptions:

TABLE 15
THERMAL BOUNDARY CONDITIONS

Primary Throat (° F)	1105
Secondary Throat (° F)	590
Pump Local Radiant Sink (° F)	580
Average TEM Cold Cladding (° F)	523

TABLE 16
THERMAL ANALYSIS SUMMARY

Maximum Magnet Temperature (° F)	717
Shunt Loss Through Top Bus (kw)	0.6
Shunt Losses Through Bottom Busses (kw)	0.4

- 1) Configuration — as shown in Figure 2
- 2) Materials
 - a) Bus — OFHC copper
 - b) Yoke — Armco Iron
 - c) Magnet — Alnico V-7
 - d) Throat — Type 316 series stainless steel
 - e) Pole piece — Hiperco 27
- 3) Bus length — 32 in. (based on typical layout drawings)
- 4) Bus efficiency — 67% (approximately optimum for this configuration)
- 5) Identical dimensions in both throats
- 6) Identical electrical current through both throats
- 7) Pump voltage and current match to TEM 14-A type pump converter (~ 355 w at 0.210 v)
- 8) Thermoelectric pump converter efficiency = 3.4%
- 9) Converter power-to-weight ratio of 15 w/lb
- 10) Associated system heat supply and rejection weight of 8 lb/kw of heat rejected

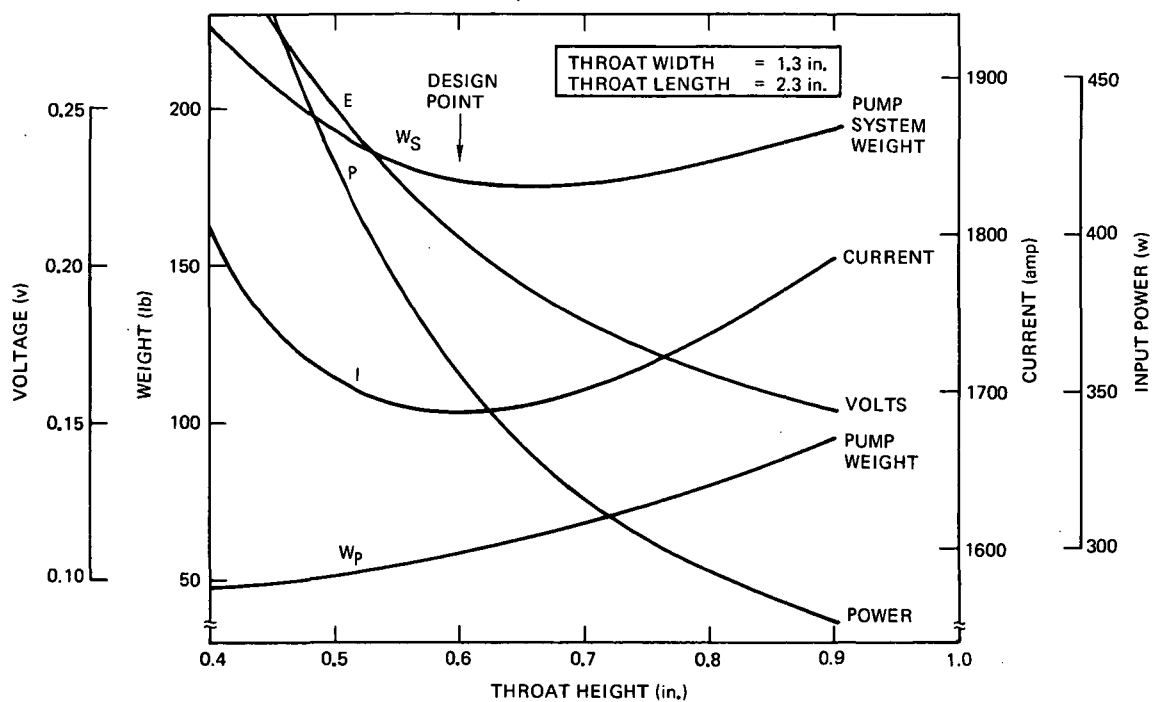
Determination of the pump design point is an iterative process. Pump performance characteristics and weights for a dual-throat pump configuration, as shown in Figure 2, are computed for many throat sizes. The minimum current necessary to obtain the required pressure at a selected flow rate is determined for a given set of throat dimensions. Magnet area and length are determined at the maximum magnet energy product, as this provides the smallest magnet, and therefore the lightest pump. For this program, the pump design selected is that pump which provides the minimum pumping system weight, where the pumping system is comprised of the dual-throat pump, pump power supply (thermoelectric modules), interconnecting buses, associated heat supply and rejection weights, and the structure required for these components. The determination of a best pump configuration is made by varying the throat

