

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1083

*Lithium-Boiling Potassium Test Loop
Interim Report*

Gerald M. Kikin
Jerry P. Davis
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TECHNICAL REPORT 32-1083

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California Institute of Technology

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Abstract

This report covers the construction, instrumentation, and initial phases of operation of the lithium-boiling potassium test loop at the Jet Propulsion Laboratory. The primary purpose of this facility is to investigate overall transient and steady-state characteristics, startup, control, and stability, of a two-loop, alkali metal, Rankine cycle system of the type contemplated for ultimate application to spacecraft nuclear-electric propulsion.

The loop, constructed of columbium-1% zirconium, operates at 30-kW heat input and temperatures up to 2100°F. The primary loop heat source, which is by electric current resistance heat generation in a section of the tube wall, may be programmed to nuclear reactor kinetic equations for simulation of power response to various system perturbations. The secondary loop includes a refractory-metal, single-wheel, reentry-type turboalternator operating at 12,000 rpm.

The system has been operated at full power and temperature. Several modes of boiling instabilities were noted during startup. Full-power, steady-state boiling was stable. The first phase of operations was terminated by a JPL power failure which caused extreme potassium flow oscillations that resulted in damage to the potassium preheater. This component has been repaired and the system brought back to operation.

This initial phase of operations has provided valuable experience in liquid-metal system startup and shutdown, high temperature instrumentation, control, boiling stability, and general operational characteristics. Further loop operations will be concerned with the specific transient test program for determination of various thermal-hydraulic characteristics.

Lithium-Boiling Potassium Test Loop

Interim Report

I. Introduction and Objectives

High temperature, alkali metal, Rankine cycle nuclear systems are prime contenders as power sources for potential electric propulsion application. When compared in a superficial sense with such alternate possibilities as thermionic and Brayton cycle nuclear systems in the power range of 100–1000 kWe, using equivalent design constraints and engineering optimism, they generally maintain a distinct weight advantage. This potential weight advantage may not be realistic. As is true with most conceptual systems early in their design evaluation, many fundamental problem areas do not influence weight estimates or the steady-state full power equations. Comparing the Rankine, Brayton, and thermionic modes of power conversion, it is apparent that the Rankine system is, in a hydraulic sense, the most complex and least understood of the three as a direct consequence of its two-phase fluid characteristics. Problems of boiling and condensing stability and overall system response characteristics are not unique to space nuclear applications. They have been encountered and handled, often empirically, in nuclear and conventional steam power plants for many years. Existing theoretical stability models have not been devel-

oped to the degree that they can confidently be applied to predict behavior even in water systems. Alkali metal systems, using boiler concepts of straight-through, non-recirculating, negligible-inventory type designed to operate in zero gravity environment pose additional unknown problems not usually encountered in land-based power plants. Additional complexity is introduced by the nature of alkali metals themselves being much more sensitive than water to geometry and bubble nucleation sites and prone to large degrees of liquid superheat.

As a consequence of these and other areas of uncertainty involving Rankine cycle systems, it was decided in 1961 to construct a two-loop lithium-boiling potassium test facility for studying these problem areas. Actual loop construction commenced in 1963 and the initial phases of operation were begun in late 1965.

The loop is constructed of columbium–1% zirconium alloy and designed to operate at temperatures up to 2100°F. The primary purpose of this facility is to investigate overall transient and steady-state characteristics of

a two-loop Rankine cycle pilot plant which contains all the essential components of a Rankine space power plant and which approximately simulates velocities, temperatures, pressures, transit times, and heat fluxes in the range of actual system interest. Transient investigations include startup, load perturbations, shutdown, and the effects of various control concepts on system performance. The primary heat source is direct resistance heat generation in a section of tube wall and liquid metal, a method which lends itself to programming of reactor kinetic equations for simulation of reactor power response to various system perturbations. The system is instrumented to the extent that steady-state local-boiling heat transfer coefficients and two-phase pressure drop data are being determined for a variety of operating parameters. Performances of individual components are also being evaluated for potential application to actual systems. The loop is not intended as a corrosion or component-life test facility.

This report covers the construction, instrumentation, component descriptions, debugging and initial operating experiences accumulated to date.

II. Loop Description

Figures 1 and 2 show a flow schematic and an isometric of the loop, and Table 1 shows the operating conditions. A photograph of the uninsulated loop is shown in Figure 3. The primary side lithium flow enters a direct current resistance-heated helical coil to which reactor kinetic equations may be programmed for simulation of power response to various system perturbations. The lithium then enters a centrifugal pump which employs a combination recirculation and liquid level indicator sump, flows in turn through an electromagnetic flowmeter, then through the boiler, and finally returns to the heater inlet. About 10% of the lithium flow passes through a bypass line to an yttrium-gettered hot trap which is located in the coolest part of the system to minimize mass transfer effects. The pump was placed downstream of the heater for arrangement considerations and therefore operates at the highest system temperature.

The secondary side potassium enters a countercurrent annular-flow boiler, exits through a flow orifice to the

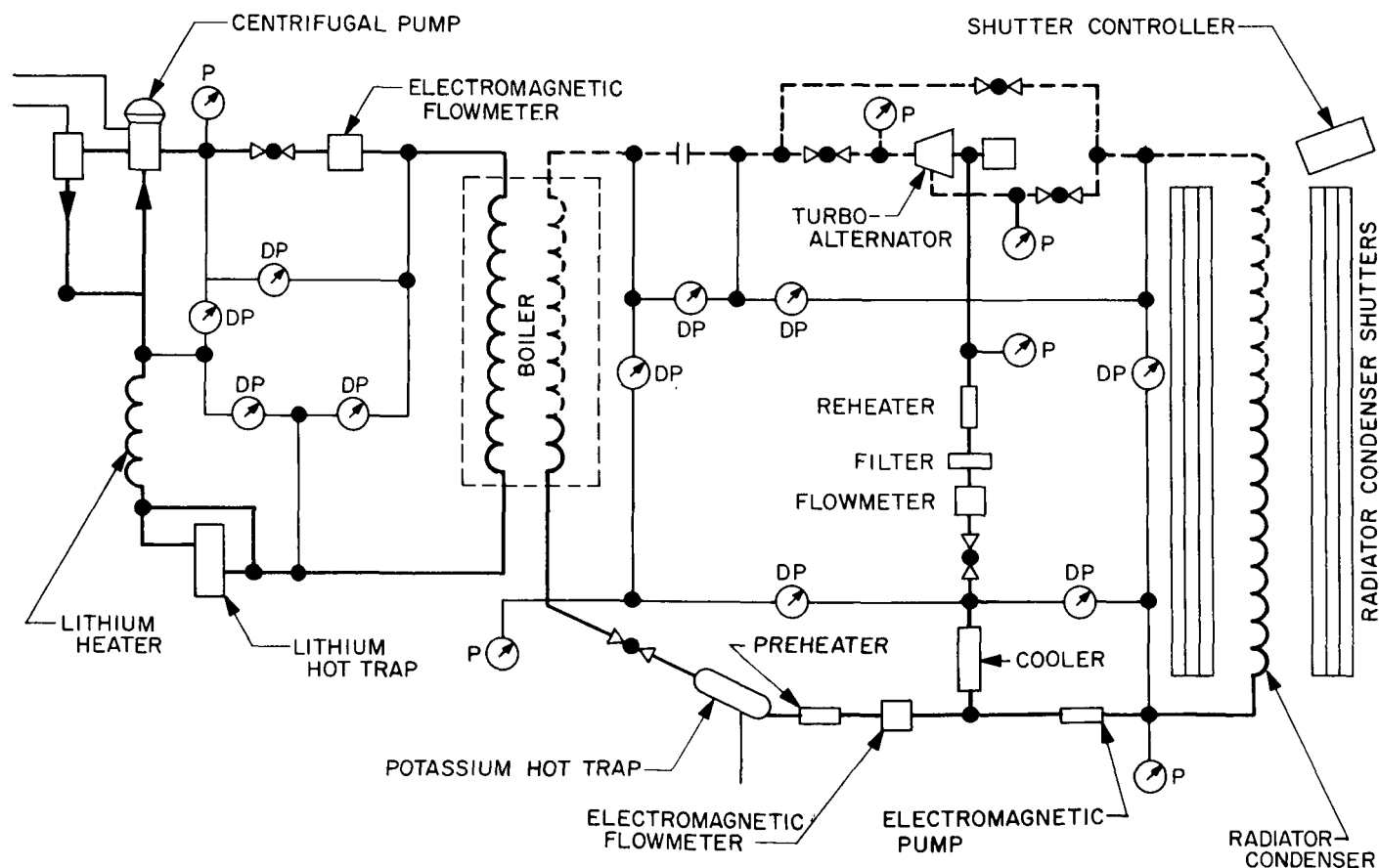


Fig. 1. Lithium-boiling potassium loop flow schematic

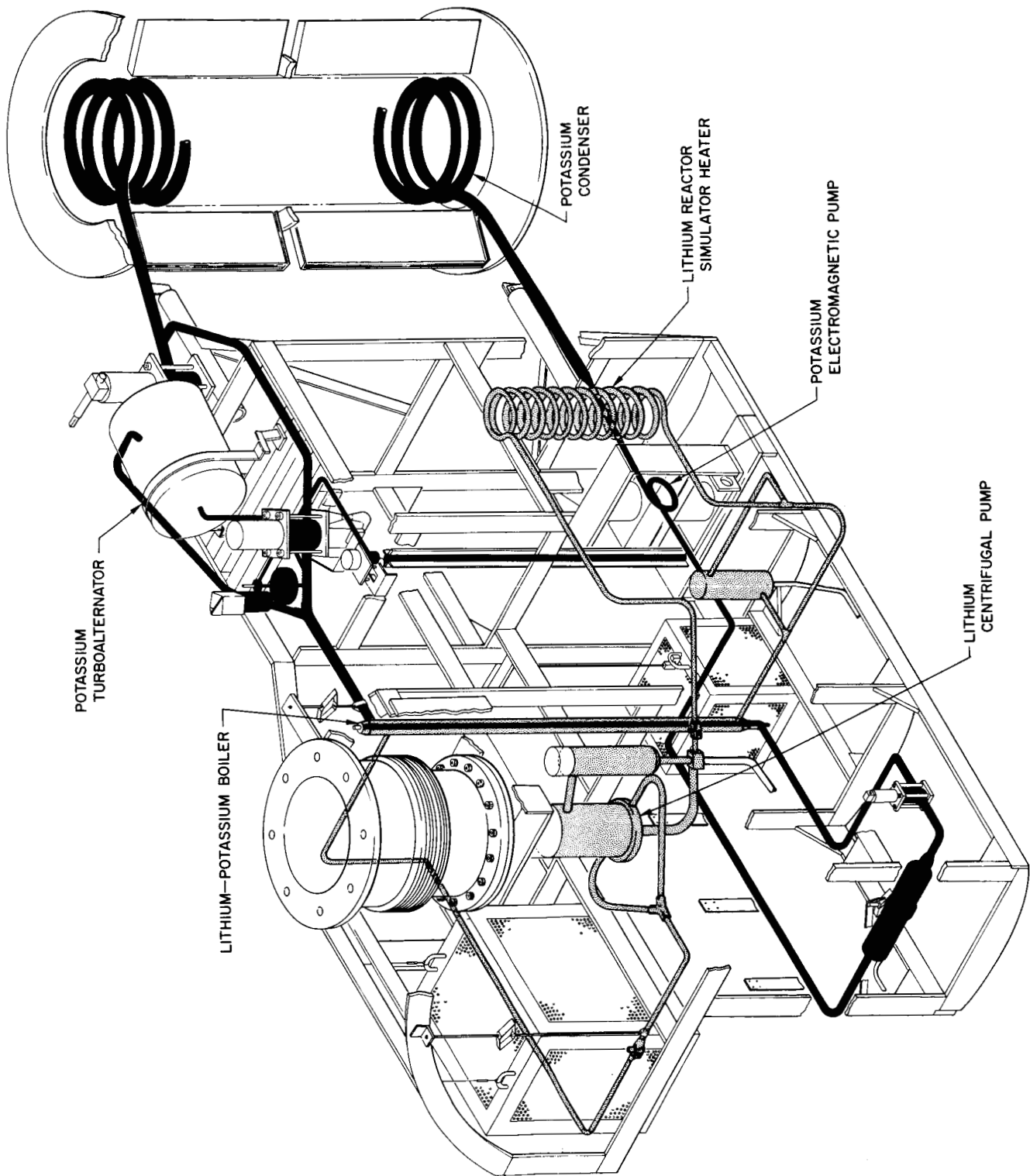


Fig. 2. Lithium-boiling potassium loop isometric

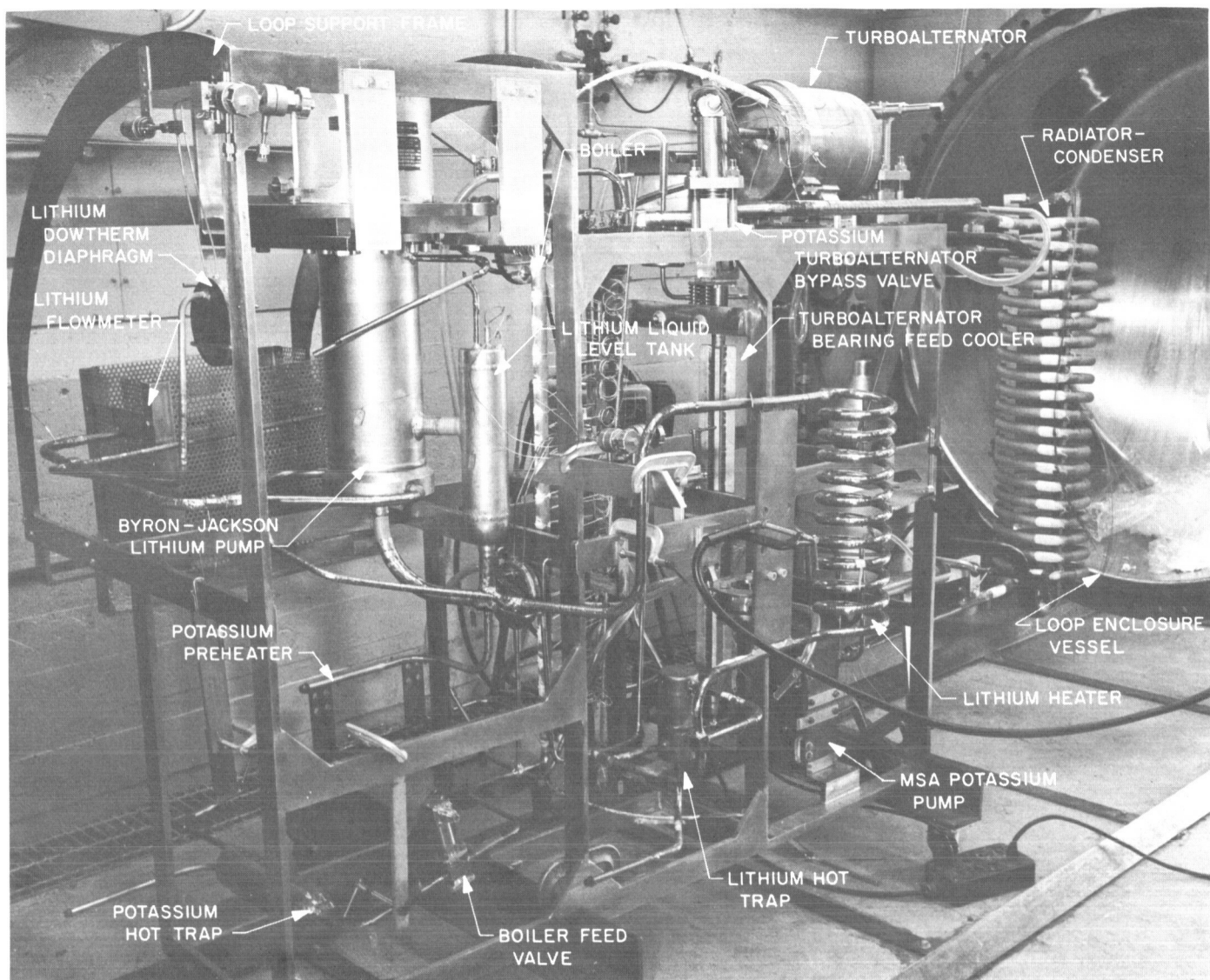


Fig. 3. Lithium-boiling potassium test loop

turbine and is then condensed in a radiating condenser. The condenser is surrounded by an array of rotatable radiation shields to vary the effective condenser radiation area. The potassium exits from the condenser subcooled, flows in turn through an electromagnetic pump, an electromagnetic flowmeter, a preheater, a full-flow zirconium-gettered hot trap, and a liquid throttle valve, and then returns to the boiler inlet.

The loop is contained in a main enclosure vessel that is 5-ft in diameter by 7-ft long; the condensing radiator and fill and dump system are contained in auxiliary enclosures as shown in Fig. 4. The system is operated in a recirculat-

ing argon atmosphere slightly above atmospheric pressure. Make-up argon has an oxygen vapor and water vapor content of about 1 ppm each.

The loop is foil-wrapped with two layers of tantalum and one layer of zirconium, and insulated with about three inches of *Glasrock* foamed high-purity silica.

All material that comes in contact with fluids above 1500°F is Cb-1Zr with the exception of tungsten valve facings, hot trap getters, and the turbine wheel. The fill and dump system is constructed of types 304 and 321 stainless steel.

Table 1. 30 kW–2100°F loop operating conditions

Item	Operating conditions	Supplier and type
Lithium (liquid)		Footc Mineral Company
Flow rate	1 to 10 gpm	
Temperature	2100°F	
Pressure	Up to 20 psig	
Potassium (liquid)		MSA Research
Flow rate	0 to 1 gpm	
Temperature	1500 to 2000°F	
Pressure	Up to 200 psig	
Centrifugal pump (lithium)	Up to 10 gpm at 100 ft 2100°F service	Byron-Jackson
EM pump, dc (potassium)		MSA Research
Temperature	1500°F	Cb-1Zr
Head-flow, nominal	90 psi–150 lbs/h	
Swing gate valves (bellows seal)		Valcor Engineering
Lithium	2100°F lithium service	5/8 in. OD
Potassium	2000°F boiling potassium service	3/4 in. Schedule 80
EM flowmeters		MSA flowmeter FM-4
Lithium	2100°F service	5/8 in. OD 1/16 in. wall
Potassium	1500°F service	Cb-1Zr duct 3/8 in. OD Cb-1Zr duct
Diaphragm	Lithium and potassium pressure measurements	Cb-1Zr
Potassium boiler	Loop design conditions	JPL
Turboalternator		Aeronutronic
Inlet temperature	1900°F	Cb-1Zr case
Exhaust temperature	1500°F	Molybdenum turbine wheel, shaft, alternator rotor
Weight flowrate	0.0324 lbs/s	SS 316 alternator housing
Design speed	12,000 rpm	
Electrical output	1.0 kW	
Dump tanks and valves (Argon, vacuum and fill)	500°F service	Material SS 304 and 321

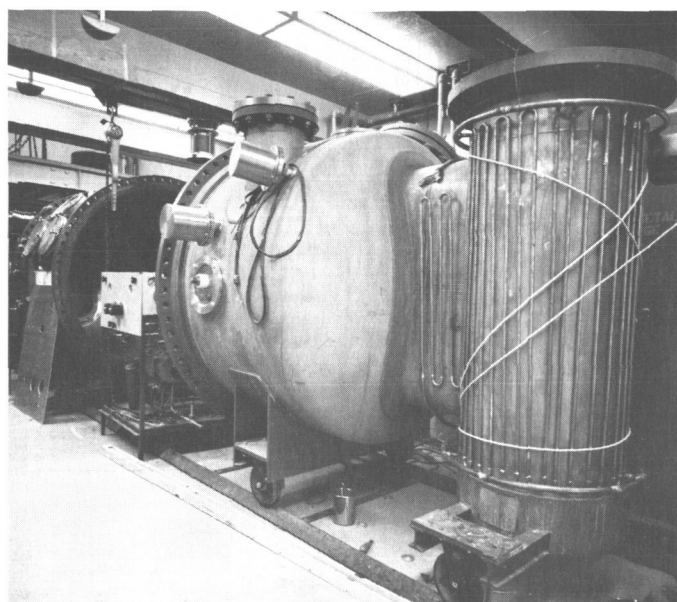


Fig. 4. Lithium-boiling potassium test loop containment vessel

An attempt has been made in the loop design to permit variation of operational parameters for studying various regimes of stable and unstable operation, particularly when the primary heater is programmed to simulate a nuclear reactor of varying negative temperature coefficients and when different system control techniques are used.

The lithium centrifugal pump is a variable speed, dc-motor-driven unit which permits change in primary coolant flow rate. The potassium system I²R preheater permits variation in boiler inlet subcooling from several hundred degrees to a few degrees below saturation. The boiler inlet throttle valve allows liquid pressure drop from the variable power electromagnetic (EM) dc conduction pump to boiler inlet to be varied from less than 1 psi to full pump head.

As a result of these characteristics, it is therefore possible to simulate a broad range of potential system operating conditions and to study their quantitative effects on system performance.

III. Loop Components and Subsystems

A. Lithium Loop

1. *Lithium centrifugal pump.* The lithium pump is a vertically mounted centrifugal unit. Figure 5 shows a section view of this pump.¹ The size of the pump discharge

¹Borg-Warner Corp., Byron Jackson Division, Vernon, Calif.

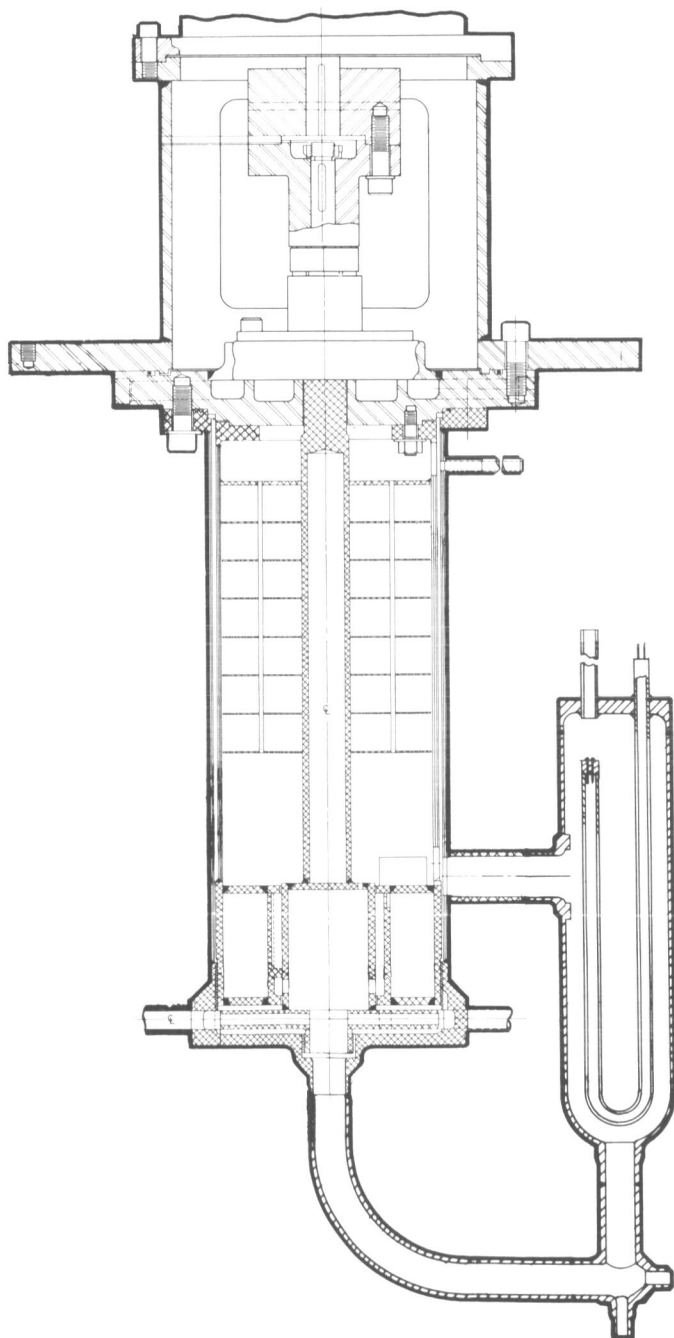


Fig. 5. Lithium centrifugal pump cross section

line is $\frac{1}{2}$ in., the suction is $\frac{3}{4}$ in., and the impeller is $5\frac{3}{4}$ in. in diameter. A photo of the assembled pump and motor is shown in Fig. 6. A lithium-lubricated, hydrostatic bearing supports the impeller shaft and is located immediately above the impeller. The upper portion of the shaft is maintained in alignment by a rigid coupling located between it and motor shaft, the motor bearings serving dual purposes in this case. The motor is a variable speed, 2-hp, dc motor with grease lubricated bearings. The pump shaft seal is a dry gas bellows seal (carbon face seal) that prevents leakage of the argon cover gas above the free surface