dimensions (length, height, and width) over a range of values, such that the end points selected always provide higher-weight pumping systems than the intermediate values. An examination of performance and weight data enables the selection of a configuration that satisfies the above requirements. Figures 48, 49, and 50, in which pump voltage, current, power, pump weight, and pump system weight are plotted as a function of the throat dimensions, illustrate how changing throat dimensions affect various parameters, and how the pump design is selected. Throat width (a) is the distance between the bus electrodes, throat height (b) is the distance across the throat between the magnets, and throat length (x) is the distance across the bus-throat joint in the direction of NaK flow. In Figure 48, the selection of throat height at 0.60 in. is principally a compromise between minimum current and minimum system weight. In Figure 49, the selection of throat width at 1.3 in. is for minimum system weight and minimum power. In Figure 50, the selection of throat length at 2.3 in. is for minimum pump system weight and minimum current. In selecting the design point in all three figures, a deliberate effort was made to select the lowest weight pump, as pump weight is indicative of size, and larger pumps result in greater integration problems in the system. In the region of the pump design point selections shown here, slight variations in throat dimensions can be made to provide an optimum pump - thermoelectric converter electrical load match. This is important, as operation of the converter at match-load conditions provides most efficient use of the heat energy available, and best overall pump system performance.

3. Performance Analysis

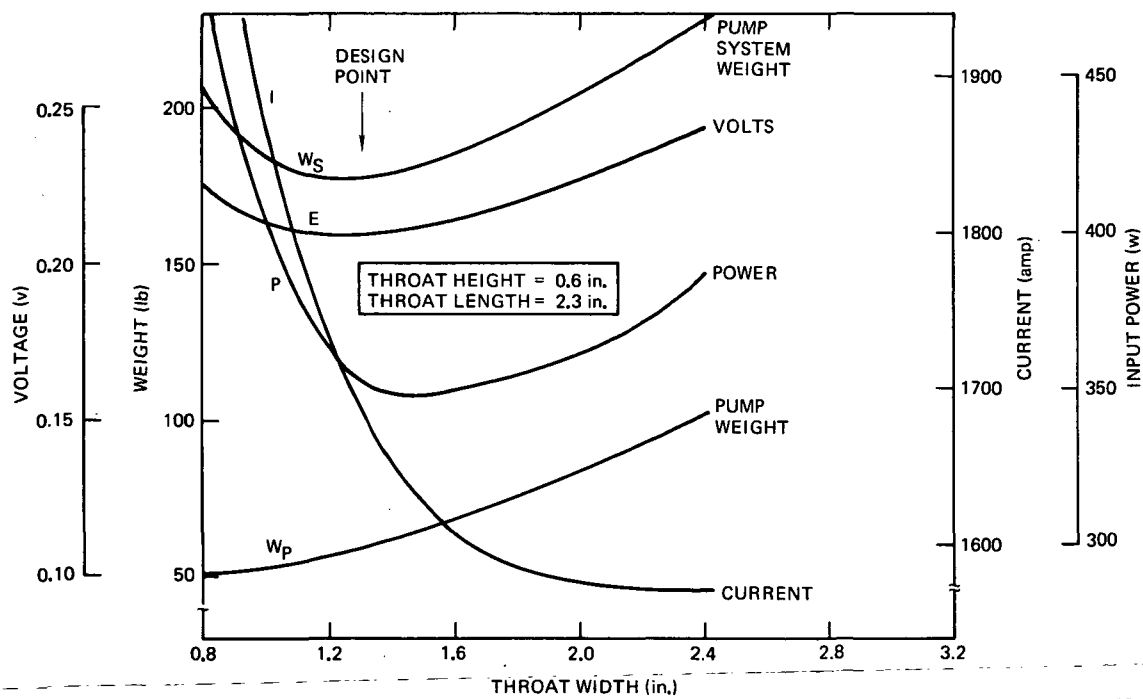
a. Operating Temperature

The performance of the prototype pump design was evaluated at the nominal operating temperatures, and at 100°F to determine startup characteristics. Anticipated performance at design temperatures is best shown in the following figures. Figure 51 shows the pressure developed in each throat as a function of flow rate at BOL and EOL conditions. Figures 52 and 53 show the relationship between pump current and individual loop pressure drop as a function of flow rate at EOL conditions, for the primary and secondary throat, respectively. (e. g., 24% drop in current, from 1690 to 1290 amp, results in ~ 16% drop in



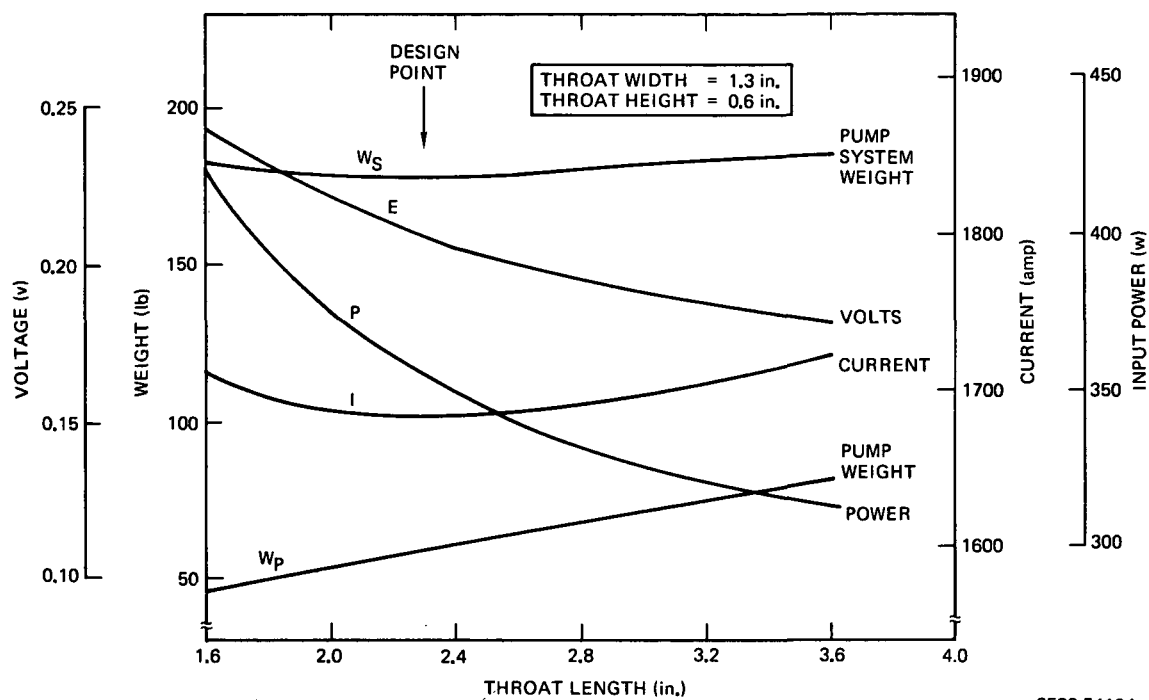
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Figure 48. dc Pump Performance vs Throat Height



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Figure 49. dc Pump Performance vs Throat Width



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Figure 50. dc Pump Performance vs Throat Length