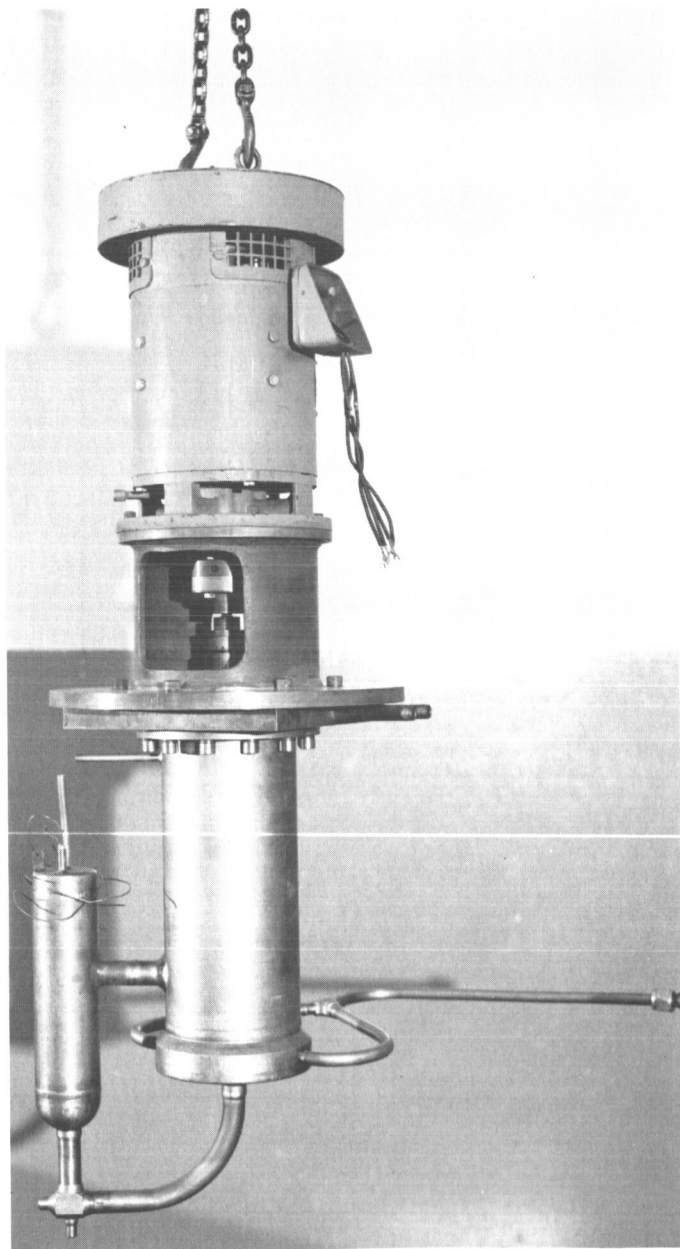


Fig. 6. Lithium centrifugal pump and drive motor

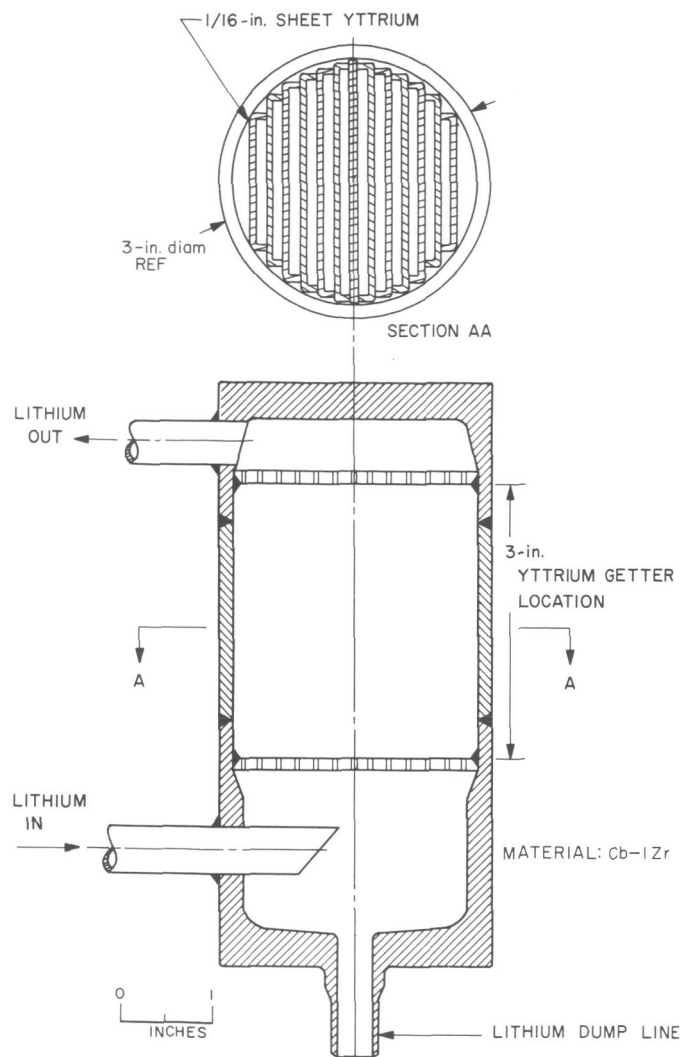


Fig. 7. Lithium hot trap cross section

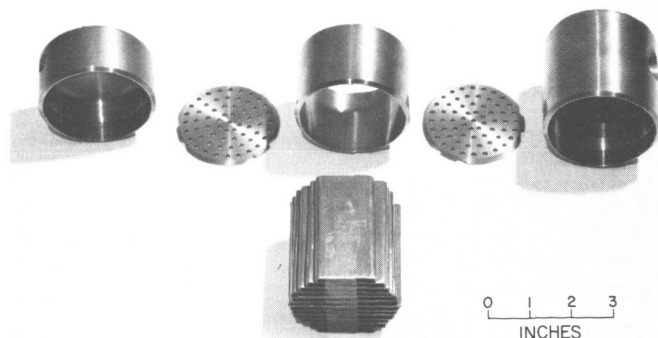


Fig. 8. Lithium hot trap component parts

of lithium. The pump motor is enclosed in a steel dome which is also under slight positive pressure of argon as a backup to prevent contamination of the lithium. The pump's outer case, inner case, bearings, impeller, shaft and thermal radiation shields are all constructed of Cb-1Zr. The pump delivers 10 gpm at 100-ft head (Li) at a speed of 3550 rpm.

2. Lithium hot trap. The lithium hot trap is in a bypass configuration that is designed to accommodate 10–15% of the lithium flow. The hot trap, constructed of Cb-1Zr, is 3 in. in diam. by 6½ in. long. The getter material is yttrium. The yttrium is in the form of bent plates as shown in Figs. 7 and 8. This allows easy flow of the lithium and insures structural integrity of the unit, thus preventing chips of getter material from disintegrating and being swept downstream after oxidation. The hot trap has an active getter area of 100 in.². A photograph of the assembled hot trap is shown in Fig. 9.

3. Lithium flowmeter. The flowmeter for the lithium circuit is an electromagnetic type. Two electrodes are welded to the ⅝-in. OD tubing mutually perpendicular to the flow and the magnetic field. The magnetic field is provided by a permanent magnet with a field strength of 914 gauss. This type of flowmeter is a linear device and the accuracy depends upon the care that is taken in obtaining resistivities of the fluid and conduit, the dimensions of the conduit, and the magnetic flux. With reasonable care, these units should be accurate to within 5% of the actual flow; therefore, this flowmeter was not calibrated before its installation in the loop, but was calibrated afterwards.

4. Lithium heater. The lithium heater is an 11-turn coil fabricated of Cb-1Zr tubing with a ⅝-in. OD and a ⅛-in. wall. A drawing of this unit is shown in Fig. 10. The coil helix has a mean radius of 5 in. Direct current electrical power is fed into the Cb-1Zr bus bar which is welded to the central coil. The bus bar which is welded to the inlet and outlet tubing of the coil is the ground strap, and also serves as a structural member for the lithium heating coil. A photograph of the potassium-heating coil and bus bars is shown in Fig. 11.

Figure 12 is a plot of the calculated lithium heating coil resistance vs temperature. A step change in the coil resistance at the melting point of lithium is due to the step change increase in resistivity of the lithium when it melts. At a nominal mean temperature of ~2050°F, the calculated coil resistance is ~3.3 mΩ. The actual measured coil resistances are slightly lower than the calculated values;

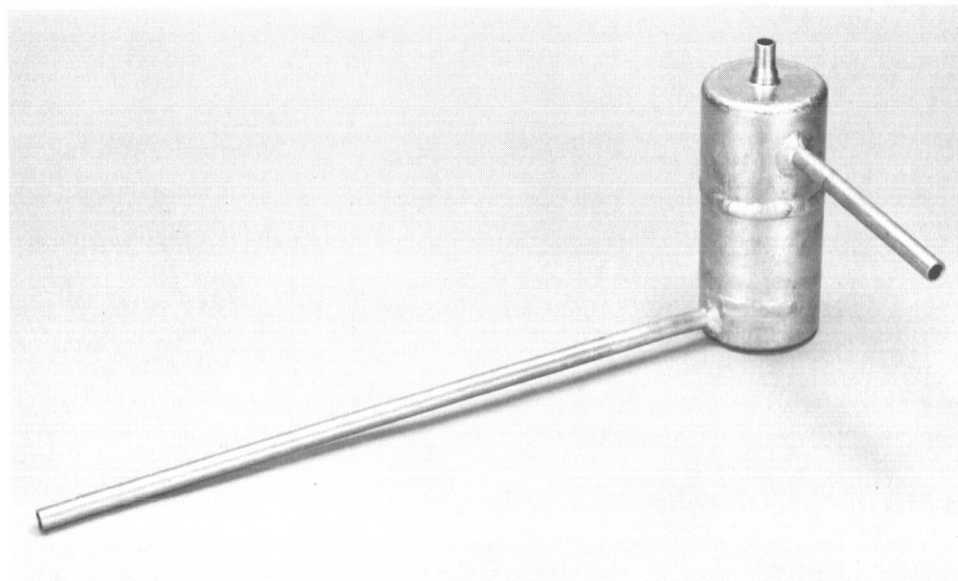


Fig. 9. Lithium hot trap

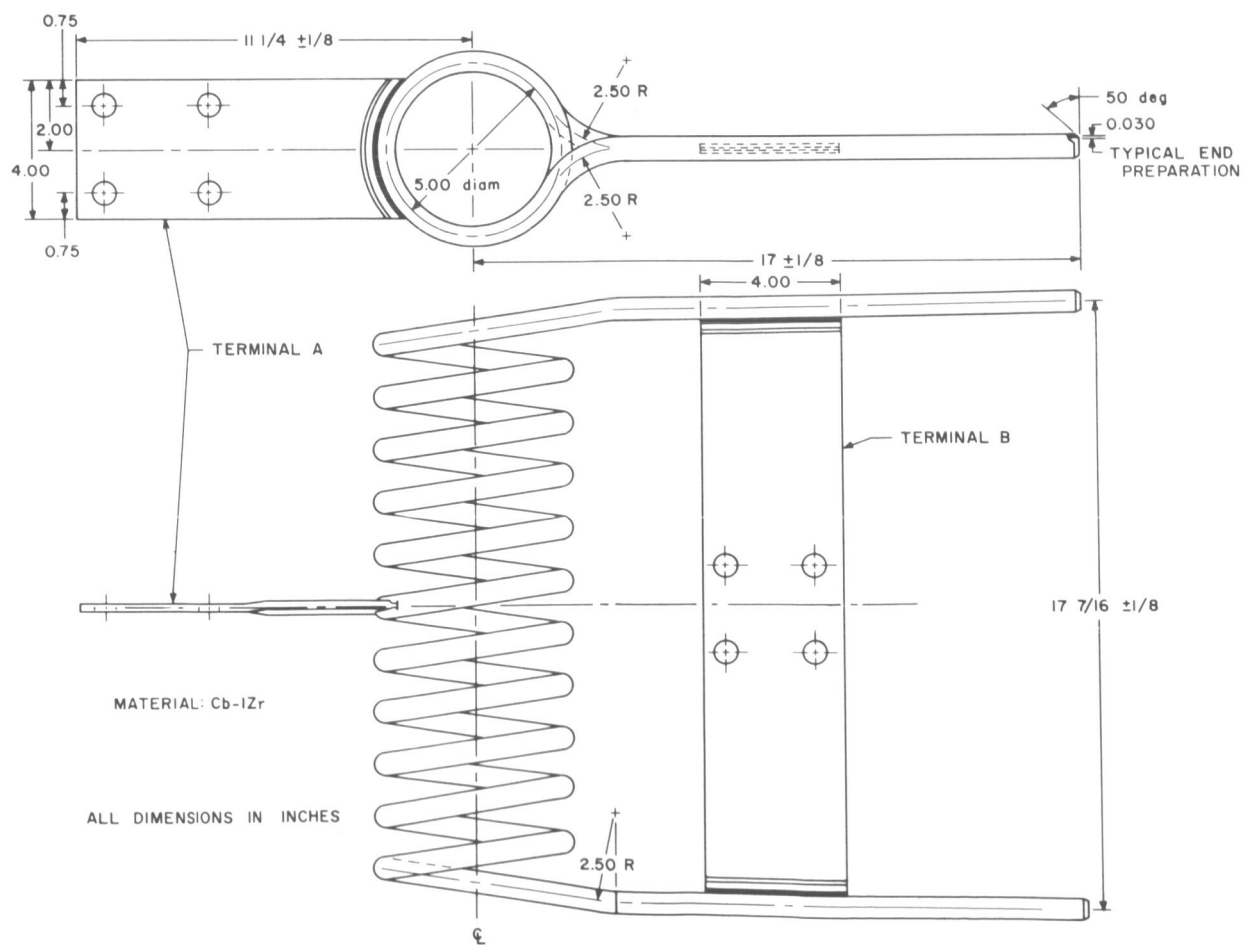


Fig. 10. Lithium heater schematic

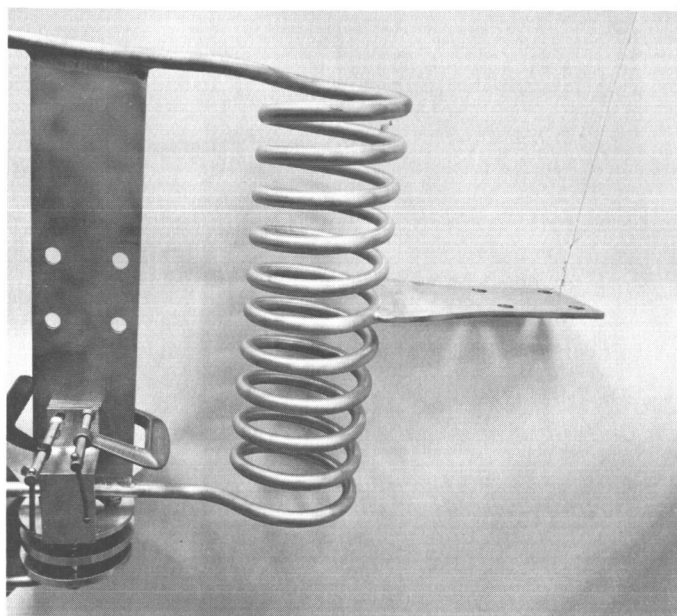


Fig. 11. Lithium heater

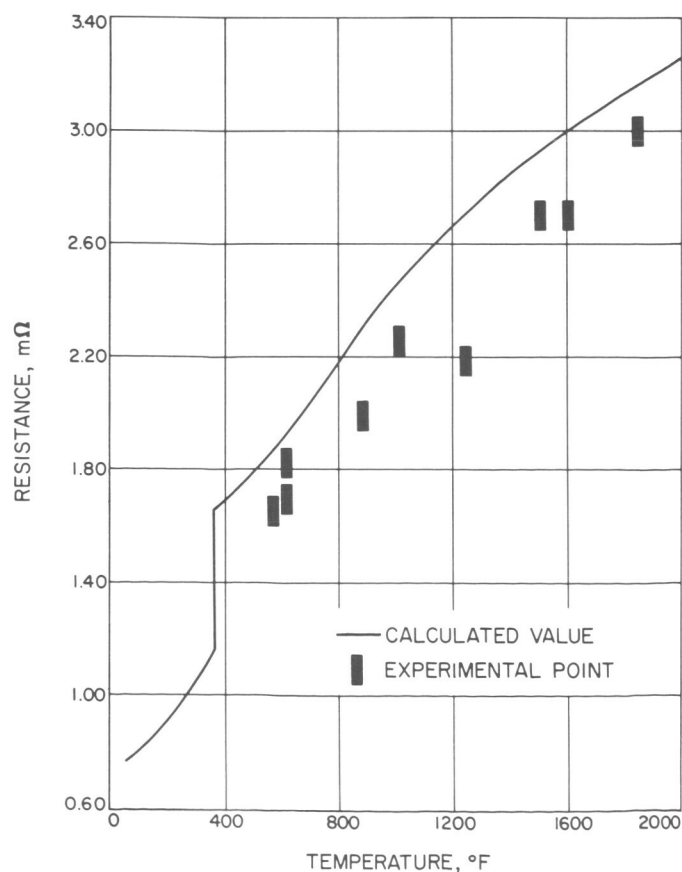


Fig. 12. Lithium heater electrical resistance vs temperature

however, as can be seen in Fig. 12, there is quite good agreement over the operating temperature range of the lithium heater. At 2050°F, the actual coil resistance is $\sim 3.15 \text{ m}\Omega$, only 4% lower than the calculated coil resistance.

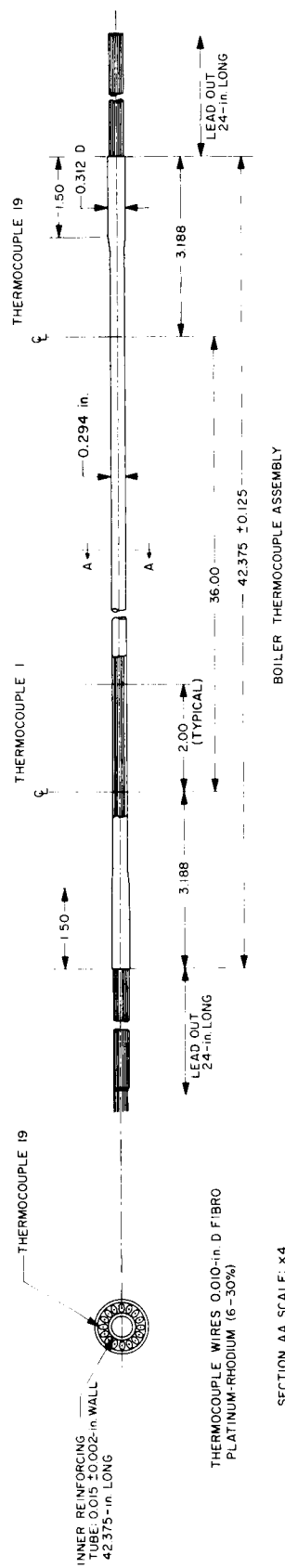
Because of lithium loop heat losses, $\sim 35 \text{ kW}$ must be generated in the lithium heater in order to have the nominal 30 kW available to transfer to the potassium at the boiler. For 35 kW input to the lithium heater, the current input to the coil will be $\sim 3340 \text{ amp}$ at 10.5 V . Because of lead cable losses, the voltage at the power supply will be $\sim 11.5 \text{ V}$.

Power is carried to the lithium heater from the power supply by 4/0 copper cables. A solid copper bar feedthrough penetration transmits the current from the external to the internal 4/0 copper cables. All high-current components of the loop have their own copper power feedthrough, but a common ground is used for the lithium heater, the potassium preheater, and the potassium dc electromagnetic pump.

Thermocouples at the inlet and outlet of the lithium heater are used to measure the rise in temperature of the lithium flowing through the heater. Knowing this temperature rise, and the electrical power input to the coil, permits calculation of the lithium flow rate and, subsequently, *in situ* calibration of the lithium flowmeter. An additional, high temperature control thermocouple is positioned on a coil midway between the center feed bus bar and the top coil. This thermocouple is used in conjunction with an automatic alarm-scam control system so that an alarm or heater shutdown will occur if the control-thermocouple temperature of the lithium heater exceeds a manually preset temperature limit.

B. Potassium Loop

1. Boiler. The boiler is a once-through, counter-flow, annular-passage unit fabricated from three tubes, with appropriate inlet and outlet nozzles. A drawing of the boiler is shown in Fig. 13. A pictorial cross section of the boiler in Fig. 14 illustrates the annular flow channels and the central thermocouple-assembly tube. Except for the thermocouples, the boiler is constructed entirely of Cb-1Zr. The outer tube is $\frac{3}{4}$ -in. Schedule 40 pipe (Cb-1Zr) with a 1.050-in. OD by 0.824-in. ID. The middle tube is centerless ground to 0.594-in. OD. The ID is 0.500 in. The inner tube is 0.294-in. OD and contains 19 thermocouples. The overall length of the boiler is 41.9 in. However, heat is transferred from the lithium to the boiling potassium



SECTION AA SCALE: x4

BOILER THERMOCOUPLE ASSEMBLY

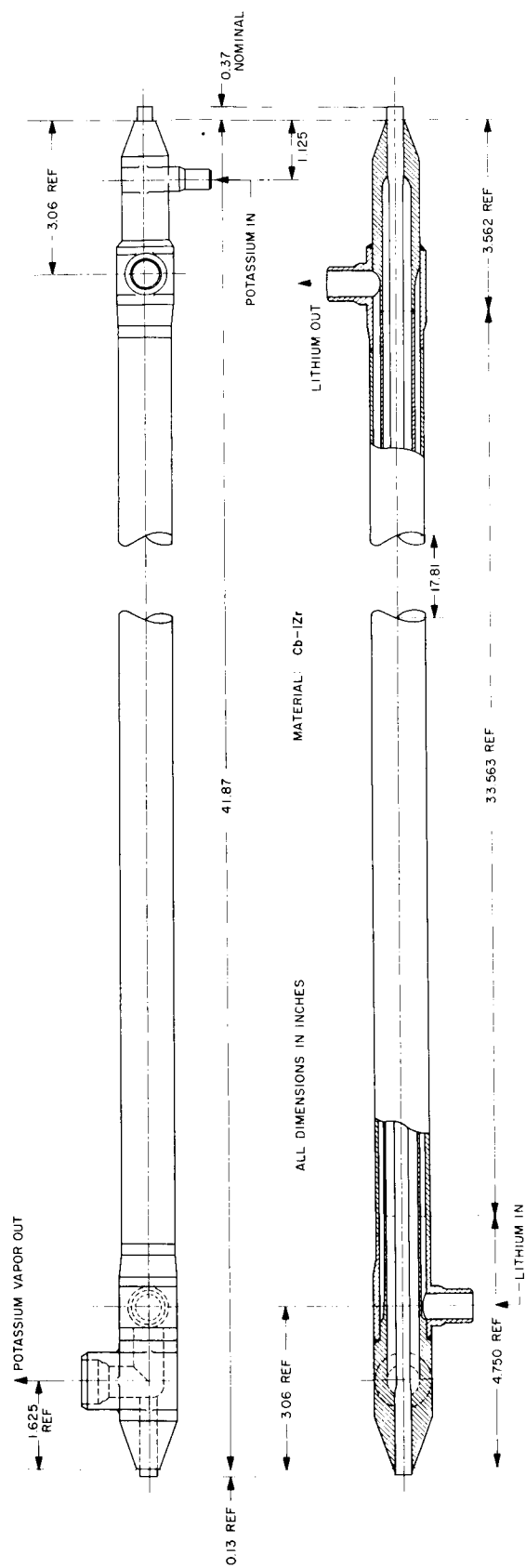


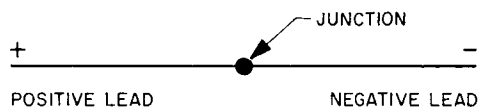
Fig. 13. Lithium-boiling potassium loop boiler assembly drawing

over a nominal length of 36 in. As installed in the test loop, the boiler is vertically oriented. A photograph of the boiler component parts is shown in Fig. 15.

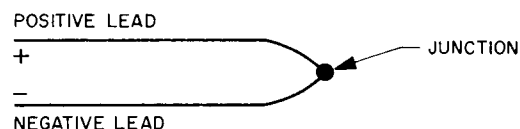
The thermocouple assembly tube, containing nineteen thermocouples, is fitted axially down through the center of the boiler. A cross section of the thermocouple tube shows that the 19 thermocouples themselves are fitted in an annular array in the thermocouple tube. The thermocouples are platinum-6% rhodium : platinum-30% rhodium; the wire diameter is 0.010 in. Unlike conventional thermocouple construction in which the thermocouple junction is formed by welding together the ends of two parallel oriented dissimilar wires, these thermocouples have their

dissimilar lead wires in-line on the same longitudinal axis (positive leads come out of one end of the thermocouple assembly tube and negative leads come out of the other end): e.g.,

TYPICAL BOILER THERMOCOUPLE

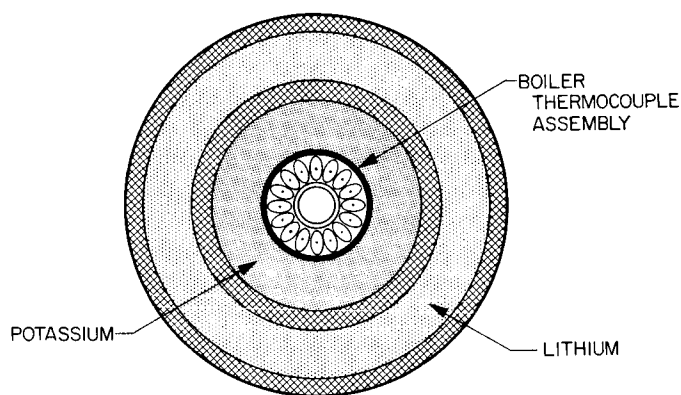


NORMAL THERMOCOUPLE



The thermocouple junctions are spaced axially on 2-in. centers and lie on a curve which forms a one-turn helix starting at the bottom and ending at the top of the boiler. These thermocouples are used to measure the potassium vapor temperature at various axial locations in the boiler.

Platinum-rhodium thermocouples are also fitted to the outer diameter of the boiler at the same axial locations at which the inner platinum-rhodium thermocouple junctions are located. This arrangement allows for the determination of overall temperature difference from the outside of the boiler to the inside of the potassium stream at any axial location. Diametrically opposite from, but at the same axial location as, the platinum-rhodium thermocouples are tungsten-rhenium thermocouples fitted on the



SECTION THROUGH LITHIUM-BOILING POTASSIUM LOOP BOILER ASSEMBLY

Fig. 14. Boiler cross section

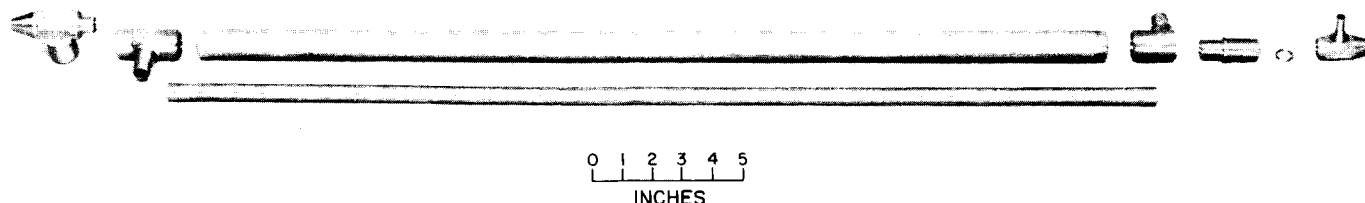


Fig. 15. Boiler component parts

outer boiler shell wall. These thermocouples will provide the temperature change of the lithium in the lithium channel and also serve as a stable reference for the external platinum-rhodium thermocouples which tend to drift at temperature. Figure 16 is a photograph of the boiler, in the inert gas weld chamber, fitted with the external platinum-rhodium and tungsten-rhenium thermocouples.

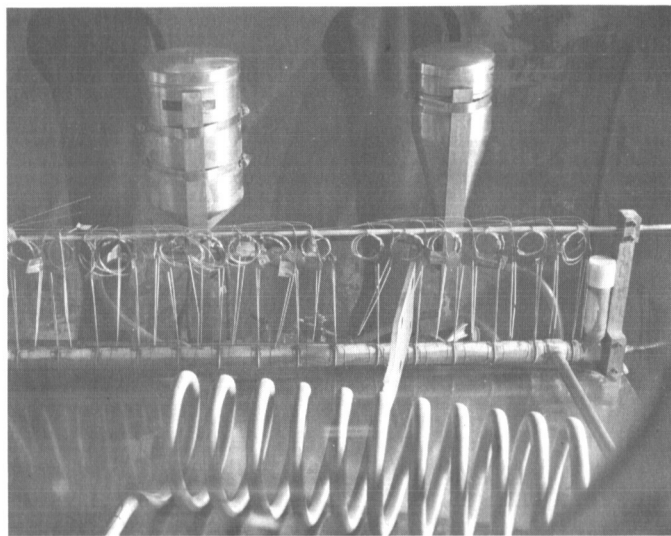


Fig. 16. Boiler with external thermocouples attached

A spiral wire (0.090-in. diam) wrap with a pitch of 11 in. is used to maintain the concentricity of the inner annulus (through which the potassium flows) with respect to the thermocouple assembly tube. This spiral wire wrap also serves to centrifuge any potassium droplets, which may be entrained in the potassium vapor, against the lithium-heated wall, thereby increasing the high quality vapor heat transfer coefficient. Subcooled potassium liquid enters the boiler at the bottom, rapidly reaches saturation temperatures, and then boils. The vapor flows upward through the inner annulus and exits at the top of the boiler. Liquid lithium enters the top of the outer-flow annular channel, flows downward, and exits at the bottom. For the nominal lithium flow rate of 1250 lb/h the lithium velocity in the boiler is 6.1 fps. At a nominal flow rate of 150 lb/h, the boiler inlet liquid-potassium velocity is 1.2 ft/s and the outlet potassium-vapor velocity (at 85% quality) is ~ 200 fps. At a point approximately one-third of the boiler height from the bottom, the calculated centrifugal acceleration on the potassium vapor and contained droplets (assuming no slip) is approximately 500 g's. This large centrifugal acceleration will cause the entrained liquid potassium droplets to collide against the outer, lithium-heated wall of the potassium

flow passage, an action which greatly increases the high quality vapor heat transfer coefficients. Figure 17 is a plot of calculated individual and overall heat transfer boiler conductance terms as a function of vapor quality with the dashed line area representing the region in which a large improvement in potassium vapor and overall boiler heat transfer coefficients is to be expected because of the use of the swirl insert. In light of the apparent necessity for high values of superheat for nucleation in boiling liquid metals, it appears desirable to have nucleation sites in the boiler. Such artificial nucleation sites were automatically achieved by the installation of the spiral wire around the thermocouple tube assembly. The welding of the spiral wire to the thermocouple tube assembly, and the presence of the cusp-shaped crevice between the wire wrap and the inner diameter of the tube separating the potassium- and lithium-flow passages, should provide adequate nucleation sites for stable boiling.

Nominally, the inlet temperature of the lithium is 2080°F and the outlet temperature is 2000°F. The nominal potassium saturation-boiling temperature is 1900°F. The nominal rating of the boiler is 30 kW. The expected quality of the potassium exit vapor is $\sim 85\%$. Boiler inlet and outlet pressure was originally measured with Statham absolute pressure transducers. These units are being supplemented by the addition of stainless steel Bourdon gages for increased confidence in, and redundancy of, pressure instrumentation on the boiler. The pressure drop across the boiler is measured with a Pace² transducer.

The boiler was constructed entirely by the TIG welding process with the exception of the closure welds between the end fittings and the thermocouple assembly. This weld was made with an electron beam welder, using a pulsing technique to avoid excessive heat (or weld speed) in this rather unwieldy unit.

2. Potassium orifice. An eccentric flow orifice is fitted into a horizontal section of the potassium vapor tube just downstream of the boiler outlet. The potassium vapor tubing is $\frac{3}{4}$ -in. Schedule 40 Cb-1Zr with an ID of 0.824 in. The orifice hole diameter is 0.25 in. and is positioned at the bottom of the $\frac{1}{16}$ -in.-thick orifice plate flush with the bottom edge of the potassium vapor tubing to allow for complete draining of any liquid potassium. A sketch of this orifice is shown in Fig. 18. Calibration of this eccentric orifice with a two-phase mixture of nitrogen and water was accomplished in a two-phase-flow hydraulic test rig.

²Pace Engineering Company, North Hollywood, Calif.

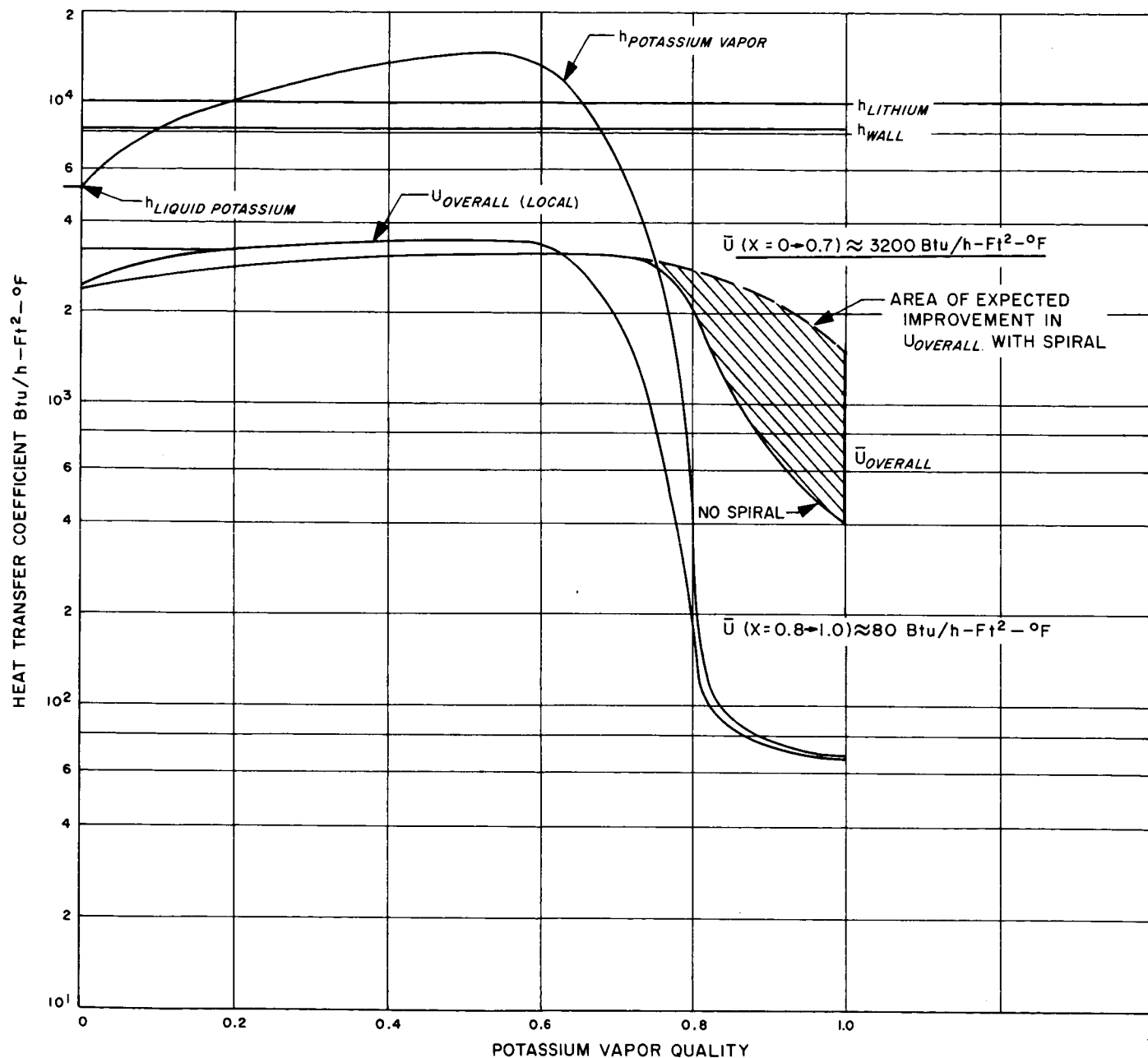


Fig. 17. Calculated boiler heat transfer conductances

These calibration tests were run at a pressure level of 26 psig, which simulates the potassium vapor density at the nominal saturation temperature of 1900°F; additional calibration tests were also performed at 40 psig. The tests were run at two values of nitrogen flow rate: 15 SCFM (Standard Cubic Feet per Minute) and 24 SCFM, the latter value corresponding to the nominal potassium vapor flow rate. From the equation expressing conservation of momentum across the orifice, the following equation may be derived:

$$\Delta P = \frac{G_g^2 v_g}{2g_c C^2 Y^2} \left[1 + S \left(\frac{1-X}{X} \right) \right] \quad \text{Eq. 1}$$

where

ΔP = pressure differential across orifice, lb/ft²

C = coefficient of discharge, dimensionless

G = mass flow rate, $\frac{\text{lbs}}{\text{ft}^2 - \text{s}}$

g_c = gravitational constant, $32.17 \frac{\text{lb mass ft}}{\text{lb force s}^2}$

S = slip = $\frac{\text{liquid velocity}}{\text{gas velocity}}$

X = quality, $\frac{\text{lbs vapor } h}{(\text{lbs vapor} + \text{lbs liquid})/h}$

Y = expansion factor, dimensionless

v = specific volume, ft³/lb

Subscript

g = gas

The unknown values in Eq. 1 are the slip (S), the coefficient of discharge (C), and the expansion factor (Y). Since we have an eccentric orifice being used to measure two-phase-flow pressure drop, Y must be determined initially. However, there are two sets of curves of Y as a function of $\Delta P/P$, for various values of β^* : one set for orifices and another for nozzles. The correct curve for Y vs $\Delta P/P$ must be determined and this curve is expected to lie between the one for orifices and the one for nozzles (Fig. 19). Within each family of curves of Y vs $\Delta P/P$, there are different curves for different values of β . (For this potassium orifice, $\beta = 0.304$.) The expansion factor is also a function of k , the ratio of the specific heats of the vapor

* $\beta = \frac{\text{orifice diameter}}{\text{pipe diameter}}$

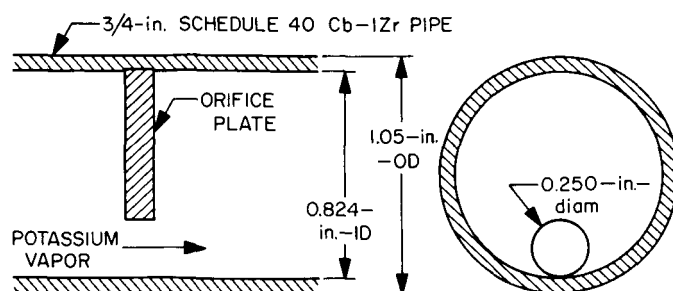


Fig. 18. Potassium vapor orifice

c_p/c_v . (The value chosen for $k_{\text{potassium}}$ is 1.40.) This variation is shown in Fig. 19 through the use of several scales for the abscissa $\Delta P/P$ for various values of k .

Plotting $Y^2 \Delta P/v_g$ vs $(1-X)/X$, for the nitrogen-water calibration data should produce a straight-line plot if the correct curve of Y vs $\Delta P/P$ is chosen. By trial and error, a value of $S = 0.29$ was arrived at [this being the slope of the final straight line plot of $Y^2 \Delta P/v_g$ vs $(1-X)/X$] (Fig. 20). Figure 21 shows the empirically determined (by trial and error) curve of Y vs $\Delta P/P$ which produced the best straight-line plot shown in Fig. 20. As expected, the curve for the expansion factor Y for the eccentric orifice lies between the curve for the orifice and the curve for the nozzle. After a value for S has been determined, the product $C \times Y$ is plotted against the pressure ratio $\Delta P/P$ in order to determine the discharge coefficient for the orifice. The intersection of the extrapolated straight-line portion of the curve with the ordinate ($C \times Y$ at $\Delta P/P = 0$) yields a value for C ; for at $\Delta P/P = 0$, $Y \equiv 1$. In this manner, the value for the discharge coefficient, C , was determined to be 0.72 (Fig. 22).

3. Valves for potassium loop. There are five valves, of two types, in the potassium circuit (exclusive of the fill and dump system). The first type is a toggle gate valve³ (Figs. 23 and 24) which is bellows-sealed. The toggle-stem is maintained in a ball socket and is moved side to side by a differential screw. The bellows movement is then a flexure rather than compression-extension as is found in more conventional valves. All valve parts that contact the liquid potassium are Cb-1Zr except the seal discs, which are tungsten. There are three such valves in the system.

The second type of valve used in the potassium circuit is a conventional plug-and-seat valve. It is activated by a

³Valcor Engineering Corp., Kenilworth, N. J.

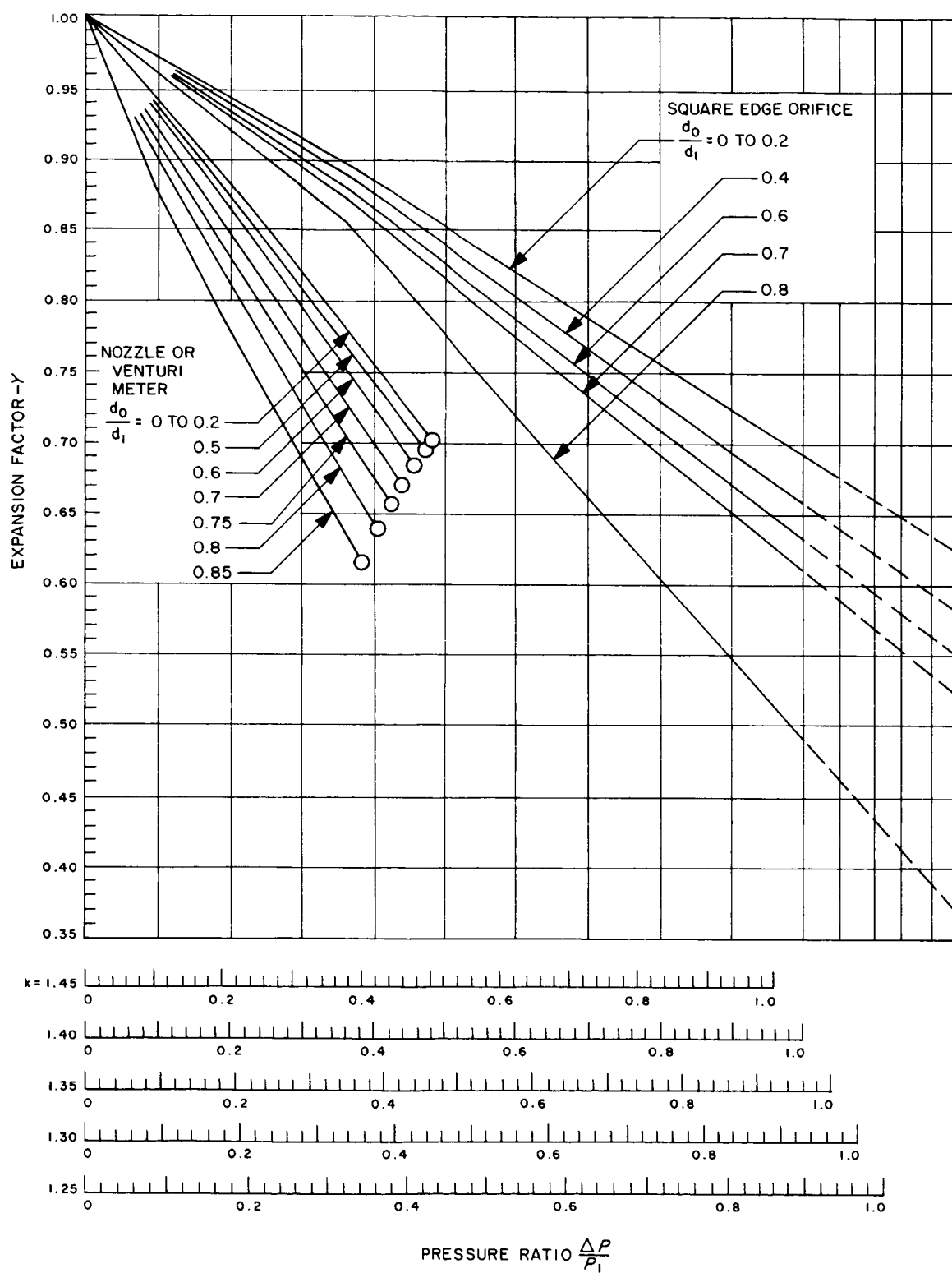


Fig. 19. Net expansion factor, Y , for compressible flow through nozzles and orifices

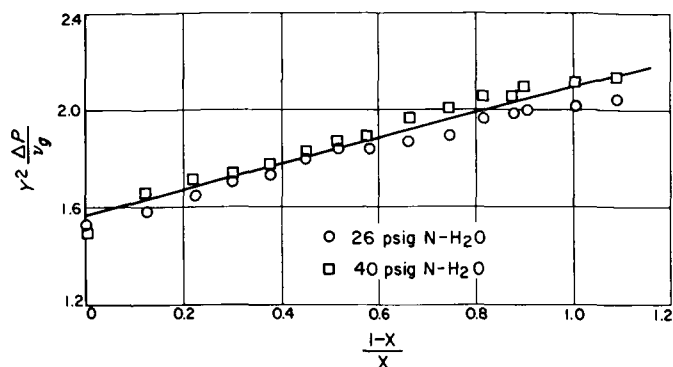


Fig. 20. $Y^2 \frac{\Delta P}{v_g}$ vs $\frac{1-X}{X}$

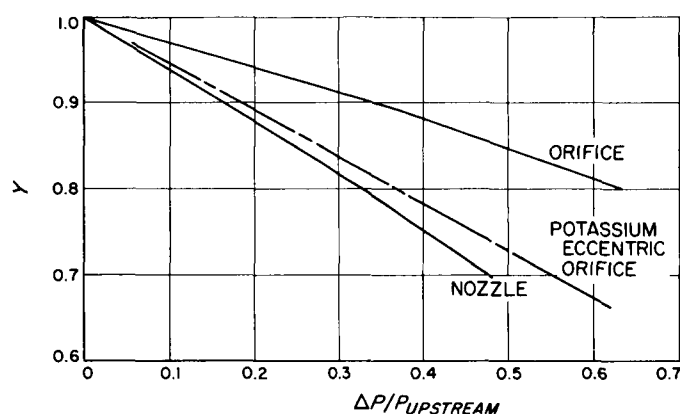


Fig. 21. Potassium orifice expansion factor Y vs pressure ratio $\Delta P / P_{upstream}$

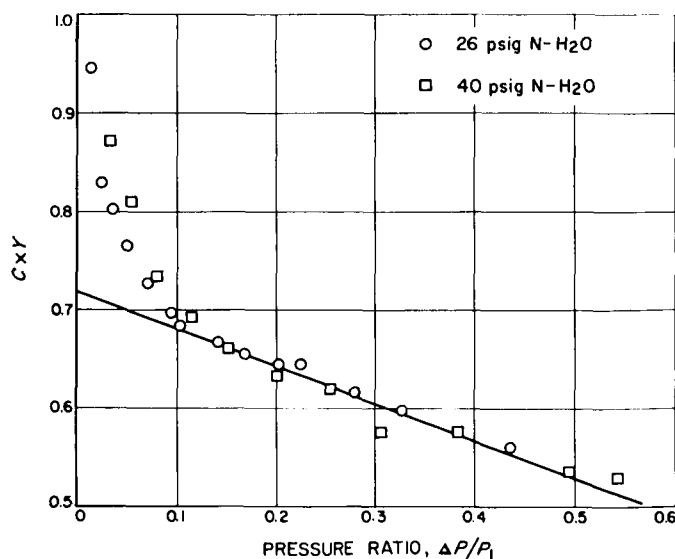


Fig. 22. $C \times Y$ vs pressure ratio

miter gear arrangement on the top of the valve body. All parts in contact with liquid potassium are Cb-1Zr except the tungsten carbide plug. The two valves of this type were fabricated at JPL.

All the bellows used in these two types of valves are of convoluted design and were formed from Cb-1Zr stock. The operation of all valves is manual.

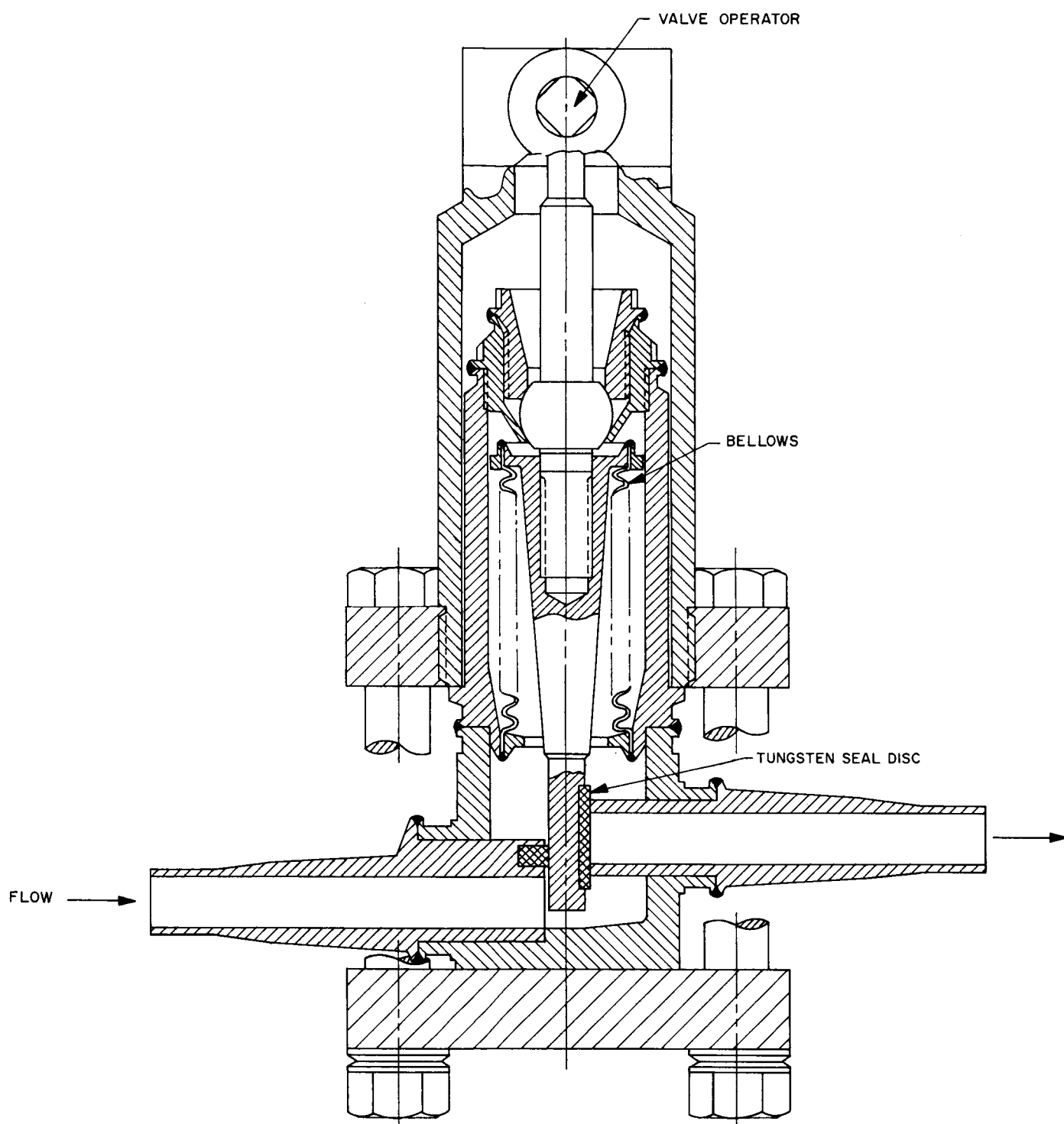
4. Potassium turboalternator. The turboalternator⁴ is driven by potassium vapor; its bearings are lubricated by liquid potassium. The unit, which has no dynamic seals, consists of a stator assembly, a rotating assembly of the turbine wheel and alternator rotor on a single shaft, and a containment vessel of Cb-1Zr. A cross-sectional view of the unit is shown in Fig. 25.