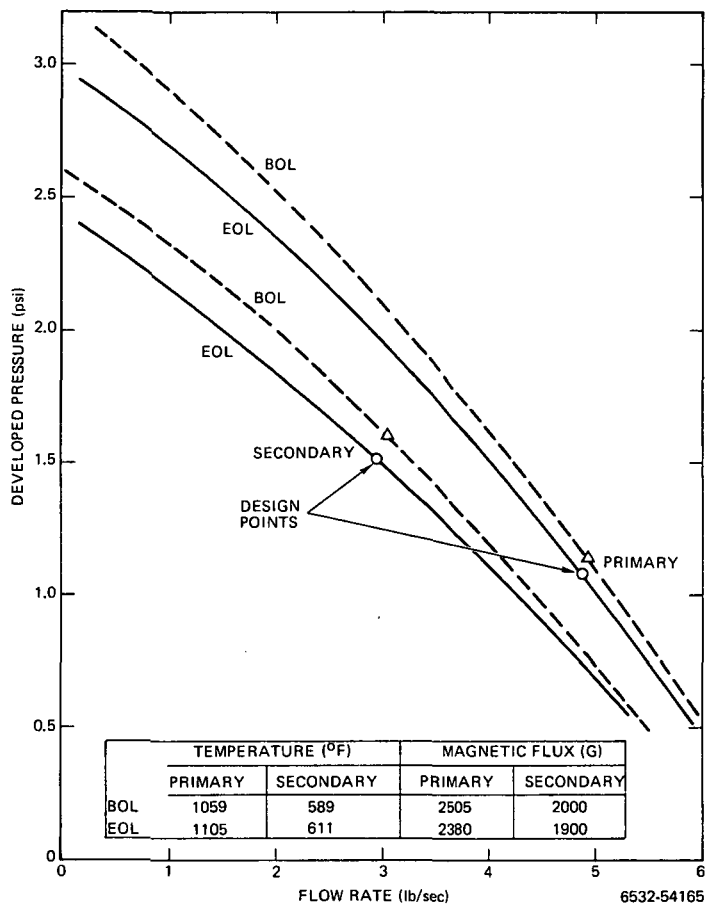


Figure 51. Prototype Pump Performance - ΔP vs Flow

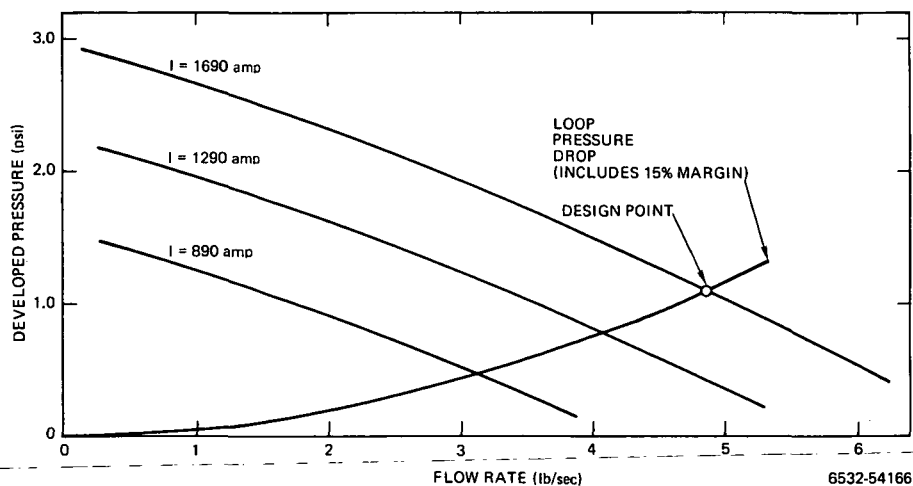


Figure 52. Primary Throat-Loop Characteristics

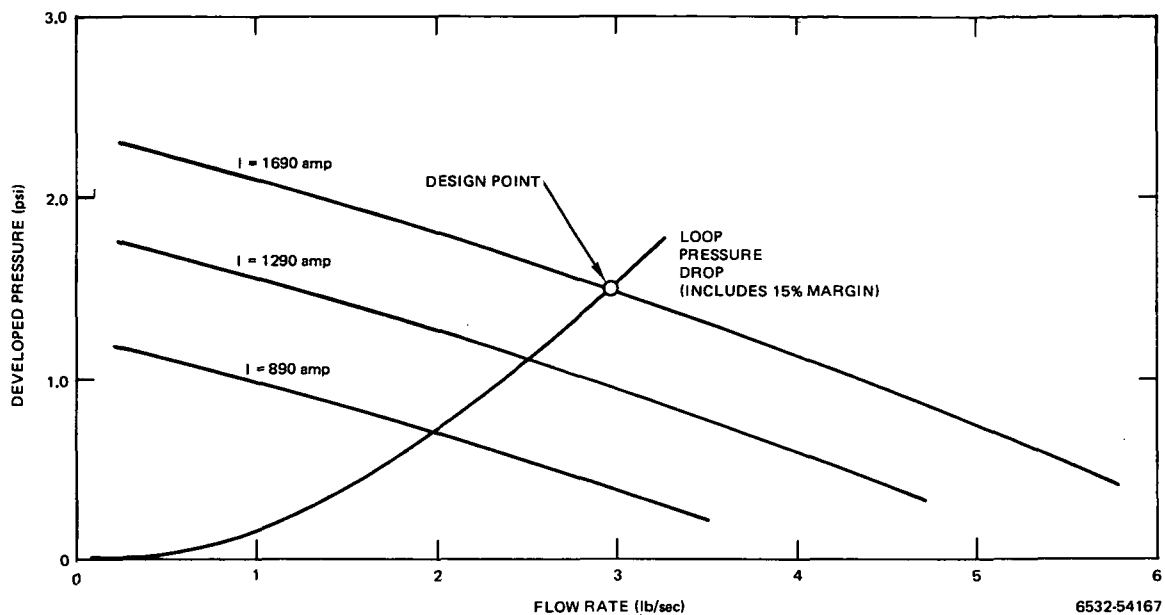


Figure 53. Secondary Throat-Loop Characteristics

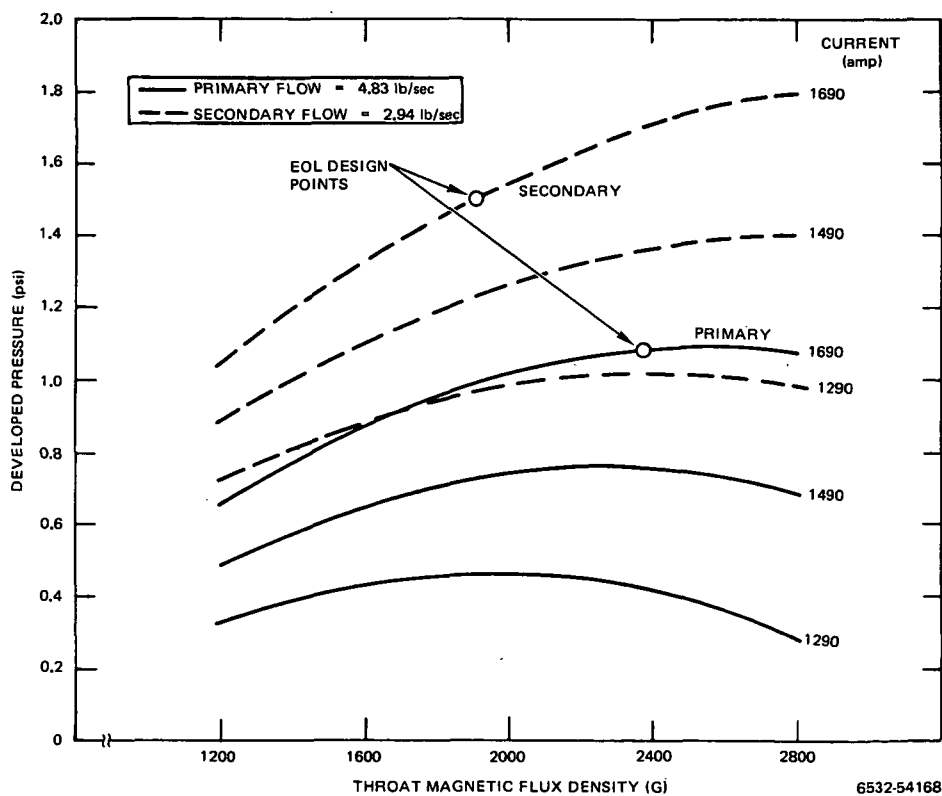


Figure 54. Pump Performance - ΔP vs Flux Density

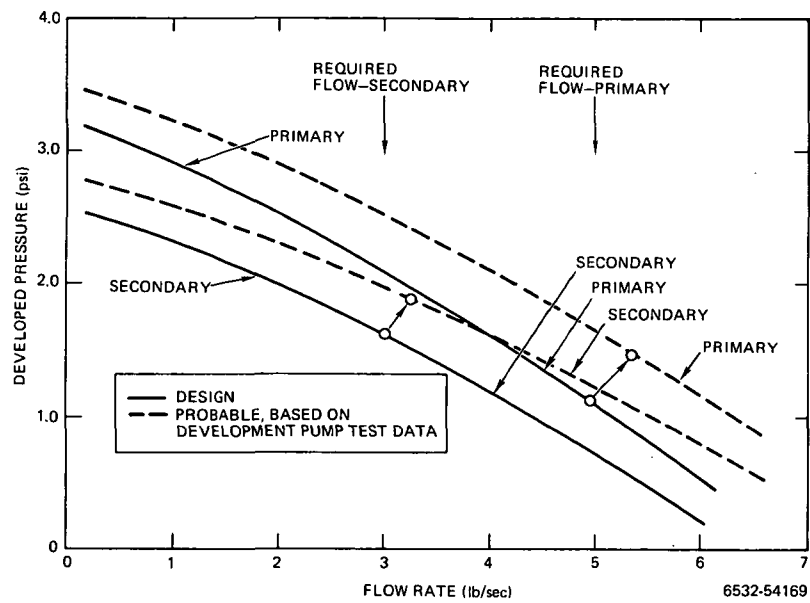


Figure 55. Probable Prototype Pump Performance - BOL

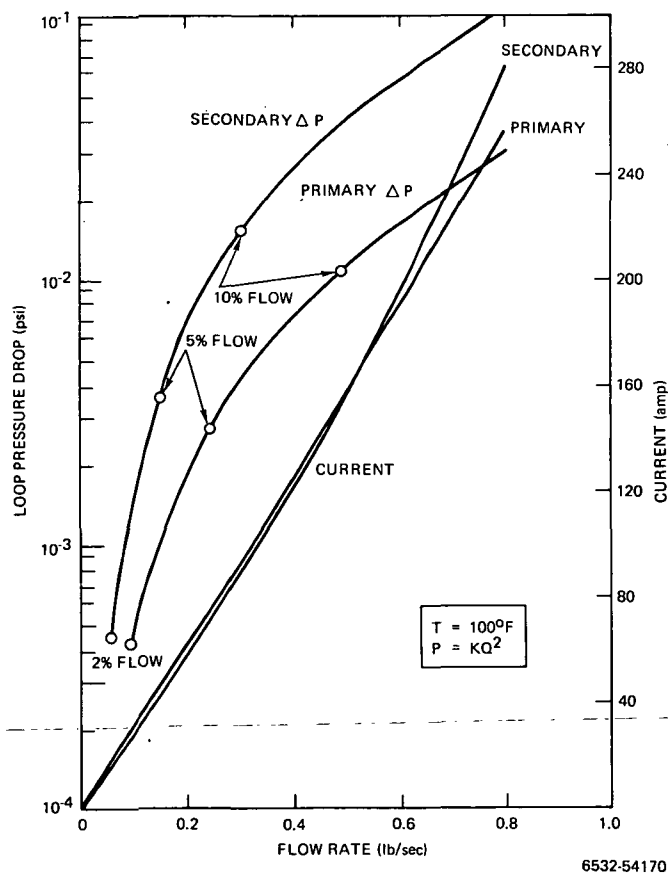


Figure 56. dc Pump Startup Characteristics

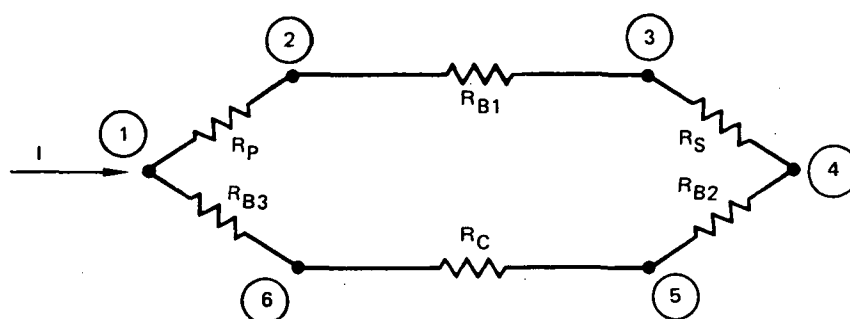
flow rate in each loop). Figure 54 shows the effect on pump performance (pressure developed at EOL conditions as a function of throat magnetic flux density) at several values of current. Performance of the pump is less affected by loss in magnetic flux density than loss in current. A 20% drop in flux density in the primary throat results in $\sim 9\%$ drop in developed pressure, and from Figure 52, ~ 4 to 5% drop in flow rate. From Figure 52, it is seen that a 100 amp loss in current (6%) has almost the same effect. Magnetic losses have a greater influence on performance in the secondary throat; but, since its physical size is the same as the primary throat and its operating temperature is lower, it could easily be magnetized to a higher level initially, to accommodate such degradation.