The turbine section consists of a single 6.3-in.-diam turbine wheel fabricated from a molybdenum alloy; the 120 blades were formed by the electro-spark method. The wheel is driven by a two-stage, partial-admission, reentry nozzle. The nozzle sections are made of Cb-1Zr. The rotating assembly is supported by a molybdenum alloy shaft and two tungsten carbide journal bearings. These bearings are hybrid in design, having characteristics of both hydrostatic and hydrodynamic bearings. Liquid potassium is fed to the bearings through the hollow shaft, and bearing leakage flow is discharged to the turbine exhaust. Photographs of the partially and fully assembled turboalternator are shown in Figs. 26 and 27.

The alternator is a three-phase, 200-cycle, 120/208-V induction machine rated at 1.0 kW and excited by static capacitors. The alternator stator assembly is a 500°F maximum-temperature unit housed in an insulated stainless steel jacket and cooled by an externally fed organic fluid (Dowtherm A). No attempt has been made to simulate a high performance alternator or a cooling system. The stator is completely sealed from the potassium by the stainless steel jacket. The induction rotor is completely canned to protect the copper rotor bars and end rings from the potassium.

The inlet and outlet design temperatures of the turbine are 2000°F and 1500°F, respectively. The mass flow rate is 0.0324 lb/s. Thermal input to working fluid is 30 kW. The nominal speed of the unit is 12,000 rpm.

⁴Philco Corp., Aeronutronic Division, Newport Beach, Calif.



2200°F LIQUID-METAL THROTTLE VALVE
 (MATERIAL: Cb-I Zr)
 MANUFACTURER: VALCOR ENGINEERING

Fig. 23. Potassium valve cross section

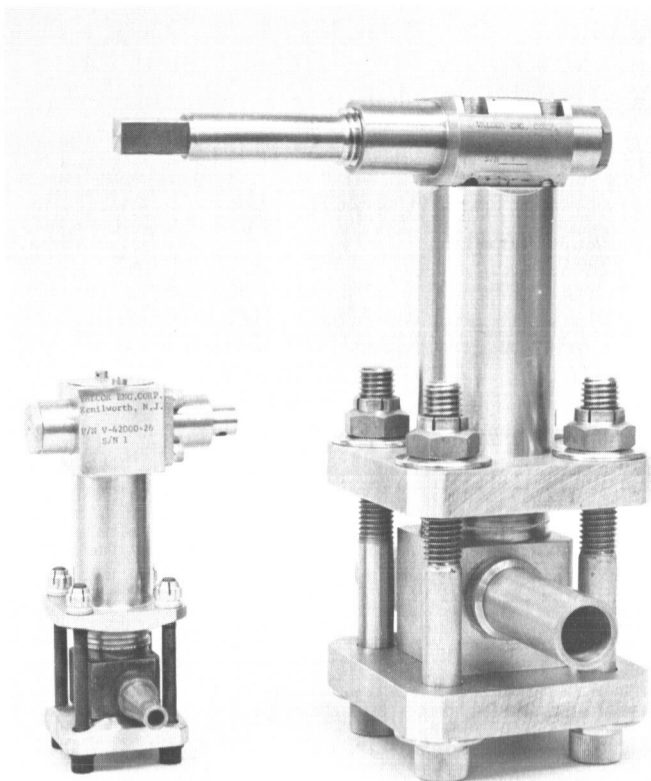


Fig. 24. Potassium valves: boiler feed-throttle valve, left; vapor valve, right

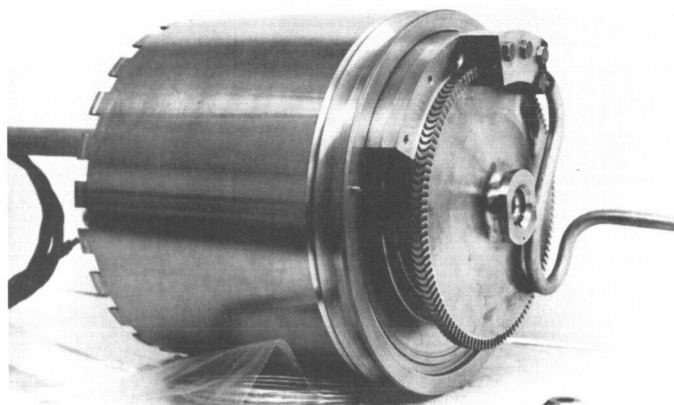


Fig. 26. Potassium turboalternator before installation in columbium containment housing

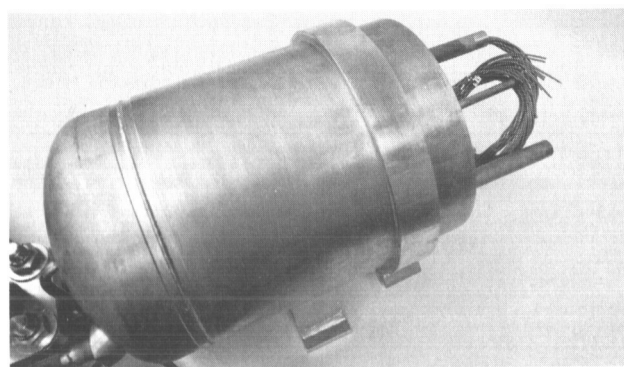


Fig. 27. Potassium turboalternator

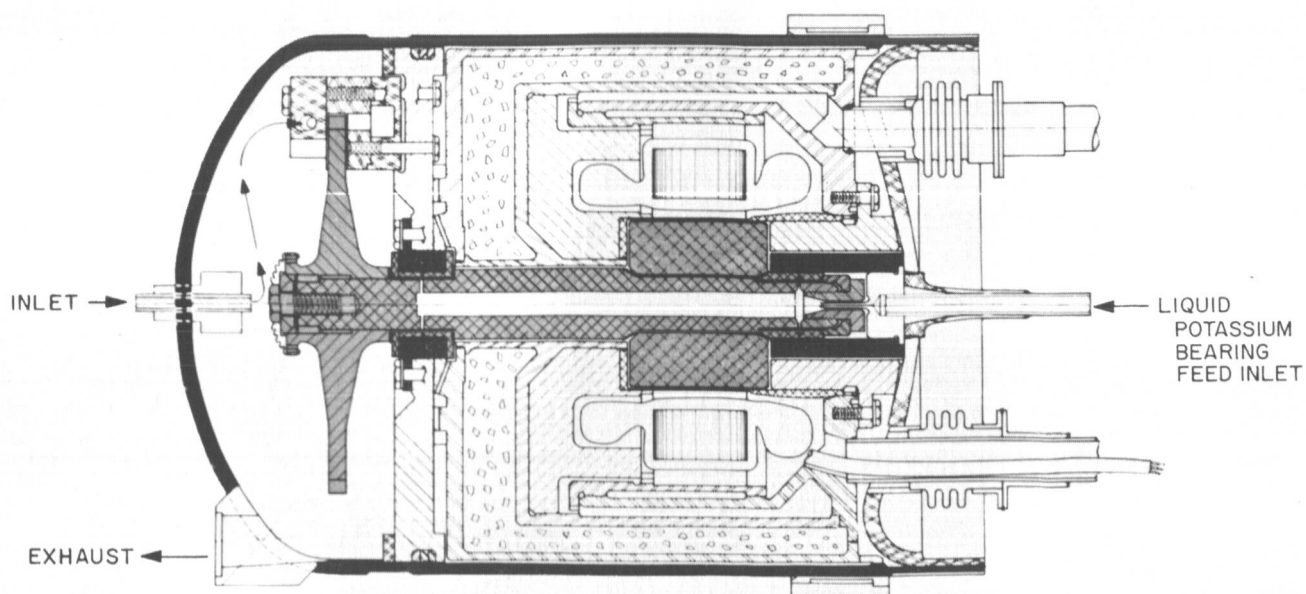


Fig. 25. Potassium turboalternator cross section

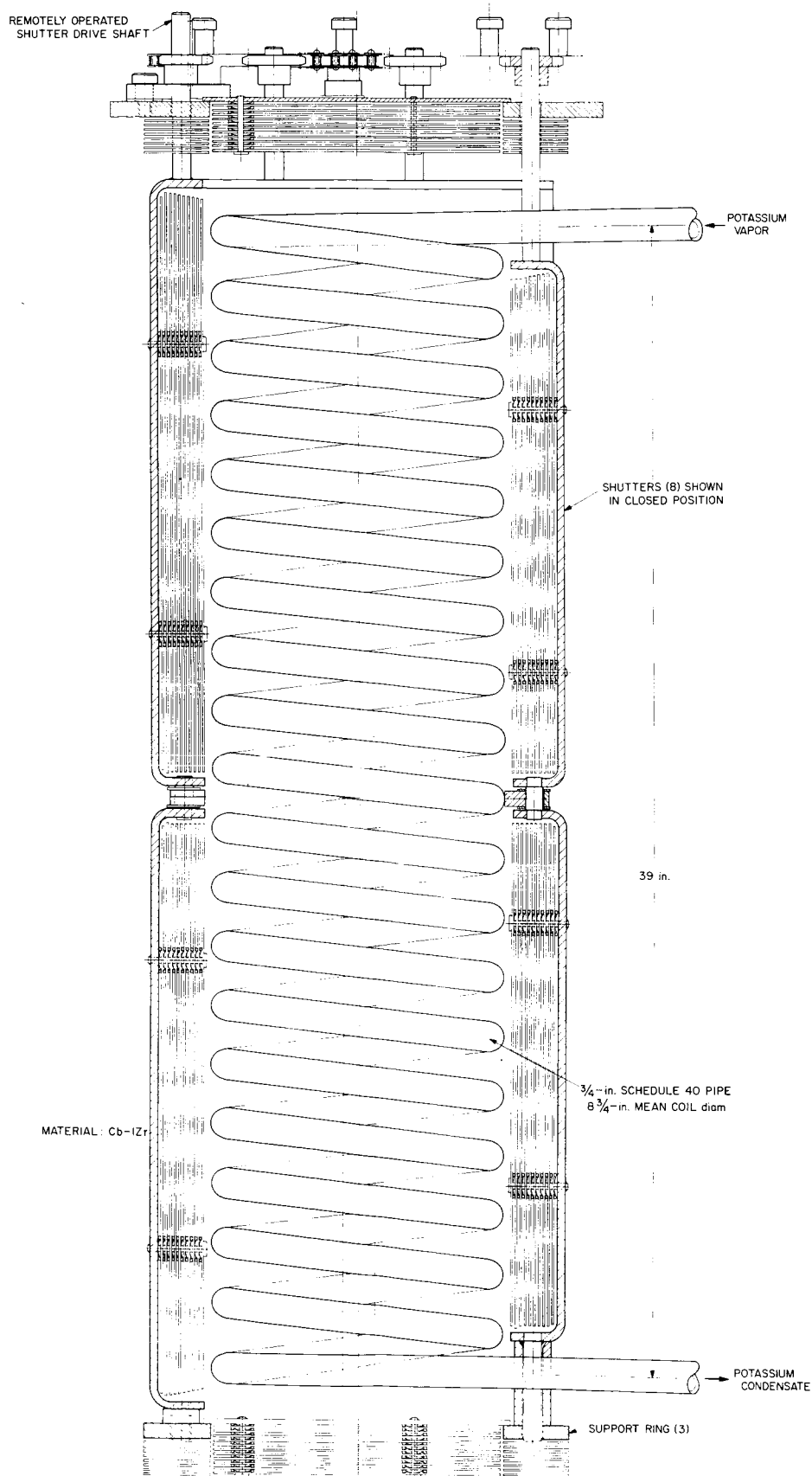


Fig. 28. Radiator-condenser assembly drawing

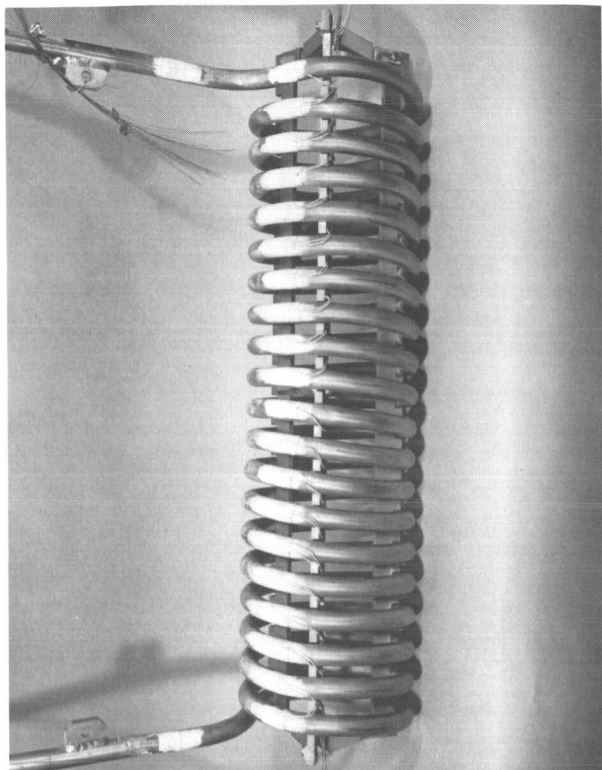


Fig. 29. Tungsten-rhenium thermocouples on condenser

5. *Potassium radiator-condenser.* A drawing of the radiator-condenser (R-C) and its control shutter assembly is shown in Fig. 28. Figure 29 is a photograph of the R-C Cb-1Zr pipe coil with tungsten-rhenium thermocouples attached. Figure 30 is a view of the R-C assembly with the shutters closed, and Fig. 31 shows the assembly with the shutters open. Figure 32 is a photograph of the top of the assembly showing the chain-drive shutter-actuating mechanism.

The R-C coil is fabricated of $\frac{3}{4}$ -in. Schedule 40 Cb-1Zr tubing. The R-C consists of a 20-turn helix having a mean coil diameter of $8\frac{3}{4}$ in. To increase the emittance of the columbium tubing, the coils were grit-blasted to roughen the surface of the tubing. Heat rejection from the R-C coils occurs primarily by radiation to the R-C chamber walls, which are water-cooled. Additional cooling is accomplished by means of the forced or natural circulation of argon gas which circulates through the test enclosure vessel. Heat rejection from the R-C is controlled by eight radiation shutters which, in their fully closed position, completely enclose the R-C coil and minimize heat rejection both by radiation and by convection. Each shutter consists of two halves. The shutters are pivoted at the top,

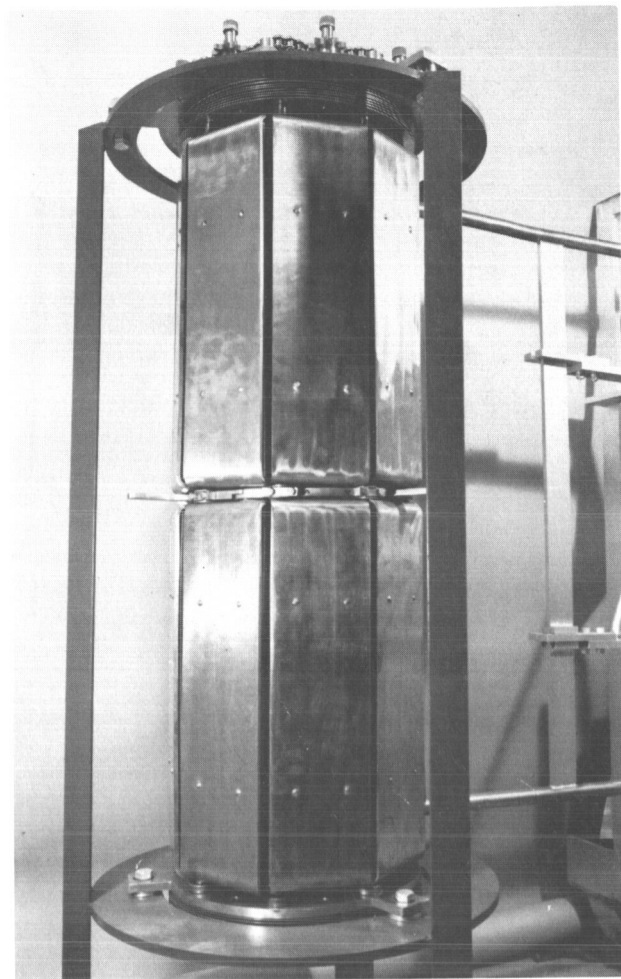


Fig. 30. Radiator-condenser, shutters closed

bottom, and middle, and are driven at the top by a gear-chain-drive assembly which is manually operated through a drive rod unit that penetrates the end enclosure housing the R-C. The individual shutters are $5\frac{3}{8}$ in. wide and are made up of a 0.250-in.-thick stainless steel structural back plate to which are affixed ten additional 0.060-in.-thick stainless steel plates arranged in a parallel manner. These plates are maintained separate from each other by the use of Belleville-type stainless steel washers. The stainless radiation plates and washers are fastened together by a stainless steel pin which is welded to the heavy shutter back plate. Similar, but nonmovable, radiation shields are provided at the top and bottom of the R-C assembly.

Because of the coiled shape of the R-C, the tubular, inconel-sheathed, nichrome-resistance element heaters as used elsewhere on the test loop were not considered feasible for trace-heating the R-C. Instead, special tubular

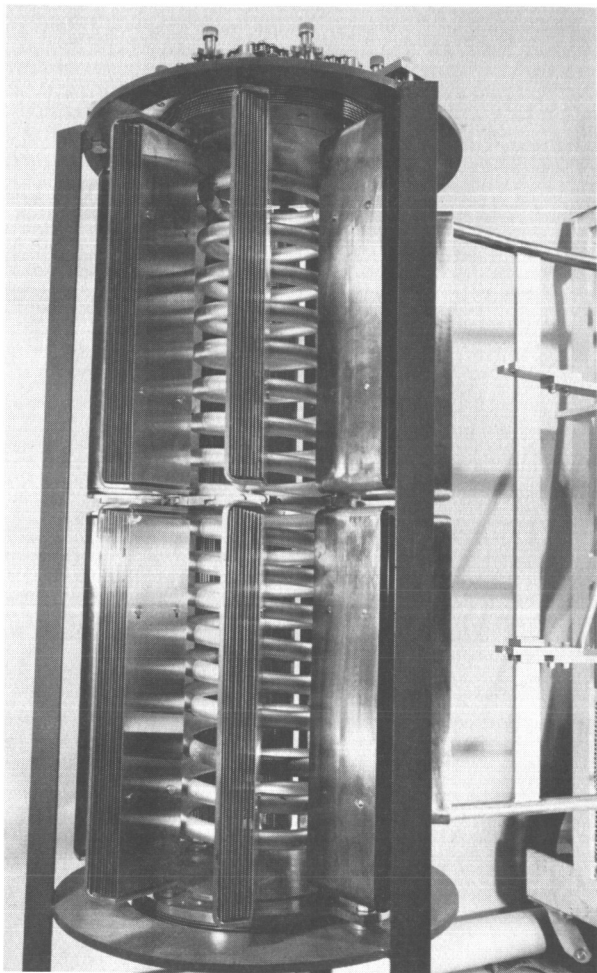


Fig. 31. Radiator-condenser, shutters open

radiation heaters were fabricated,⁵ with the sheath material of iniconel and the heating element of molybdenum. Designed to dissipate 1500 W at a surface temperature of 1900°F, the heaters are 45 in. long and have a heated length of 37 in. Originally only three of the heaters, which are positioned inside the R-C coil, were used. Following initial operations, however, three additional heaters were installed to increase the maximum preheat temperature of the condenser and also to make up for the condenser heat losses that were greater than had been expected.

Each coil of the R-C has a tungsten-rhenium thermocouple which is physically attached to, but electrically isolated from, the columbium tubing. Installation of these thermocouples is described in Section V, *Liquid-Metal Loop Instrumentation*.

⁵Arco-Vec Corporation, Los Angeles, Calif.

Pressure transducers are located downstream of the R-C outlet. These transducers also measure the potassium pump inlet pressure. A Pace differential pressure transducer measures the pressure drop across the R-C.

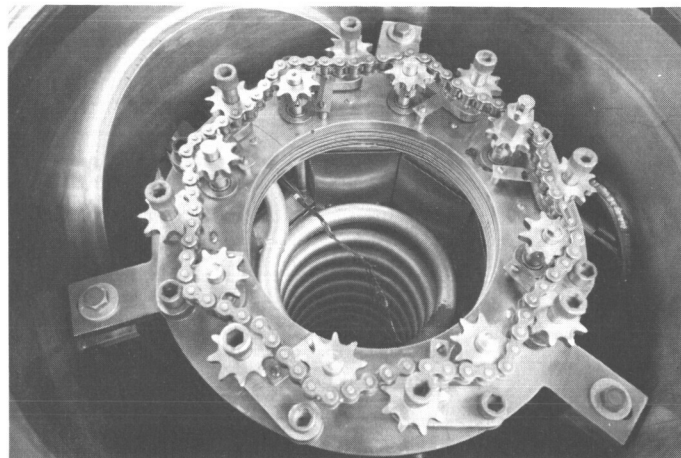


Fig. 32. Radiator-condenser shutter actuating mechanism

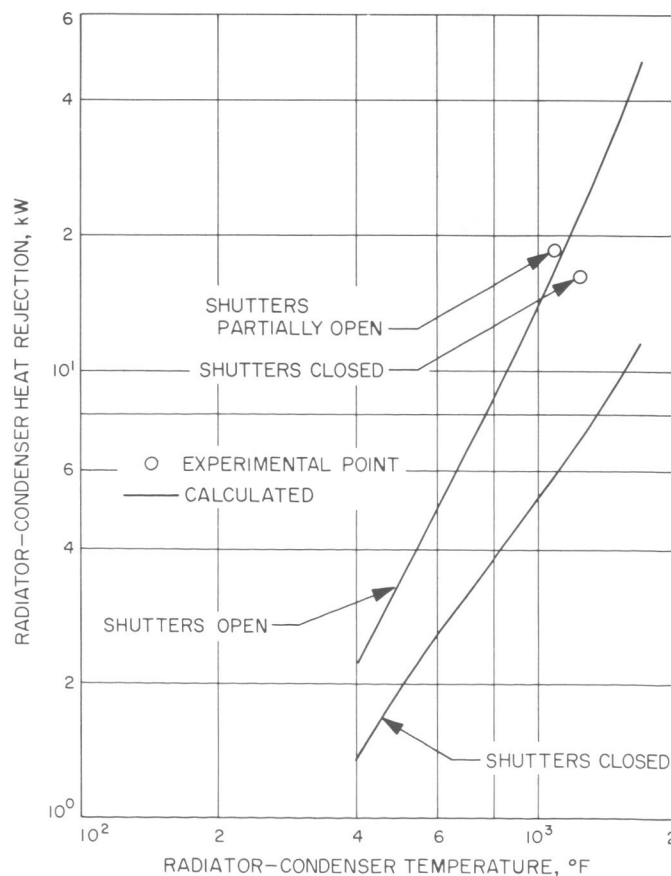


Fig. 33. Radiator-condenser heat rejection vs temperature

Figure 33 is the calculated heat rejection for the R-C with the shutters fully open and fully closed. Initially, the total argon flow exiting through the auxiliary R-C enclosure resulted in a considerably greater R-C heat rejection rate than had been expected. To alleviate this problem, a tantalum radiator shield was wrapped around several of the lowermost coils of the R-C; and the argon flow ducting was rerouted to prevent the total argon flow from flowing through the R-C and overcooling it.

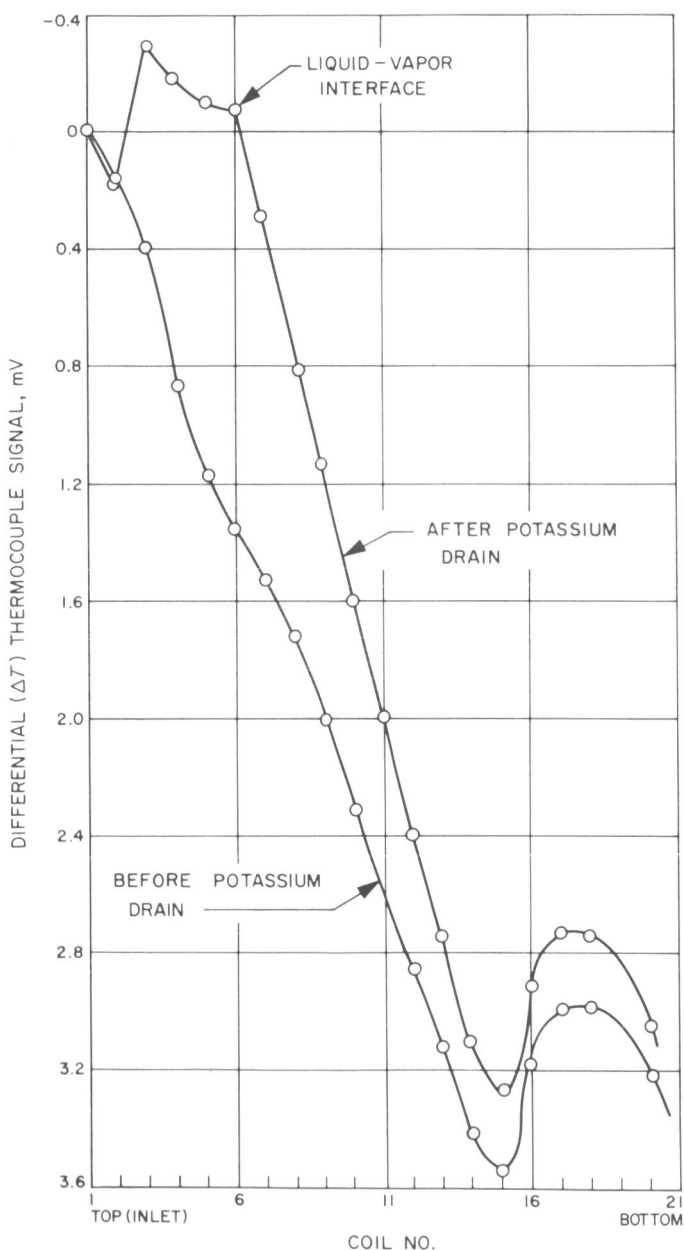


Fig. 34. Radiator-condenser temperatures before and after potassium drain

The R-C thermocouples serve not only to provide condenser temperatures but also to determine liquid potassium height during operation. A typical R-C coil temperature trace is shown in Fig. 34. During operation, the liquid potassium level is clearly evidenced by the change in slope of the temperature vs coil position curve.

Because of its inherent function as a radiator and the necessity for maintaining high heat-rejection rates at nominal rated power, the R-C is the only component in the loop which is not protectively wrapped with tantalum and zirconium foils. The lack of foil protection is compensated for by the extra thickness of the R-C tubing which has a wall thickness of 0.113 inches.

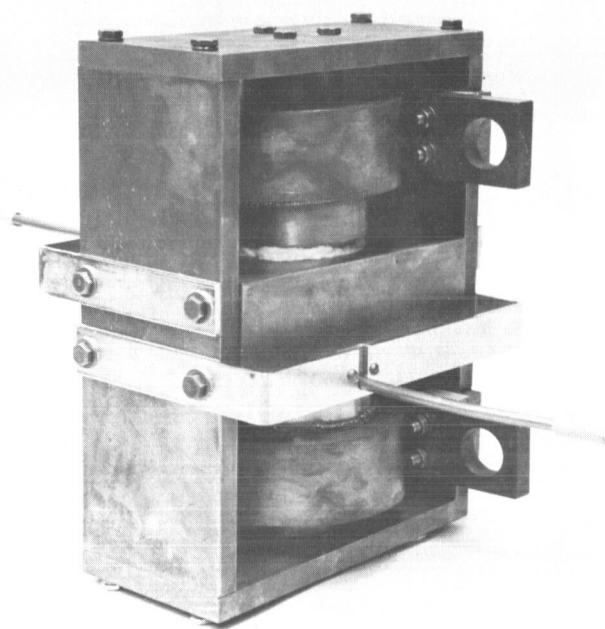


Fig. 35. Potassium dc electromagnetic pump

6. Potassium dc electromagnetic pump. The potassium pump now being used is shown in Fig. 35. The original potassium pump which was supplied by MSA Research Corporation⁶ was a conventional unit as shown in Fig. 36. This original unit consisted of a $\frac{3}{8}$ -in.-OD by 0.062-in.-wall Cb-1Zr duct to which laminated nickel bus bars were brazed. The specified nominal pump characteristics were for a potassium flow rate of 150 lb/h and a developed pump head of 90 psi at a nominal operating temperature of 1500°F. The original pump which MSA delivered was

⁶MSA Research Corp., Callery, Pa., a subsidiary of Mine Safety Appliances Company.

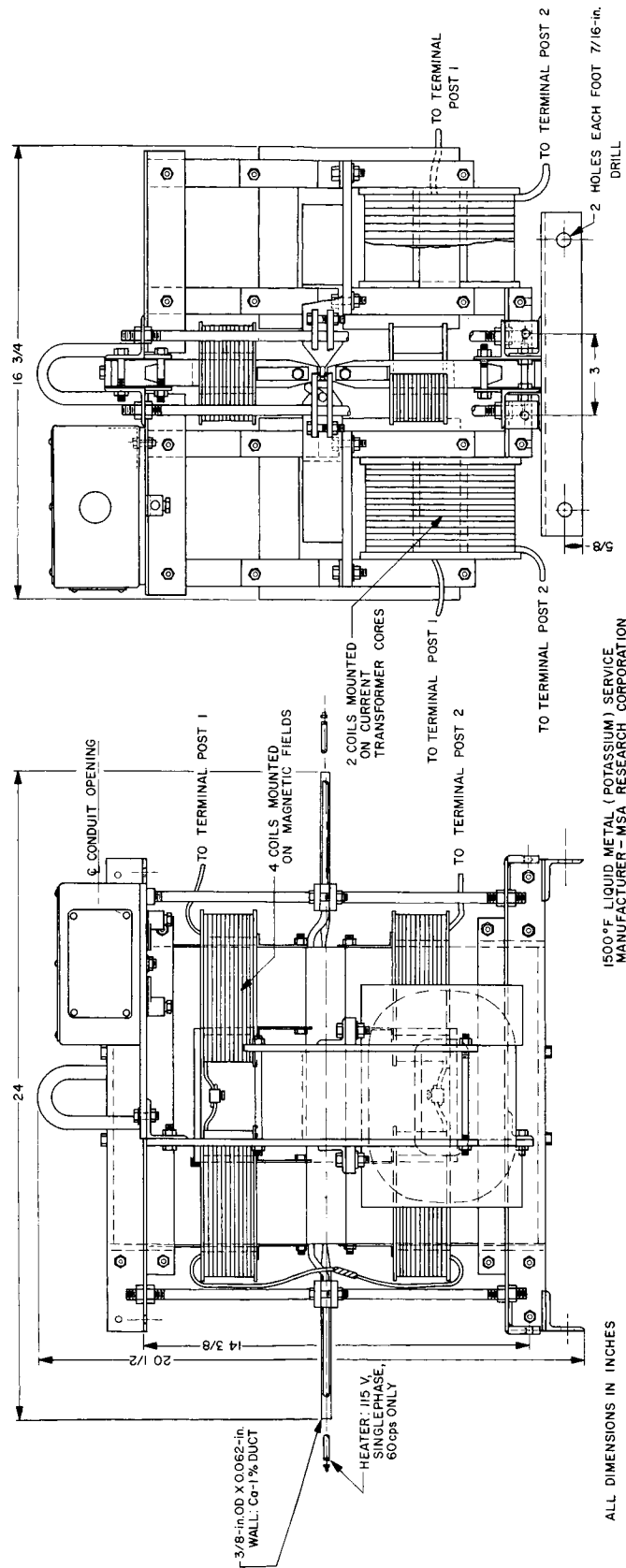


Fig. 36. Original potassium pump assembly drawing

a modified version of their stainless steel unit. The standard MSA Style II pump that pumps NaK 56 at 500°F had a developed pump pressure of >96 psid at the nominal flow rate of 0.4 gpm. However, calculations to determine the expected performance of this pump with a columbium duct, pumping potassium at 1500°F, indicated that the maximum developed pump head would be about half of the desired value at the nominal flow rate of 0.4 gpm (150 lb/h).

These calculations raised reasonable doubts about the ability of this pump to satisfy the nominal requirements in the potassium loop. A small test loop was set up to test the pump performance with NaK 78. The results of this test agreed very well with the calculations which indicated that the maximum head developed by the pump was about half the desired value.

This pump was subsequently returned to the manufacturer and exchanged for a newly designed high-head, liquid-metal pump with a performance guaranteed to meet or exceed our requirements. A schematic of this pump (Fig. 35) is shown in Fig. 37. Although the operational principle is that of a conventional dc conduction pump, the actual design, geometry, and fabrication are quite novel.

The pumping section is a seven-turn helical cylinder of ¼-in. OD by 0.049-in.-wall Cb-1Zr tubing positioned concentrically around a vertical, solid iron, magnetic, cylindrical bar which serves as a part of the magnetic flux loop. The individual coils of the pumping section are electron-beam welded to each other to form a good electrically conductive path. The top and bottom of the columbium tube helix are electron-beam welded to intermediate columbium cylindrical bus bars which, in turn, are electron-beam welded to copper bus bars which are wrapped in a radial plane to form a three-turn spiral.

As seen in Fig. 37, current flows into the upper spiral copper bus bars, through the intermediate columbium bus bar, through the pumping section, and through the second columbium intermediate bus bar, and exits through the lower spiral copper bus bar. The current flowing through the spiral copper bus bars creates a magnetic flux which travels vertically through the central iron bar and radially through the helical pumping section to the outside iron frame which completes the magnetic loop. The current flows vertically through the pumping section and at right angles to the radially oriented magnetic flux field

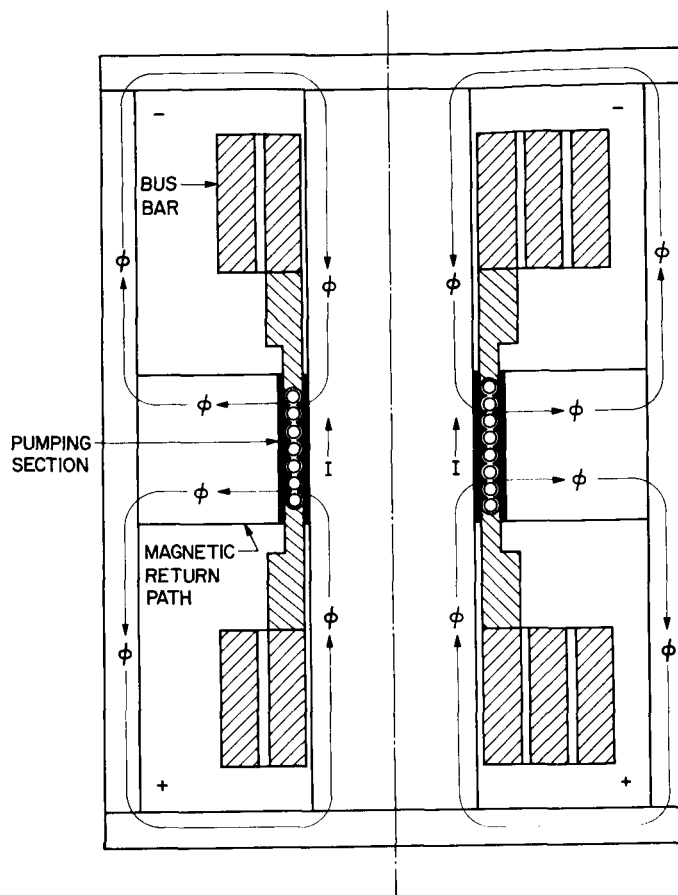


Fig. 37. Potassium pump schematic

in the pumping section. The interaction of the current and the magnetic flux produces a thrust on the potassium that causes it to flow. This pump is the first such unit fabricated with a columbium duct. Previous units manufactured by MSA used stainless steel pumping sections and were tested with NaK 56. Based upon experimental data for the stainless steel-NaK 56 pump, the calculated performance for a pump with a columbium duct pumping potassium at 1500°F is shown in Fig. 38. These curves are head-flow curves for various pump input currents up to 2400 amp, the nominal design pump current. Overall pump efficiency at nominal design operating conditions is ~3%.

Cooling ducts on the pump direct the argon coolant flow over the upper and lower bus bars and the central iron magnetic bar, to maintain these parts at reasonable temperatures (<1000°F). Inlet and outlet absolute pressures are measured with Statham pressure transducers, and the pump head with Pace ΔP transducers.

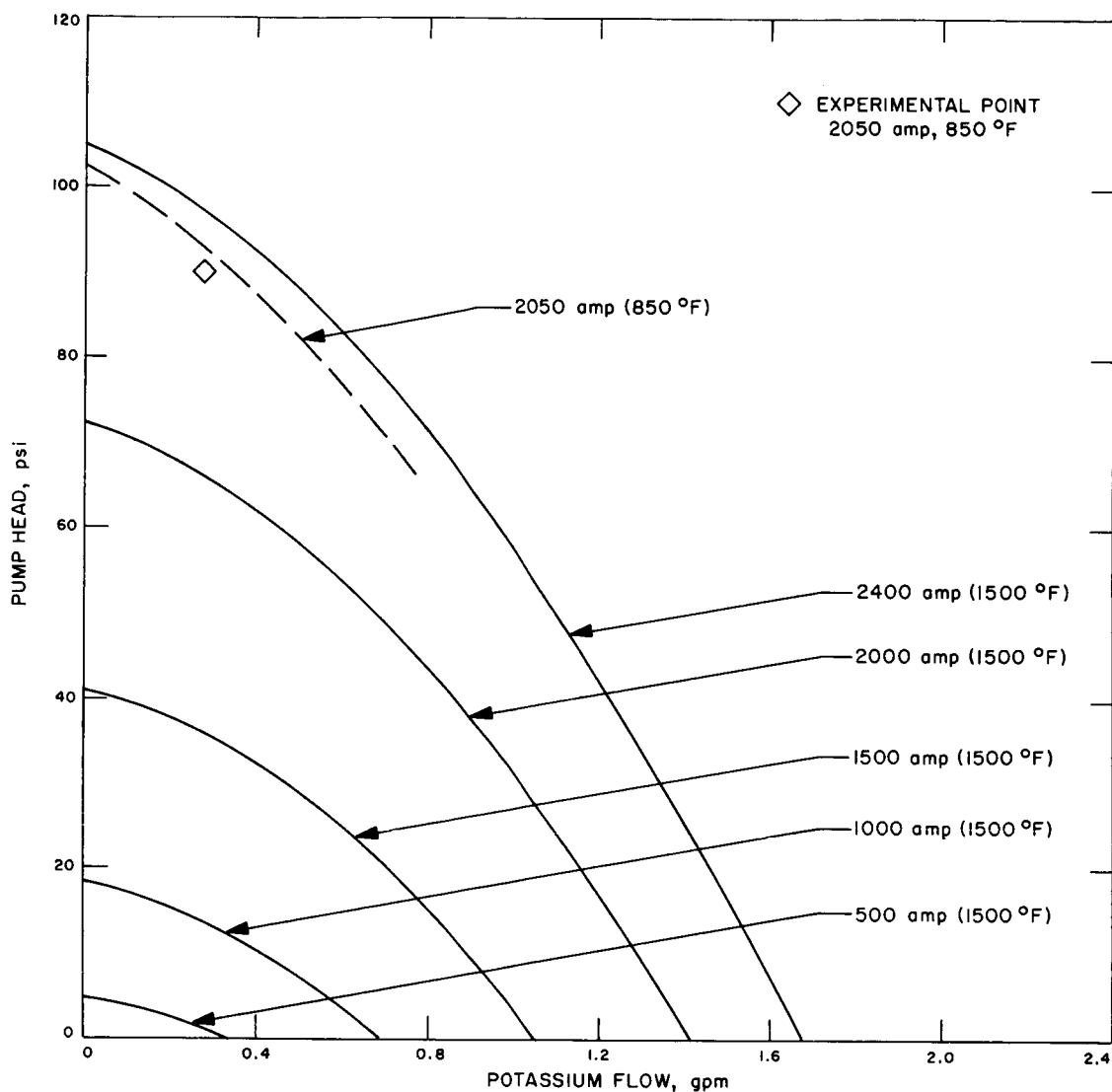


Fig. 38. Potassium pump performance curves

7. Potassium preheater. The potassium preheater consists of a 20-in.-long section of $\frac{3}{8}$ -in.-OD by 0.049-in.-wall Cb-1Zr tubing to which columbium bus bars have been welded. A sketch of this unit is shown in Fig. 39. The bus bar in the center of the preheater serves as the power feed bus; the two end bus bars form the ground loop. This configuration of bus bars is used to minimize stray current flow through other portions of the loop.

Figure 40 is a plot showing the calculated preheater electrical resistance as a function of temperature. The triangular points are experimentally determined resistance values which are in good agreement with the curve representing calculated values. At an average temperature of 1500°F, the nominal preheater resistance is ~ 1.0 m Ω .

Figure 41 is a plot of necessary current input for the preheater vs the desired preheater power input.

Thermocouples are located at the preheater inlet and outlet for the purpose of calorimetric determination of potassium flow rate. A control thermocouple is fitted on the preheater tubing between the central bus bar and the downstream ground bus bar for the purpose of monitoring the maximum preheater temperature. This thermocouple activates a manually preset automatic alarm-scam system which shuts off preheater power in the event of a temperature excursion. A loss-of-flow signal may also be used to shut down the preheater in the event of a pump failure or the plugging of a flow passage.

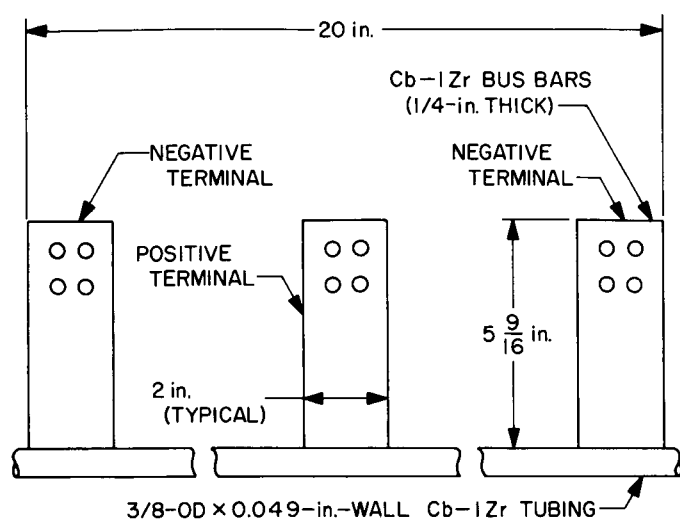


Fig. 39. Potassium preheater drawing

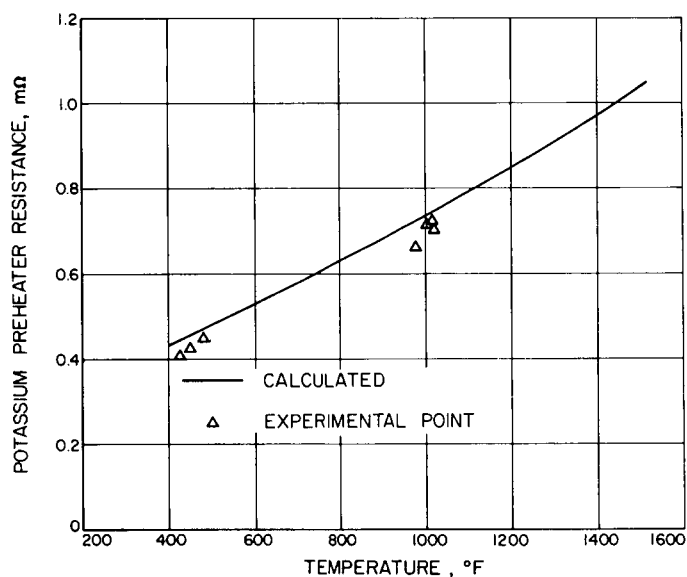


Fig. 40. Potassium preheater electrical resistance vs temperature

Measurement of the temperature rise of the liquid potassium (for a given preheater power input) passing through the preheater will permit the calculation of the potassium flow rate and *in situ* calibration of the potassium flowmeter.

8. Potassium hot trap. The potassium hot trap is in a full-flow configuration. The hot trap is 2 3/8 in. in diam by 12 in. long and is constructed of Cb-I Zr (see Figs. 42 and 43). The getter material is zirconium, and the hot trap

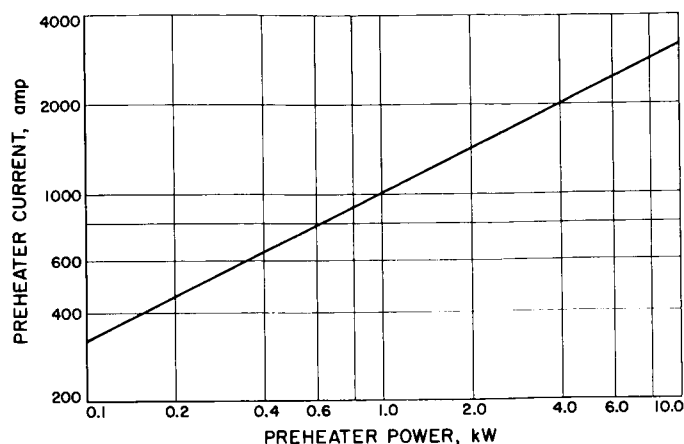


Fig. 41. Potassium preheater current vs power

has an active getter area of 154 in.². The assembled hot trap is shown in Fig. 44.

9. Potassium flowmeter. The two potassium flowmeters are of the same electromagnetic type as the lithium flowmeter. One, located on the boiler inlet line, has a permanent magnet with a field strength of 3050 gauss. The conduit is 3/8-in.-OD tubing. The second flowmeter, located on the turboalternator bearing feed line, has a magnet with a field strength of 10,000 gauss. The flow conduit is 1/8-in.-OD tubing. This particular flowmeter is needed more to indicate the onset and continuation of flow to the turboalternator than to indicate any quantitative flow.

C. Subsystems

1. Potassium and lithium fill and dump system. The purpose of the fill and dump (F-D) system is:

- (1) To provide storage capacity for clean liquid metal to be used in the test loop.
- (2) To provide capacity for emergency dumping of liquid metals.
- (3) To provide for purification and filtration of liquid metals.
- (4) To provide for the measurement of the amount of liquid metal deposited or removed from the F-D system.
- (5) To provide a motive force for transferring liquid metals to and from the F-D system.
- (6) To provide necessary thermal energy for heating and liquefying liquid metals.

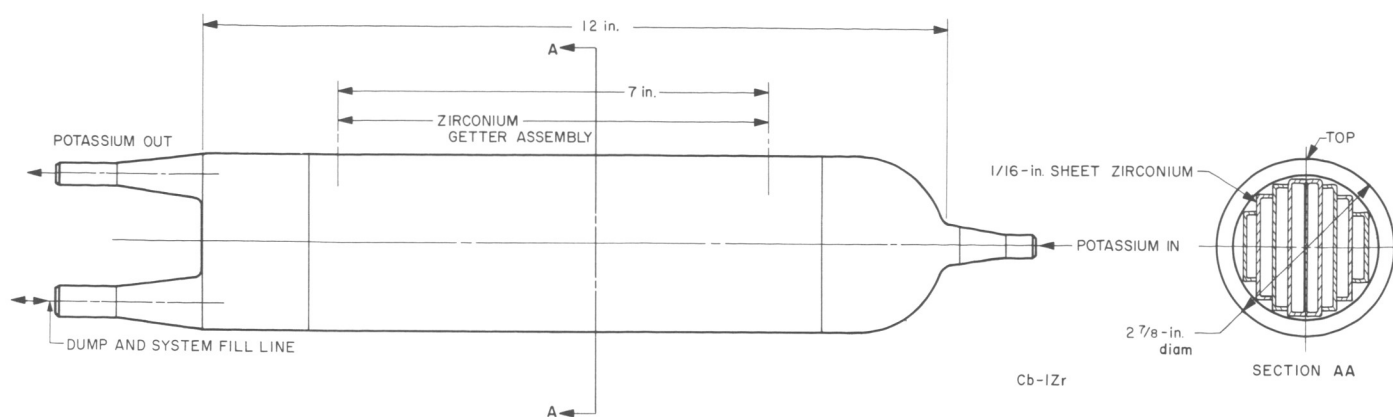


Fig. 42. Potassium hot trap drawing

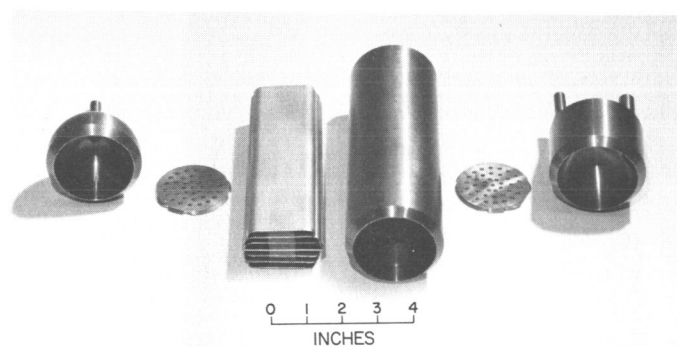


Fig. 43. Potassium hot trap components

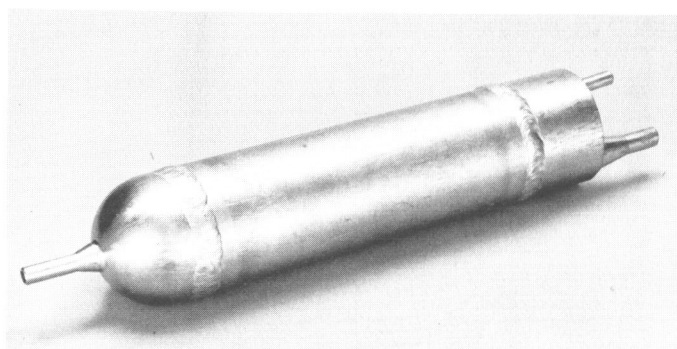


Fig. 44. Potassium hot trap

- (7) To provide means of hydraulically coupling liquid metal shipping containers to the F-D system with mechanical fittings which are easy to assemble and disassemble.