The optimization studies of the previous section, and the performance analysis of this section, were conducted prior to a complete evaluation of the development pump test data. These analyses included an armature reaction term in the computer program,⁽⁵⁾ and the same end leakage resistance term as that originally used for the development pump analysis. It is of interest, therefore, to show the performance that would most probably be expected of the prototype pump, as depicted in Figure 2, with the elimination of the armature reaction term and a higher, more reasonable, value of current leakage resistance (e. g. , a term equal to twice that used in the analysis). This is shown in Figure 55, in which the probable BOL performance is compared with the BOL performance, as shown in Figure 51. Using the computer code, modified in this manner, would have resulted in a slightly smaller pump in the optimization studies of the previous section, but program close-out precluded additional pump and system analyses.

b. Startup

Prior to startup of the reactor in space, it is necessary to provide flow in the system to keep the NaK from freezing. An evaluation was performed to determine the current required to provide low flow rates in each loop during this period. Figure 56 shows the relationship between the current applied across each throat and the flow rate. Also shown are the pressure losses in each loop as a function of flow rate, assuming pressure is proportional to the square of the flow rate ($P = KQ^2$). Providing reasonable currents across the

throats is difficult, because of the metallurgically bonded low-resistance circuit depicted in Figure 57, a circuit that cannot be broken.



TERM	COMPONENT	RESISTANCE ($\mu\Omega$)
R_P	= PRIMARY THROAT	~ 35
R_{B1}	= FLEX BUS	~ 5
R_S	= SECONDARY THROAT	~ 35
R_{B2}	= FLEX BUS	~ 5
R_C	= THERMOELECTRIC CONVERTER	~ 30 (WITH Ni END RINGS)
R_{B3}	= FLEX BUS	~ 5
R_T	= $R_P + R_{B1} + R_{B2} + R_{B3} + R_S + R_C$ = TOTAL CIRCUIT	

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Figure 57. Thermoelectric Pump Assembly Electrical Schematic

If current is applied across Points 1 and 4, the effective current through the throats is

$$\frac{R_{B2} + R_{B3} + R_C}{R_T} \times I = \frac{40}{115} \times I \approx \frac{1}{3} I . \quad (6)$$

Therefore, only one-third of the current supplied is providing useful work, and pre-startup hydraulic pumping requirements could be fairly high, depending on flow requirements and length of time before reactor startup. If current can be applied across Points 1 and 2, then about two-thirds of the current will pass through

$$\frac{R_T - R_P}{R_T} \times I = \frac{80}{115} \times I \approx \frac{2}{3} I \quad (7)$$

the primary throat, and about one-third will pass through the secondary throat, resulting in a lesser flow in the reverse direction in the secondary loop. This may or may not be acceptable, depending on system operating characteristics and requirements, and will need to be evaluated.

E. VERIFICATION TEST PLANS

Verification testing of the prototype thermoelectric pump assembly was to have been performed in the same vacuum-NaK test facility that was used for the development thermoelectric pump assembly. This facility, as modified, would consist of four separate NaK loops, enabling individual control of temperatures and flows to the pump throats and thermoelectric pump power modules (Figure 35). Tests would be performed in a vacuum, and would include performance mapping throughout the range of temperatures, flows, and loop pressures expected in the 5-kwe Reactor Thermoelectric System, thermal cyclic tests, and endurance tests at nominal operating temperatures, to measure and characterize performance degradation. Startup characteristics of the pump assembly would be determined, using an external dc current power supply, while adjusting loop pressure losses to approximate those of the 5-kwe System.

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