A schematic of the potassium and lithium F-D system which provides for these functions for the test facility is

shown in Fig. 45. The F-D system is self-contained in an enclosure measuring $\sim 36 \times 36 \times 30$ in. high and is positioned outside, and close to, the lithium loop end of the test enclosure tank. Two photographic views are shown in Figs. 46 and 47.

The F-D system is constructed entirely of type 304 or 316 stainless steel except for O-ring seals in the bellows valves used on the argon gas lines. The F-D system contains a potassium tank having a capacity of 700 in.³ and a lithium tank having a capacity of 2600 in.³. Two remotely operated Annin valves are used for emergency dumping of the lithium from the test loop into the lithium F-D tank. Another remotely operated Annin valve on the potassium F-D tank is for emergency dumping of the potassium loop. The lithium and potassium F-D tanks each have a pipe well which is closed at the lower end into which a liquid-metal liquid-level inductance probe may be inserted for determining potassium or lithium levels. These liquid-metal probe measurements are used for calculating the volumes of liquid metal added or removed from the F-D tanks and the potassium and lithium loops. Each tank is equipped with a 10μ porous stainless-steel filter which is positioned hydraulically in parallel with the main Annin valve on each tank. During charging of the loop, the Annin valves are kept closed and the lithium and potassium are charged through the filters.

Each tank has an argon line and a vacuum line. Before charging the F-D system with lithium or potassium, the lines and F-D tanks are outgassed and held under vacuum. After the loop has been charged with liquid metal, inert argon gas is used as a cover gas and as a pressurizing

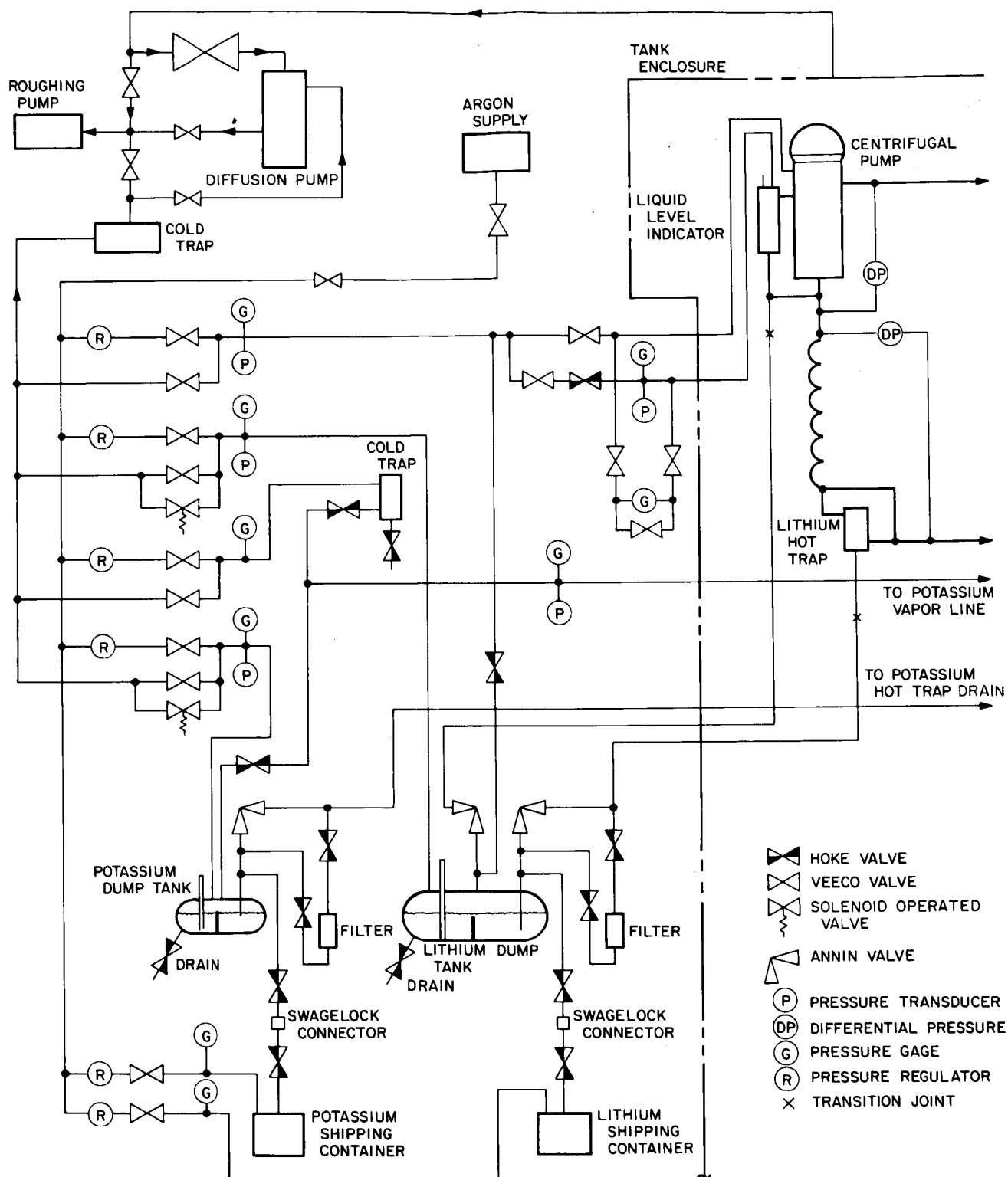


Fig. 45. Fill and dump system schematic

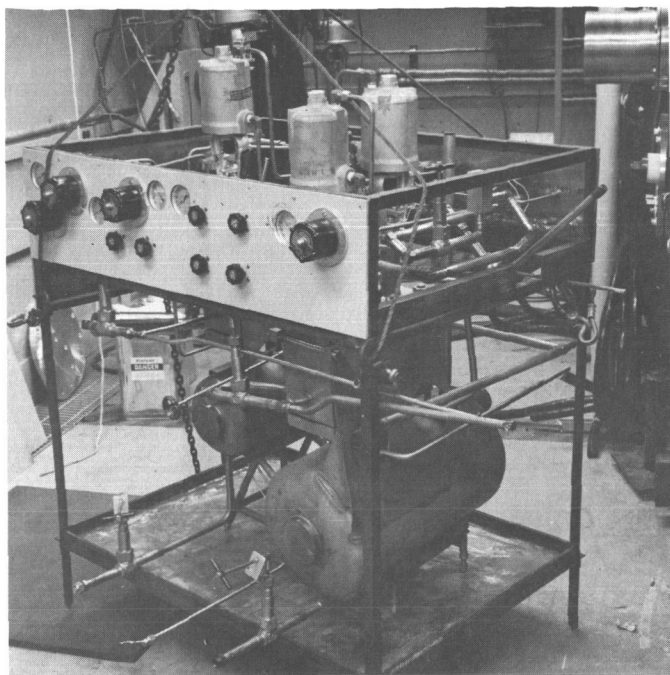


Fig. 46. Fill and dump system, front and side view

medium for forcing the liquid metal from the F-D system into the test loop. Located at the bottom and the end of each tank is a drain line with a Hoke stainless steel bellows valve of all-welded construction. The downstream nipple of the valve is capped with a Swagelock fitting. When desired, the F-D tanks may be externally drained into an external container by connecting a stainless steel tubing line from the external vessel to the Swagelock fitting on the F-D tank drain line.

A similarly fitted stainless steel line is positioned on the F-D tanks from the external lithium and potassium shipping containers.

All the pipe lines and tanks in the F-D system are heated using Cal-rod-type heaters or flexible cable-type, monel-sheathed, resistance heaters. These heaters are either bent to fit a particular length of tubing or wrapped around the tubing to form a helix. The F-D tanks are heated by four tubular heaters which are fitted longitudinally to the underside of the lithium and potassium F-D tank. All heaters are manually controlled by a variable powerstat and each heated section has its own chromel-alumel thermocouple. Because the F-D system is enclosed in a box-like enclosure, insulation of this system was easily and economically accomplished by simply

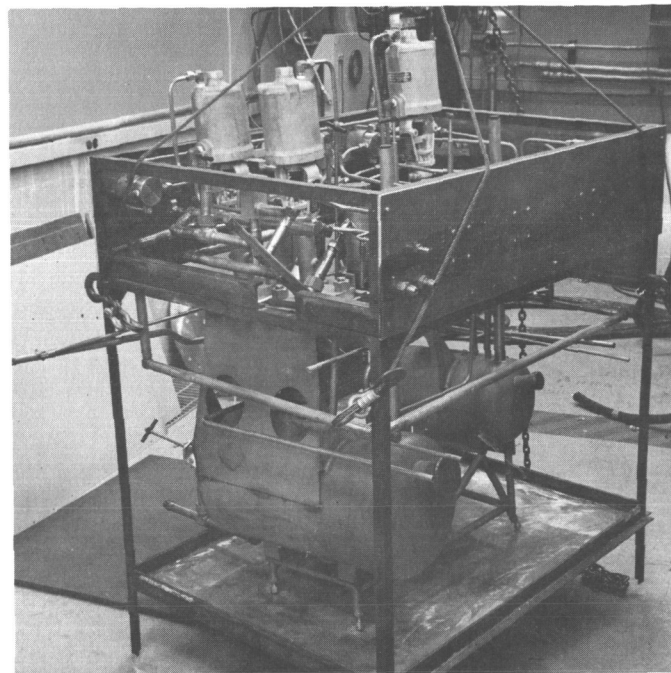


Fig. 47. Fill and dump system, side and rear view

pouring Vermiculite insulation (a granulated form of expanded mica) into the F-D system enclosure. Stainless steel compound Bourdon gages are used extensively in the F-D system for pressure measurement.

The F-D system is connected to the test loop through six stainless steel tubes which penetrate one end of the loop enclosure. Two lines go to the lithium loop for liquid lithium fill and drain. The other liquid line is for potassium fill and drain. Of the three other lines, two are used for argon supply to the lithium pump and the lithium pump liquid-level tank and the remaining line is a gas line which is connected to the main potassium vapor line, downstream of the boiler. This line is used in evacuating or pressurizing the potassium loop with argon when dumping potassium.

Since the loop is entirely columbium, the stainless steel lines must make a transition to the columbium; it is not desirable to use stainless steel in a refractory-metal loop, because of deleterious mass transfer effects. The stainless-to-columbium transitions are accomplished by using Nuclear Metals⁷ stainless-columbium co-extruded joints.

⁷Textron, Inc., Nuclear Metals Division, West Concord, Mass.

2. Dowtherm coolant system. Supplementary cooling is required for the centrifugal lithium pump and the potassium turboalternator (TA). The cooling requirements for these components dictated a fluid having

- (1) Good heat transfer characteristics.
- (2) Temperature stability up to 500°F.
- (3) Low vapor pressure.
- (4) Compatibility with stainless steel.

Dowtherm A,^{*} which meets these requirements, was the liquid chosen. The major portion of the heat load to be removed by the Dowtherm is from the TA stator and

^{*}Dowtherm A is a eutectic mixture containing 26.5% diphenyl and 73.5% diphenyl oxide by weight.

lesser amounts of heat are to be removed from the TA jacket and the lithium centrifugal pump.

A nominal flow rate of 6 gpm was chosen for the TA stator and 2 gpm for the TA jacket and lithium centrifugal pump, which have their Dowtherm cooling channels hooked up in a series configuration. That is, after the Dowtherm flow leaves the TA jacket, it then flows to the lithium pump. A schematic of the Dowtherm system is shown in Fig. 48. A gear-type positive displacement pump driven by a ½-hp motor is used to pump the Dowtherm. Two motor-pump units are used in a tandem configuration so that in the event of a motor or pump failure, the other motor-pump unit takes over to ensure continuous flow of Dowtherm coolant to the lithium pump and the TA. The Dowtherm flows from a 20-gal stainless steel reservoir tank to the pump, then through a water-cooled

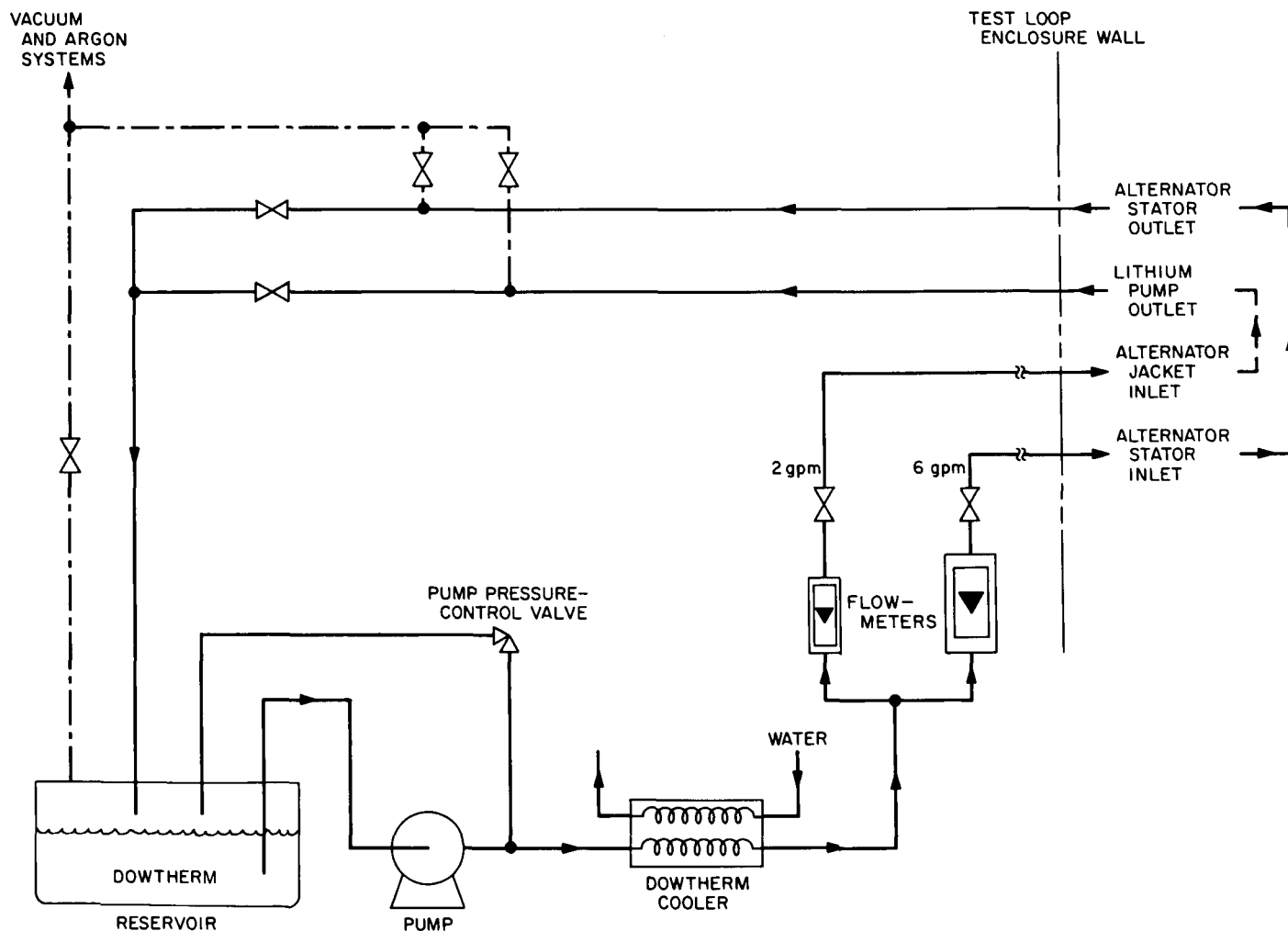


Fig. 48. Dowtherm coolant system schematic

heat exchanger. The flow then divides into two streams: one to the TA stator, the other to the TA jacket and then to the lithium pump. Each of the two coolant lines has a throttling valve and a rotameter for fluid flow measurement. The two coolant flow channels return from the loop and empty into the reservoir tank. A manually preset pressure-control valve limits the output pump pressure by allowing a portion of the pump flow to return directly to the Dowtherm reservoir. The Dowtherm reservoir is vacuum- and pressure-tight for the following reasons:

The Dowtherm coolant flowing through the TA stator cools the stator by flowing through an annular passage formed by the canned-rotor can and the stator itself (see Fig. 25 for a cross-sectional view of the TA). During operation, potassium vapor and liquid surround the TA rotor within the isolation can, which is 0.010 in. thick. For this configuration, the Dowtherm pressure on the outside of the rotor can must not exceed the potassium pressure on the inside of the rotor can by more than 5 psi; otherwise, the rotor can will deflect sufficiently to rub the rotor. Therefore, since the pressure of the potassium inside the rotor can is essentially turbine exhaust pressure, the pressure of the Dowtherm coolant system must be reduced at the reservoir tank to less than atmospheric pressure (to maintain no more than 5 psi across the rotor can wall) whenever the potassium condensate exhaust saturation temperature falls below $\sim 1100^{\circ}\text{F}$.

3. Argon recirculation system. This system provides the loop containment vessel with a continuous supply of high purity argon at approximately 150°F . The system consists of an air-to-argon full-flow heat exchanger where the argon temperature is reduced from around $350\text{--}150^{\circ}\text{F}$, a centrifugal blower, and a bypass purifier^a which diverts 10% of the argon flow through catalytic beds to reduce the O_2 and H_2O concentrations to below 1 ppm. The blower shaft is equipped with a carbon face seal. In addition, the blower motor is housed in a leak-proof container which is also filled with argon as a backup to the carbon face seal. Figure 49 is a picture of heat exchanger and blower housing. The catalytic beds and drying towers are dual: one set of each is on the line while the other set is in a regeneration mode. These operations are accomplished on a time cycle arrangement and are completely automatic. The argon circuit is 4-in.-pipe for the most part and has an orifice flowmeter in the main circuit, while

the bypass to the purifier has a rotameter to indicate its flow rate. Several ball valves and an argon makeup system complete the system. The argon makeup also serves the F-D system and thereby the lithium and potassium loops. This makeup argon is supplied by a liquid argon dewar and has guaranteed levels of contamination <5 ppm each of oxygen and moisture.

4. Vacuum system. The vacuum system consists of a 130-cfm mechanical pump, a 10-in. diffusion pump with cryogenic baffles, and the necessary valving to permit the evacuation of the various subportions of the system including the main chamber, the containment dome of the lithium pump motor, the F-D system, and the lithium and potassium loops. In addition, there is a cryogenic cold trap between the vacuum system and those portions of the system possibly containing liquid metals or their vapors. There is also a filter in the main 4-in. line to the mechanical pump to trap particulate matter. This system is used only for initial loop and tank evacuation and outgassing.

5. Control panels. The main control panel is shown in Fig. 50. Its physical layout is similar to the loop schematic shown in Fig. 1. This layout is an aid in the location and assessment of the various parameter displays. Indicator lights on the panel are located in the same manner as they would be on the schematic. Certain key parameters such as pressures, flows, voltages, currents, speed, and some of the temperatures have individual meters indicating their value. The bulk of the temperatures are selected on one of four stepping switches, with the indicator lights showing their location. Many meters are equipped with set points to switch on warning lights and buzzers to indicate when a parameter has gone out of limits. In addition, the heater temperature, overvoltage and undervoltage (both lithium and potassium heaters), and the lithium and potassium flows are wired to trip relays in the heater power supplies if they go out of limits. This interlock feature can be overridden.

All trace heaters are manually set and adjusted by autotransformers mounted below the main control panel and also in an adjoining rack. Controls for the pumps and heater power supplies are also located on these two panels. Data acquisition, conditioning, and recording are described in another section of this report.

D. Miscellaneous

1. Insulation. Insulation requirements for the lithium-boiling potassium loop are quite stringent. To be

^aPurifier Model HXV, United States Dynamics, Newton Highlands, Mass.



Fig. 49. Argon heat exchanger and blower housing

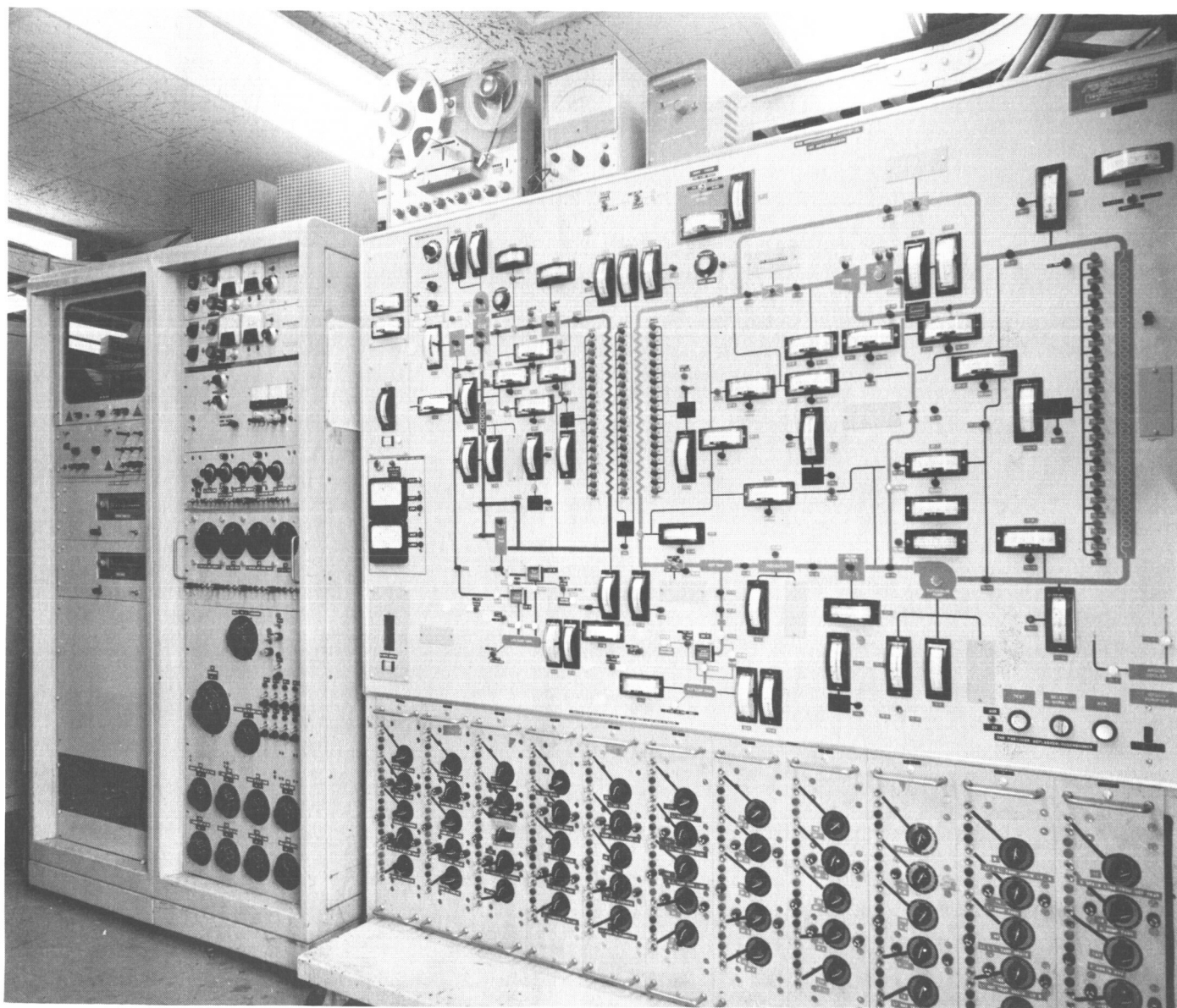


Fig. 50. Lithium-boiling potassium test loop graphic display/control panels

considered suitable, insulation materials must satisfy certain conditions. First of all they must have low thermal conductivity; in addition, they must be

- (1) Stable at temperatures up to 2300°F.
- (2) Compatible with Cb-IZr at temperatures up to 2300°F.
- (3) Easily outgassable.
- (4) Structurally resistant to thermal shock and vibration.
- (5) Reasonably priced and readily available in moderate quantities.

The candidate insulation materials chosen for further investigation were

- (1) Fiberfrax, an alumina-silica fibrous blanket.
- (2) Q-felt (Microquartz), a silica fibrous blanket.
- (3) Glasrock, a foamed porous silica block.
- (4) Alumina Block, a foamed porous alumina block.
- (5) Zirconia Block, a foamed porous zirconia block.

As a result of compatibility tests conducted at the Jet Propulsion Laboratory (JPL) (Ref. 1) and actual operating experience at Pratt and Whitney Aircraft (CANEL), and because of its relatively low cost and ease of outgassing, Glasrock foamed-silica block¹⁰ was chosen as the primary loop insulation material.

Glasrock is a foamed, highly purified (99.8% silica), open-pored block structure. The blocks chosen for use measure 18 × 12 × 3 in. and have a density of ~ 22 lb/ft³. Figure 51 shows some small test pieces of Glasrock which were cut out of standard size (18 × 12 × 3 in.) block.

¹⁰Glasrock Products Inc., Atlanta, Ga.

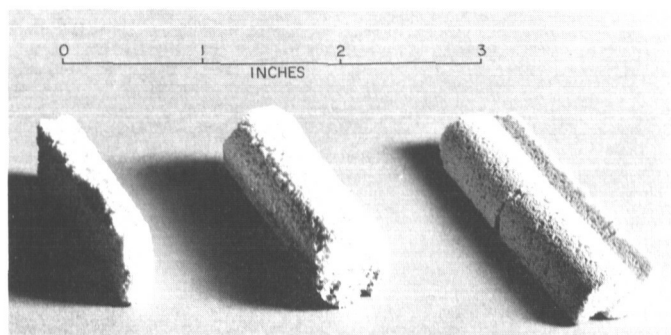


Fig. 51. Glasrock insulation test samples

Because of the open pore structure of the blocks, outgassing is readily accomplished by heating the blocks in a vacuum or inert-gas atmosphere before they are installed on the loop. The foamed silica block is easily cut with a hacksaw either by hand or by machine. After a block is shaped to fit a pipe or a component, the insulation is placed around the object to be insulated and tied together with stainless steel bands or wire. Where several blocks or layers of insulation were required, staggered installation of the blocks kept the direct-radiation heat-leakage paths to a minimum. After as much of the test loop was insulated with Glasrock as was possible, Q-felt (silica fiber formed into a soft blanket insulation) was used to fill in any cracks between the Glasrock insulation blocks, and to insulate in any other place where it was not feasible to use the foamed silica block.

The Q-felt insulation was not used to any great extent (except as first described) because of its structure, which consists of a large number of silica fibers having a mean diameter of only 2 μ . It was thought that the large surface area of the large number of very small-diameter fibers would present an outgassing problem. The distinct advantage of this *blanket* form of insulation is that it can be readily applied to circular and other complicated geometries. Because of this application feature, Q-felt will be extensively used to re-insulate the loop when repairs are necessary, as the accessibility of the loop after being permanently welded to the test tank enclosure is quite limited.

A plot of the calculated loop insulation heat losses, excluding the R-C, is shown in Fig. 52. A point representing the actual system heat loss (excluding the R-C) is also shown in Fig. 52 for comparison. The actual total system heat losses were about 3-4 kW greater than anticipated. The major portion of these additional loop heat losses occurred in the liquid potassium line between the condenser outlet and the boiler inlet.

2. Trace heaters. Because both lithium and potassium are solid at room temperatures, the potassium and lithium loops must be preheated before a flow can be established. To provide such preheating, all liquid-metal lines are trace-heated with inconel-sheathed, tubular, electric-resistance heaters. For the smaller diameter lines, 0.25-in.-OD heaters are used; for the larger lines ($\geq 5/8$ -in.-OD), 0.33-in.-OD heaters are used. The heater voltage is 208 V. These heaters have a 6-in.-long cold length at each end of the heater, with an electrical junction at the end of the 6-in. unheated section.

After a heater is bent to fit a length of pipe of a component, a 90° bend is made in the cold section of the

heater ~ 1-in. downstream from the junction of the unheated and heated portion of the heater. This unheated

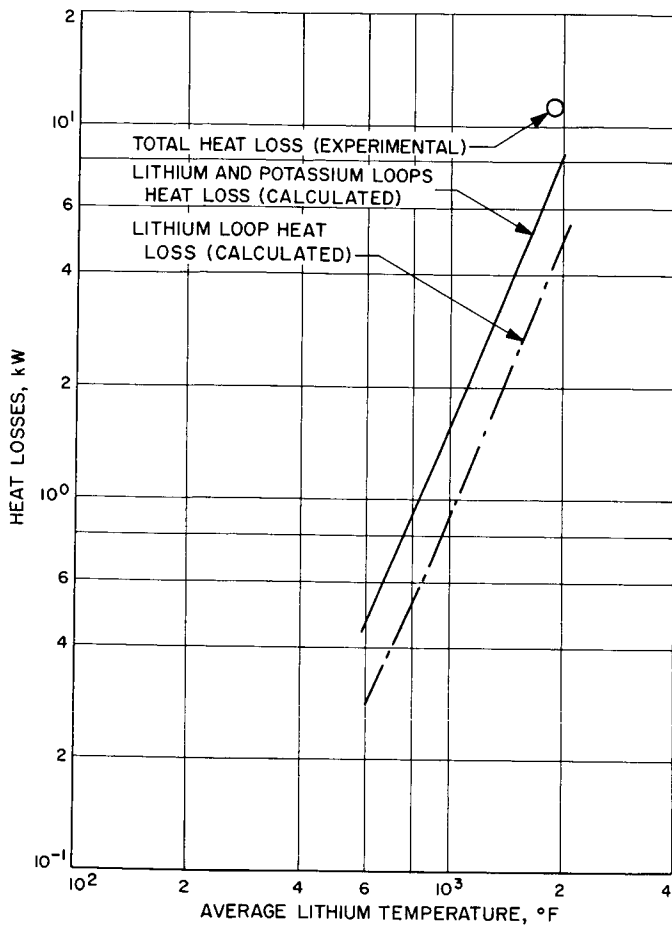


Fig. 52. Lithium-boiling potassium loop heat losses (excluding radiator-condenser)

portion of the heater, which is now essentially normal to the longitudinal axis of the pipe, passes through the pipe insulation positioning the electrical junction outside the pipe insulation, as is shown in Fig. 53.

Each heated length of piping is fitted with two identical heaters, one of which serves as a redundant, or backup, heater. The heaters are fitted to the system tubing after the system tubing has been fitted with its

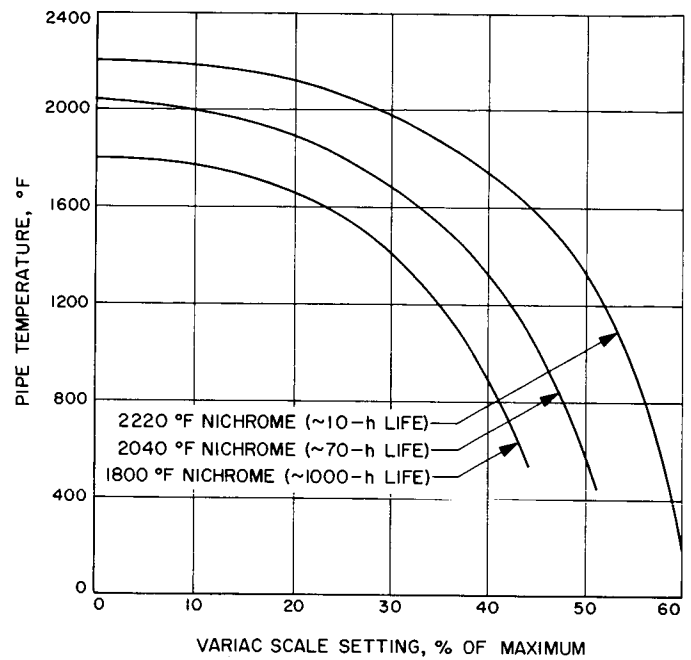


Fig. 54. Trace-heater powerstat setting vs pipe temperature for various heater lifetimes

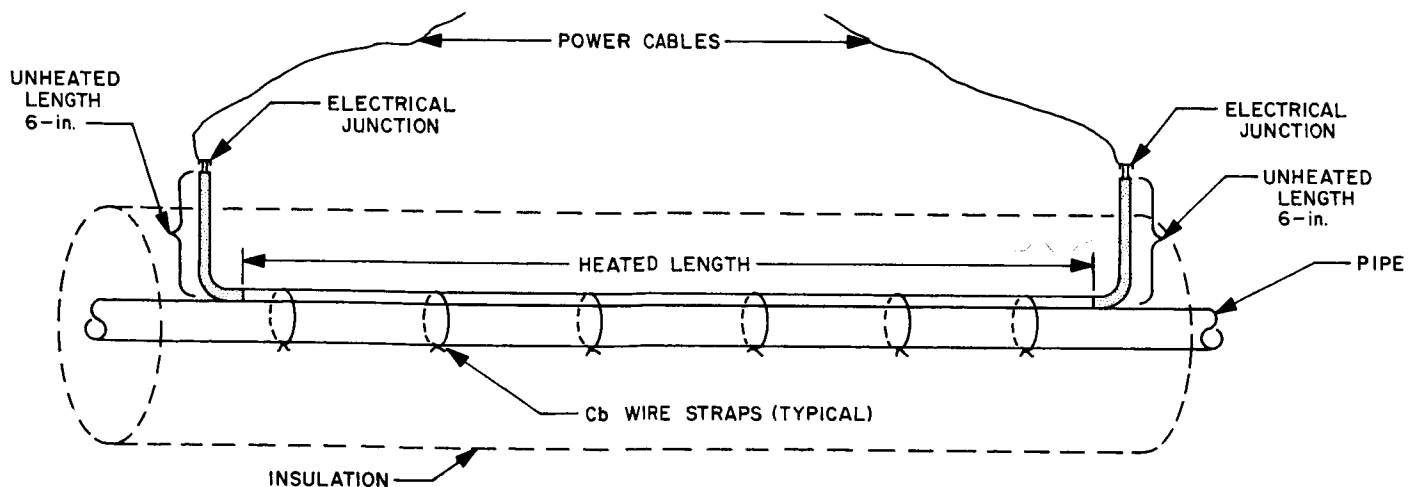


Fig. 53. Typical application of tubular electric-resistance heaters to loop piping

three protective foils of tantalum and zirconium. The heaters are tied around the piping with columbium wire.

Current is brought to the heaters through hermetically sealed feedthrough connectors which are located on flanges bolted to the tank walls. Each connector has 36 pins and is, therefore, capable of handling 18 heaters or 9 heated sections (9 mainheaters + 9 backups). External to the tank enclosure, the wiring for each main heater and its redundant heater is brought to a manually variable powerstat autotransformer which permits individual adjustment of power for each heated section of pipe or component.

Figure 54 is a calculated graph which serves as a guide in determining the amount of power and the powerstat

setting that should be used for an individual heater, based on the temperature of the pipe being heated for various heater lifetimes. Experience has indicated these curves to be useful and not overly conservative.

IV. Fabrication and Construction

A. Subassemblies

The individual components used in the system were described in a previous section. Fabrication of these components into subassemblies was undertaken by TIG welding in a drybox shown in Fig. 55. Subassemblies were then welded together in the containment tank, using a



Fig. 55. Welding dry box

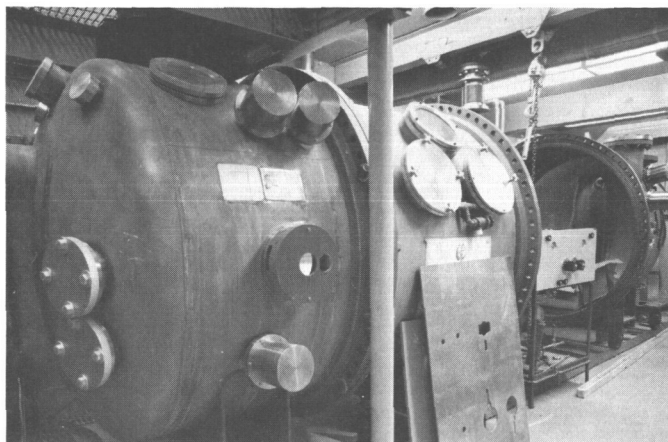


Fig. 56. Lithium-boiling potassium loop containment tank with welding spool-piece insert

spool piece insert with drybox gloves which allowed the containment tank to function as a drybox (Fig. 56). Annealing the final welds on the lithium side was accomplished in the containment vessel under vacuum conditions.

All components were received in a fully annealed condition. The subassemblies of the lithium system were annealed after welding. The following items were selected as subassemblies and are shown in Fig. 3:

- (1) Primary lithium heater and hot trap.
- (2) Lithium centrifugal pump.
- (3) Lithium flowmeter.
- (4) Boiler.
- (5) Turboalternator, bypass, and valves.
- (6) Condenser.
- (7) Potassium electromagnetic pump.
- (8) Potassium preheater, hot trap, and throttle valve.
- (9) Turboalternator bearing feed system.

Each of the four lithium system isolation diaphragms was treated as a subassembly.

B. Weld Technique

The lithium loop subassemblies on the lithium side of the system were chosen on the basis that each field weld on the mainstream portion of the loop was made at the juncture with each two pressure transducer isolation diaphragm lines. Thus three field welds could be made in a small area and all three welds could be annealed in one operation.

The selection of subassemblies on the potassium side was made on the basis of the maximum size of component which could be handled in the drybox.

During all welding operations both oxygen and moisture were monitored. Specifications on impurities were 5 ppm maximum moisture or oxygen. Oxygen was monitored by an Analytical Systems¹¹ instrument and moisture was monitored by a CEC¹² monitoring instrument. Welding experience indicated that the impurity levels of moisture and oxygen were approximately 1 ppm each, which is within the aforementioned impurity specifications. Moisture and oxygen concentrations above 5 ppm are reduced by evacuating and back-filling the weld chamber with high purity argon as often as necessary. Although other workers in the field have observed moisture increases during the welding operation, we did not observe this phenomenon during our welding. This lack of moisture increase has been attributed to the use of heavy (0.032-in.-thick) sulphur-free gloves and double O-ring seals at the cuffs of the gloves.

The use of a standard TIG welding torch requires electrical insulation and cooling water. The care with which joints in cooling water lines are made will also affect moisture buildup. When it was found that the standard cooling lines provided with the torch were not impervious to moisture, the lines were cut to a minimum length. The joints were coated with high quality vacuum grease and hoses were clamped with fine wire. In addition, cooling water lines in the drybox were constructed of polyvinyl chloride with Swagelock seals.

C. Atmosphere Protection

Since outgassing of the loop, insulation, associated equipment, and containment vessel was expected as operating temperatures were increased, a method was needed for removing these impurities from the atmosphere and protecting the columbium from them.

The argon received was guaranteed to contain less than 5 ppm total impurities and was generally found to contain less than 2 ppm oxygen, plus water vapor. Thus, the primary concern was outgassing during operation. Hydrogen was observed at levels of approximately 10 ppm; the majority of this, however, was believed to be a blank resulting from the sampling techniques used. Nitrogen

¹¹Teledyne, Inc., Analytical Instruments Division, Pasadena, Calif.

¹²Consolidated Electrodynamics Corp., Pasadena, Calif.

was always below 100 ppm, the limit of detection capability of the apparatus used in the gas analysis.

Thus, protection of the columbium by a sacrificial foil wrap was needed. Data available from Pratt & Whitney Aircraft (CANEL), and Oak Ridge National Laboratory (ORNL) indicated that sticking probabilities for oxygen were greatest with molybdenum and less with zirconium and tantalum. Experiments were run using each of these foils wrapped on Cb-1Zr alloy capsules and oxides of these wrapping materials were placed on the inside of the capsules. As expected, the molybdenum reacted most rapidly, becoming brittle and breaking away from the capsule. Thermodynamic predictions were also verified by the reduction of the molybdenum oxide by the columbium. Thus, on the basis of its oxide stability and reaction rate, the zirconium was selected as an inner wrap against the columbium. Two outer wraps of tantalum foil were then placed over the zirconium foil. Tests of this combination have proved its effectiveness based on analyses of the foils and columbium base metal after test.

Wrapping of the loop was done in the open air by spot welding the foils. A heavy argon-cover-gas flow was used at the spot welding tip to minimize contamination.

The wrapping technique was satisfactory for the entire loop except for the R-C. Wrapping the R-C would impair its heat rejection capability to an unacceptable extent. Thus, commercially available oxidation-resistant coatings were tested for possible use on this portion of the system. Results of these tests have been presented in detail in a JPL report (Ref. 2) and are only summarized here.

The chromium-modified silicides produced chromium diffusion into the columbium bare metal. Tin-aluminum coating appeared satisfactory although one of the samples tested appeared contaminated. The most acceptable technique appeared to be a diffusion layer of molybdenum coated with molybdenum disilicide. However, a decision was made not to coat the condenser coil, since (1) the supplier who did the molybdenum coating was unable to assure the purity of the chlorine used in a halide vapor-deposition process, (2) the molybdenum coating thickness was very nonuniform, and (3) the supplier of the molybdenum disilicide process coating was unwilling to guarantee performance. This decision was also based on the heavy wall thickness of the coil and the effects of oxygen contamination of a portion of the potassium loop.

Oxygen contamination of the Cb-1Zr containment material in the lithium portion of the loop would result in penetration of the columbium by lithium and 'weeping'

of the tubing. In the case of potassium, oxygen contamination would not cause failure of the Cb-1Zr component but might cause an increase in mass transfer rates of the Cb-1Zr material, an effect that would be negligible during this test. Another possible effect is that of increased consumption of the zirconium hot trap material. This effect, also, is believed to be negligible because of the large amount of zirconium contained in the hot trap compared with the potassium inventory of the loop. The third possible effect is deterioration of the mechanical properties of the Cb-1Zr. However, no hardening of the columbium tubing was observed. A chemical analysis of the protective foils on other portions of the loop indicated levels of oxygen contamination below those necessary to cause property deterioration.

D. Annealing Techniques

Field welds on the potassium section of the loop were not annealed. All subassemblies on the lithium loop were annealed prior to field welding, thus leaving only four areas on the lithium loop to be annealed. Each of these areas was a cross containing three new welds and a fourth previously annealed weld. Annealing was done after the loop was foil-wrapped for protection from contamination.

Two flat-plate heating elements were enclosed in an outgassed, foam insulation box which was cut to fit snugly around each area to be annealed. The area was thermocoupled and the loop enclosed in the containment vessel. Annealing was done under a vacuum of 10^{-3} mm/Hg or better. Heating was done slowly to maintain the vacuum. Each area was held at 2200°F for one hour, then cooled. Examination of the protective foil indicated contamination of only the outer wrap, and not the two inner wraps. The outer foil wrap was replaced in these areas.

E. Insulation Methods

The selected insulation material, *Glasrock Foam* 25-lb density, was supplied in slabs measuring $3 \times 12 \times 18$ in. Each slab was outgassed at 2200°F in argon for two hours and then allowed to cool. It was then cut to fit; and Q-felt (Microquartz), a soft, fibrous, blanket insulation was used to fill the cracks between the blocks to minimize heat losses. The insulation blocks were held in place with stainless steel bands or wires.

F. General Construction Comments

Considering the system as a whole, several construction notes are worthy of comment. The loop is contained in a vessel 5 ft in diameter and 7 ft long. The loop is supported

within a stainless steel framework that provides the anchor and support points. A stress analysis of the loop, performed before final assembly, was made by hand computations and then rechecked with an IBM code. The two methods showed good correlation. These analyses indicated the desirability of making a few changes in the anchor and support points for the loop, that were in fact incorporated into the final assembly.

The containment vessel provides either a vacuum or an argon environment for the loop. The main flange and the several smaller flanges are compression-sealed with Viton-A gaskets or O-rings. In addition, there are numerous penetrations in the tank for instrumentation, power, valve and shutter actuators, and the lines going to the loop proper (fill and drain lines, gas lines, and Dowtherm A coolant lines). Some of these penetrations are sealed with O-rings; others, using bellows for alignment and movement, are welded.

The F-D system is situated outside the containment vessel. This location was possible because there are no refractory-metal components in the F-D system. This system, in addition to the reservoir tanks of lithium and potassium, contains the filters, argon and vacuum manifolds, valving and connections to shipping containers, and

valving and connections necessary for draining the lithium and potassium drain tanks.

G. Auxiliary Systems

The auxiliary systems, which have nothing unique in their construction, were described in a previous section. Suffice to say that their design and construction was dictated by the need for unattended operation. These systems are the vacuum, argon, Dowtherm A coolant and power supply coolant loops. These systems are external to the test cell and control room.

V. Liquid-Metal Loop Instrumentation

Instrumentation for the liquid-metal loop consists of three main parts:

- (1) Transducers located inside the loop containment enclosure.
- (2) Cabling between the transducers and control room.
- (3) Instrumentation inside the control room.

Most of the instrumentation on the loop is routine except for three areas: 2000°F temperatures, materials

Table 2. Liquid-metal loop measurement summary

Parameter	Number	Transducer	Nominal ranges	
			Physical input	Electrical output
Temperature				
Loop t_{abs}	70	W-Re thermocouples	150–2200°F	0.8–22 mV
Boiler inside ΔT	19	Pt-Rh thermocouples	10–300°F	0.06–1.8 mV
Boiler outside ΔT	19	Pt-Rh thermocouples	80°F ^a	0.48 mV ^a
Condenser ΔT	20	W-Re thermocouples	100–500°F	1–5 mV
Monitor	70	C-A thermocouples	70–1500°F	–1–37 mV
Pressure				
Absolute, lithium	2	Strain gage transducer	0–50 psia	0–10 mV
Absolute, potassium	6	Strain gage transducer	0–200 psia	0–10 mV
Absolute, miscellaneous	4	Strain gage transducer	0–20 through 50 psia	0–10 mV
Differential, lithium	4	Variable reluctance transducer	0–5 through 50 psid	0–250 mV
Absolute, potassium	6	Strain gage transducer	0–5 through 150 psid	0–250 mV
Miscellaneous				
Flow	2	EM flowmeter	0–1 through 3.5 gpm	0–2 mV
Voltage	5	Voltage divider	0–1 through 250 V	0–1 V
Current	4	Shunt	0–12 through 4000A	0–1 V
Position	6	Potentiometer	0–100°	0–1 V
Liquid level	1	Resistance element	0–100%	0–1 V

^a ΔT with 30-kW power input

technology required to meet loop containment enclosure atmospheric conditions, and high noise superimposed on low level signals. These three areas will be discussed in some detail, but routine instrumentation technology will receive only brief mention.

The loop was operated for approximately seven months before a shutdown occurred that was caused by the potassium preheater failure. During the shutdown period, essentially all of the cabling and most of the thermocouples inside the vacuum tank were replaced and, at the same time, significant improvements were made.

The basic scope of the instrumentation is indicated in Fig. 57 and Table 2. Figure 57 shows a block diagram of the liquid-metal loop instrumentation system. Basic breakdown of the three main parts—transducers, cabling, and control room instrumentation—are given on the diagram. Major signal groupings and instrumentation components are also given. Table 2 summarizes the required measurements.

The transducers, cabling and the control room instrumentation are discussed in this section. A discussion of the initial operational experience, and future modifications to the instrumentation, is included in Section VI.

A. Transducers

The transducers described include any special signal leads required to connect the signals to conventional copper cabling. Three basic groups of parameters are measured: temperature, pressure, and miscellaneous signals.

1. Temperature transducers. Three types of thermocouples are used on the liquid-metal loop to measure various temperatures:

- (a) Tungsten-Rhenium (W-Re): all primary temperature measurements except for the boiler temperatures.
- (b) Platinum-Rhodium (Pt-Rh): all boiler differential temperatures.

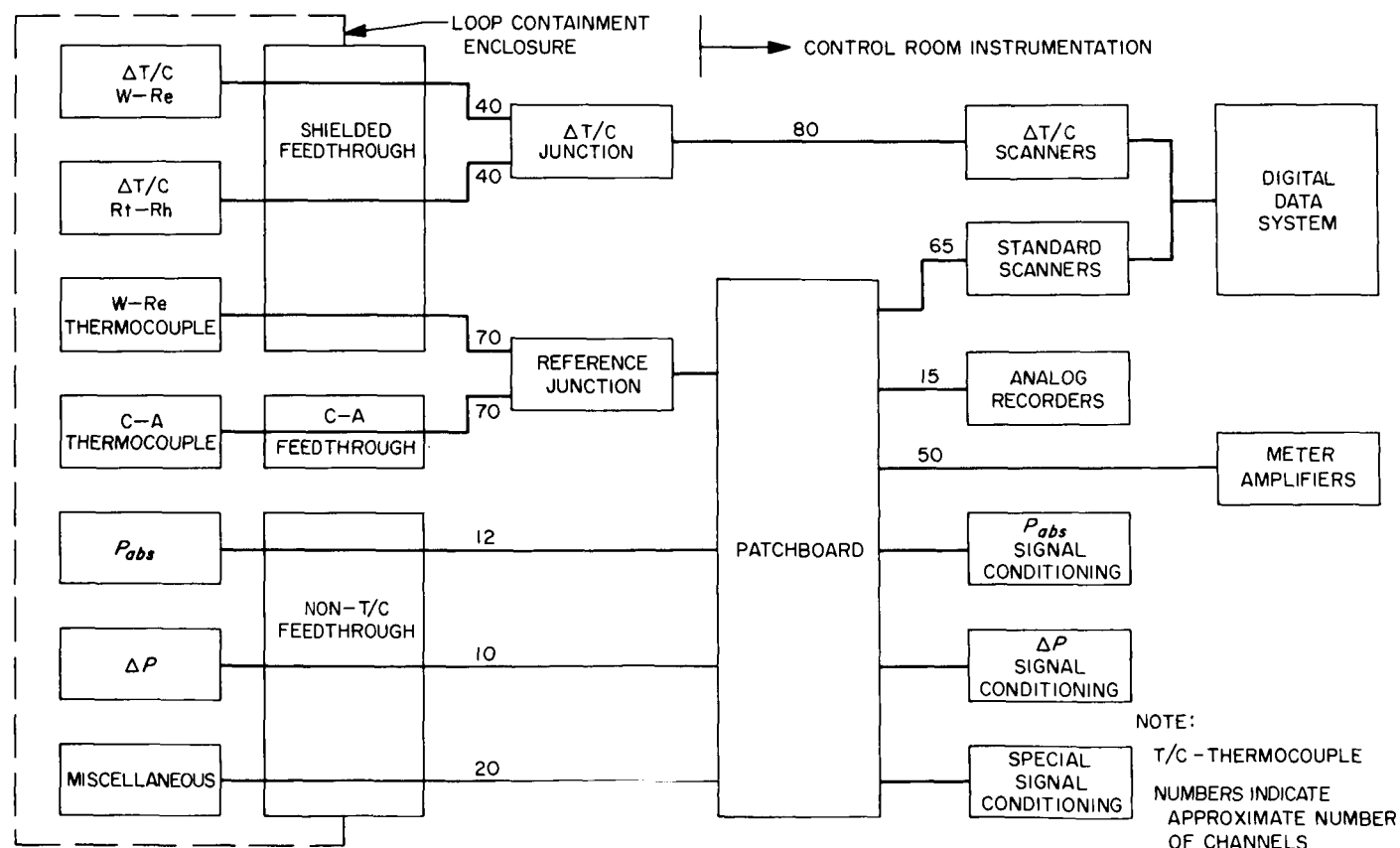


Fig. 57. Liquid-metal loop instrumentation block diagram

- (c) Chromel-Alumel (C-A): all noncritical temperatures on the liquid-metal loop. These temperature measurements are used primarily during heat-up and cool-down operations.

a. *Tungsten-rhenium thermocouples.* Tungsten-rhenium thermocouples are used to monitor all critical temperatures, except for the boiler, because of their low drift in an inert atmosphere. Several studies conducted by other firms have indicated that the drift of a W-Re thermocouple is appreciably less than either noble metal or base metal thermocouples in such an atmosphere. Possible drift of other thermocouples and future requirements to measure temperatures on other liquid-metal loops dictated the use of W-Re thermocouples for all possible critical temperature measurements on the liquid-metal loop.

Because of the limited experience with W-Re thermocouples, it became necessary to work out techniques to cope with the idiosyncrasies of these materials. These techniques can be divided into essentially two areas: methods of making the actual thermocouple junction, and lead wire techniques.

Junctions. Conventional procedures for forming junctions used for base metal or noble metal thermocouples are generally unsatisfactory when used with W-Re thermocouples, because of embrittlement of the tungsten metal. A typical, welded thermocouple junction is extremely brittle and will break under normal handling procedures; extreme caution, considerably above that normally exercised during thermocouple installation processes, is required to avoid breakage of the junction. Also, the susceptibility of the welded junction to vibration could result in its failure after some operational life.

Another stringent limitation was imposed by refractory-metal technology. The columbium loop is operated at high temperature; and freedom from contamination and thermal stress loads is of overriding importance. This consideration eliminated certain mechanical attachment techniques and limited the materials that could come in contact with the columbium.

Some differential-thermocouple temperature measurements required that the thermal resistance between the columbium pipe and the thermocouple junction be held to an absolute minimum because of thermal fluxes of approximately 300 BTU/ft². Any slight variation in the junction-to-columbium thermal resistance would cause

an appreciable error. Because of these problems, a junction-forming technique was developed which utilized a plasma spray to form the actual thermocouple junction. A thin (about 0.005 in.) layer of tantalum, which is compatible with columbium, is sprayed over a 2-in.-long area on the columbium pipe. Next, a layer of alumina is plasma-sprayed on top of the tantalum coat. Another layer of tantalum is then plasma-sprayed over the alumina layer.

These last two steps provide for an ungrounded thermocouple junction and may be eliminated from the procedure if an ungrounded thermocouple junction is not necessary. The two thermocouple legs are placed over this area, then bonded to the tantalum base with a tantalum bead approximately 1/8-in. thick and 1/4-in. in diameter. This tantalum bead provides both an electrical junction, and mechanical and thermal bonds to the columbium pipe. Thermal resistance of this combination is repeatable. The entire assembly is then sprayed with alumina to provide electrical insulation, with all spraying done in an inert atmosphere. Figures 58 and 59 show closeups of completed, sprayed thermocouples. Figure 29 shows the 20 thermocouples on the condenser assembly; these thermocouples are used for differential temperature measurements.

Replacement thermocouples cannot be installed with this technique because of mechanical limitations associated with the inert atmosphere requirement. A similar procedure has been used to make junctions on 0.062-in.-thick columbium tabs which are formed to mate with the columbium pipe. A typical columbium tab is nominally 3/4-in.-long and is bent to concentrically cover a 180° arc of the pipe. Although this technique has a higher, and

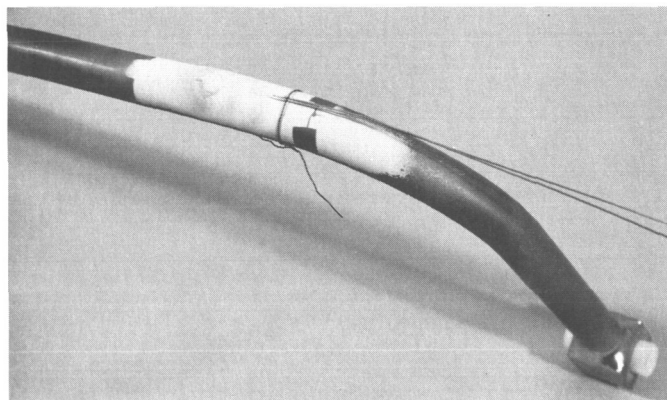


Fig. 58. Completed sprayed tungsten-rhenium thermocouple

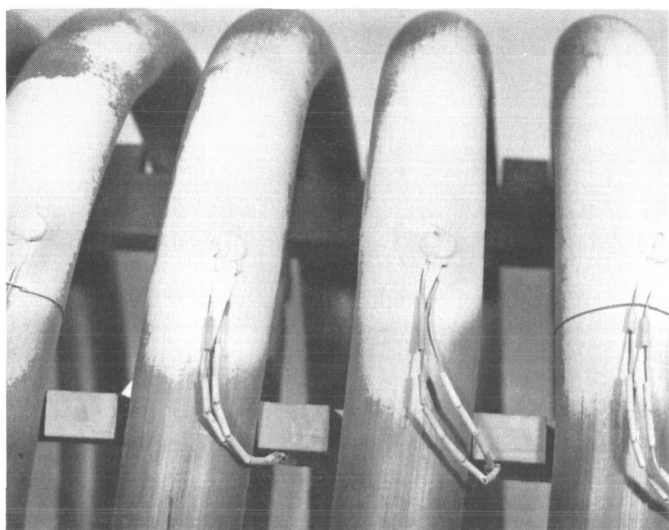


Fig. 59. Tungsten-rhenium thermocouples on condenser

less repeatable, thermal resistance, it does provide a feasible method for forming junctions when conditions do not permit direct attachment of the thermocouple to the pipe.

Lead wires. The cost of the W-Re thermocouple wire precluded its use between the W-Re junction and the reference junction, a distance of approximately 30 ft.

Matching lead wire has a specified error of $\pm 110 \mu\text{V}$ (approximately $\pm 10^\circ\text{F}$) over a temperature range of $32\text{--}500^\circ\text{F}$. This would provide an unacceptable error in many of the required measurements, especially where differential temperature measurements are required. To reduce this error to an acceptable value, it was necessary to determine the possible errors associated with various temperatures at the junction between the thermocouple wire and the lead wire. Experience with the initial thermocouple installation indicated that these errors were associated with each lot of thermocouple wires and lead wires; different lots of lead wire will cause different errors when mated with the same thermocouple. A series of tests to accurately determine the characteristics of the particular wires used in this installation was conducted. These tests indicated that a negligible junction ($< \pm 1^\circ\text{F}$) error could be achieved with a junction temperature of 306°F . The test also continuously determined the slope of the error vs the junction-temperature curve (Fig. 60).

The first installation on this loop used a different lot of lead wire than that used in the last installation. Experimental tests, conducted in the same manner as those

described previously, determined that junctions between the two lots of lead wires could cause significant errors (Fig. 61). However, this error can be used to compensate for the thermocouple alloy error, since the slope is of opposite polarity.

Calibration of millivolts with temperature during the loop operation was a laborious process. Further calibration of the errors caused by the two unconstrained junction temperatures would increase this problem considerably. The junctions between the thermocouple and new alloy lead wire, and between the new and old alloy lead wires will, therefore, be controlled to take advantage of the opposite slopes of the error curves. The ambient temperature inside the loop containment enclosure was determined to be at least 350°F during full power operation. Control simplicity dictates that any junction temperatures will be controlled above this temperature to avoid the complications required by any cooling systems. Consequently, the junction temperatures between the thermocouple wire and lead wire will be controlled at 400°F , which will give an error of -50 mV (Fig. 60). The junction between the new and old alloy lead wires will be held at 330°F , which will give an error of $+50 \text{ mV}$. Junction blocks between the thermocouple and new alloy lead wires will be used to reduce the length of the expensive thermocouple wire required. All junctions between the new and old alloy lead wire will be made in an isothermal zone. Temperature of these blocks will be monitored and controlled to keep the net resulting error to less than $\pm 20 \text{ mV}$, or $\pm 2^\circ\text{F}$.

Calibration. Calibrations conducted on the wire during the first installation disclosed that the manufacturing process did not produce absolutely homogeneous wire, and that repeated calibrations would be required to accurately determine the exact sensitivity of all W-Re thermocouples used on the loop. Calibrations were conducted on selected thermocouples used in the current installation. These calibrations agreed within $\pm 3^\circ\text{F}$ of the data provided by the manufacturer. These calibrations also showed that this batch of thermocouple wire was much more homogeneous than the previous batch, indicating that the manufacturing process has been significantly advanced over the last year.

These calibrations used a copper freezing point standard as a reference, and were conducted in an argon atmosphere of the required purity. The entire instrumentation system was included in this calibration: the cabling, reference junction, grounding and shielding

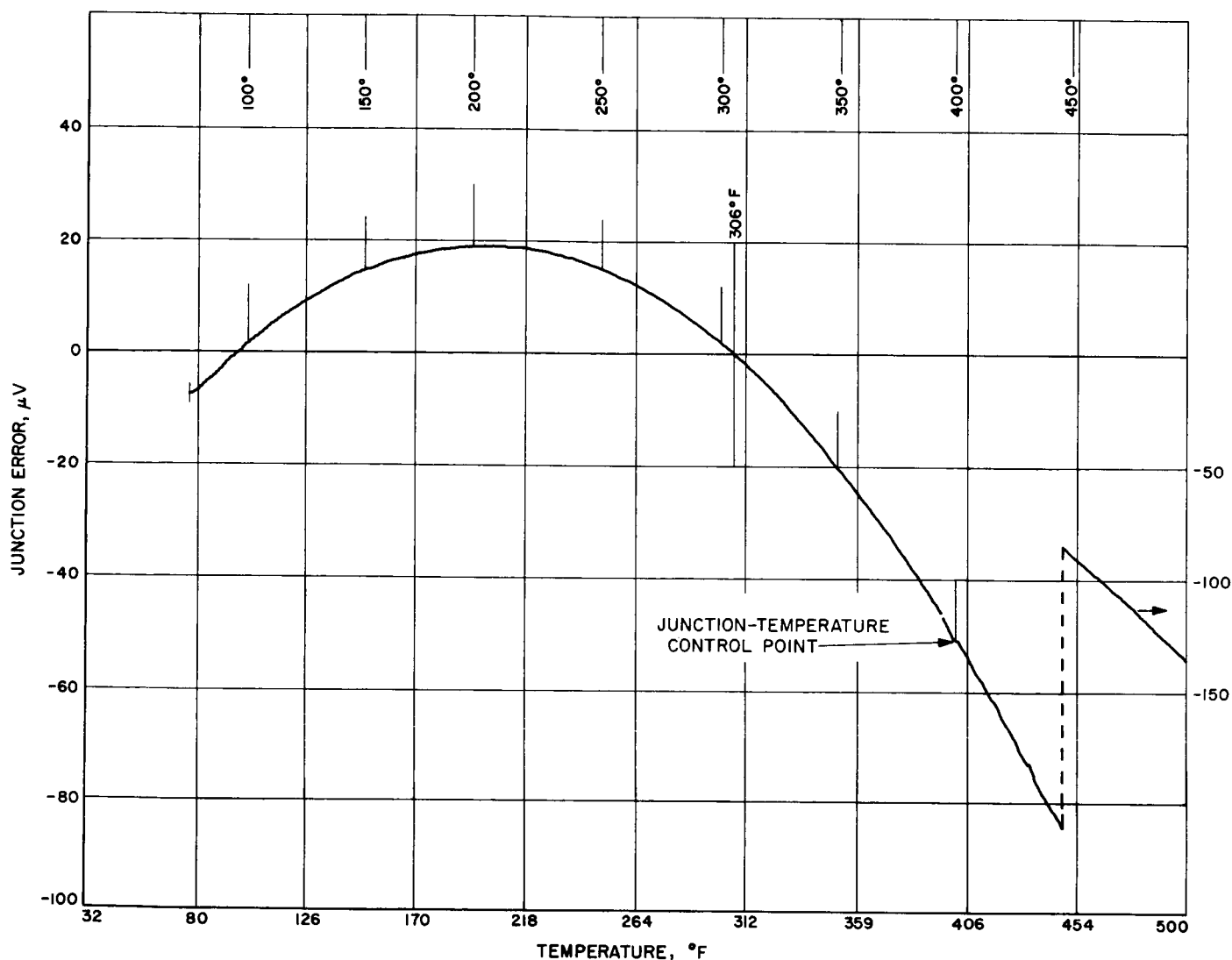


Fig. 60. Tungsten-rhenium to lead-wire junction error

practices, and final digital data recording system. This recording system was calibrated with a 0.01% voltage standard before the tests were started, and the calibration was monitored periodically. Typical calibration data is shown in Table 3.

b. Platinum-rhodium thermocouples. Platinum-rhodium thermocouples are used to measure the temperatures of the inside and outside of the boiler—the most critical temperature measurements of the entire loop. The possibility of drift in the Pt-Rh thermocouples was recognized, but economic considerations prevented the use of W-Re thermocouples. To reduce drift, Pt-6% Rh:Pt-30% Rh thermocouples are used. Drift of this combination is

less than that of the more common 10%-Rh thermocouple. However, reduced drift is obtained at the expense of less output: sensitivity is approximately 6 mV/°F.

Thermocouples to measure temperature on the inside of the boiler are included in a specially fabricated assembly that is completely described in Section III-B-1.

Junction temperatures between the Pt-Rh thermocouples and copper lead wires must be made at the same temperature to avoid any extraneous effects. No lead wire is available for the Pt-6% Rh:Pt-30% Rh thermocouples. In addition, normal tolerances associated with lead wire could not provide sufficiently accurate measurements.

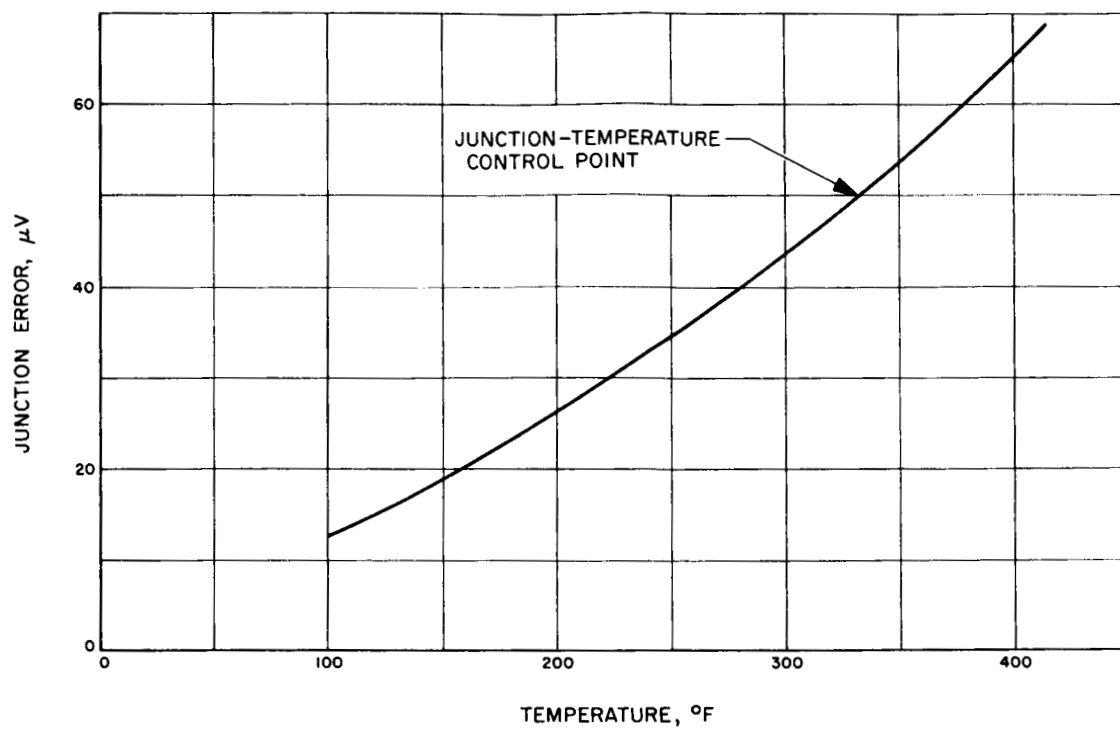


Fig. 61. New lead-wire to old lead-wire junction error

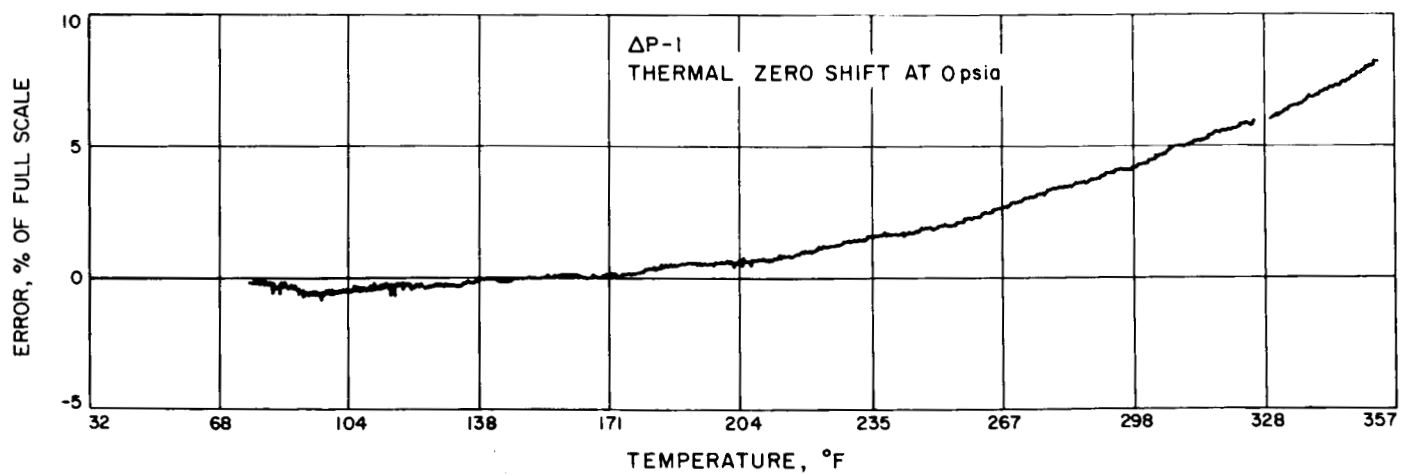


Fig. 62. Differential pressure transducer zero shift with temperature

Table 3. Tungsten-rhenium thermocouple calibration data

Oven up		Oven down	
Temperature	W-Re, mV	Temperature	W-Re, mV
774.8	6.27	1649.0	14.77
827.4	6.82	1507.8	13.48
874.1	7.29	1397.5	12.46
919.4	7.76	1308.5	11.61
1011.0	8.70	1234.0	10.89
1113.0	9.73	1163.5	10.22
1202.5	10.62	1102.0	9.61
1276.0	11.36	1047.4	9.06
1338.5	11.96	999.3	8.56
1386.1	12.43	955.0	8.12
1530.5	13.77	914.5	7.70
1613.5	14.51	877.5	7.32
1649.8	14.83	844.0	6.97
1679.5	15.09	811.5	6.64
1711.4	15.36	781.5	6.33
		752.5	6.04
		720.0	5.71
		689.4	5.39
		604.1	4.51
		552.0	3.98

All Pt-Rh thermocouples are used to measure boiler inside and boiler outside differential temperatures. The upper thermocouple is used as a reference. Because of this arrangement, no reference junction is required for the Pt-Rh thermocouples.

c. Chromel-Alumel. Chromel-alumel thermocouples were used wherever possible on the loop to avoid the cost and complexity associated with the W-Re or Pt-Rh thermocouples. Their primary use is to monitor heater temperatures, component temperatures less than 1000°F, and other parts associated with heatup and cooldown procedures. Chromel-alumel thermocouples are installed with conventional techniques.

The literature indicates that for good stability C-A thermocouples should be used in an oxidizing atmosphere. The tendency of the C-A thermocouple to drift in a high-purity argon atmosphere was confirmed at the time that the W-Re calibrations were conducted. A C-A thermocouple drift of 3-4°F was recorded during a single 4-h temperature cycle from ambient temperature to 1700°F and return. Drift was accurately checked with a copper

freezing point standard. Thermocouples made from adjacent lengths of the same wire and subjected to similar temperature time cycles in an oxidizing atmosphere showed essentially no drift. The accuracy required of these thermocouples was such that drift did not constitute an operating problem.

2. Pressure transducers. Two types of pressure transducers, absolute and differential, are required for this loop. Accuracy requirements are low, but widely varying temperatures and materials compatibility presents serious problems.

a. Absolute pressure transducers. Absolute pressure transducers are conventional strain gage units with a 500°F environmental rating. These transducers were purchased without expensive temperature compensation, since each transducer is individually calibrated.

b. Differential pressure transducers. Differential pressure transducers are the variable reluctance type. Purchased in 1962, these transducers do not represent the best transducer that is available at the present time. Strain gage units would be preferred to standardize the signal conditioning and calibration procedures, but suitable high-temperature, differential pressure, strain gage transducers were not available at the time these differential pressure transducers were purchased.

Significant zero and sensitivity shifts were exhibited by the differential pressure transducers, as described in the next section. These errors required thorough and complete calibrating of each individual transducer.

c. Calibration. At the time of sale, the manufacturer would not guarantee any specific limits on zero or sensitivity temperature effects on the differential pressure transducers. Preliminary investigations showed that these errors could be at least 10%, and would vary with different transducers. Equipment and procedures were developed to permit efficient calibration of all pressure transducers. This provided a complete calibration of the following parameters:

- (1) Temperature vs zero shift.
- (2) Temperature vs sensitivity shift.
- (3) Linearity.
- (4) Line pressure vs zero shift (differential pressure transducers only).

All data is presented in the form of X-Y graphs with the forcing parameter on the X axis and the resulting

error, expressed in percent of full scale, on the Y axis. Approximately 100 graphs describing the characteristics of all absolute and differential pressure transducers were prepared. Typical calibration graphs are shown in Figs. 62, 63 and 64.

3. Miscellaneous transducers. The temperature and pressure transducers described provide the bulk of data in this experiment. However, flow, position, voltage, and current measurements are also required. Flow signals are obtained from electromagnetic flowmeters and provide

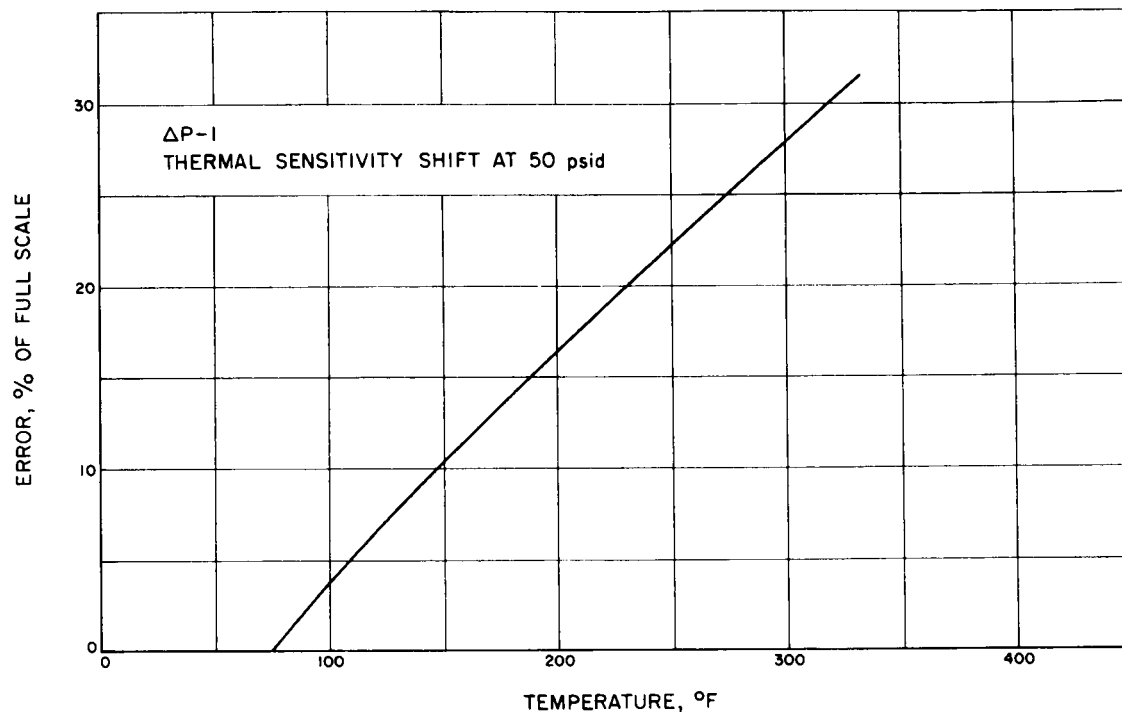


Fig. 63. Differential pressure transducer sensitivity shift with temperature

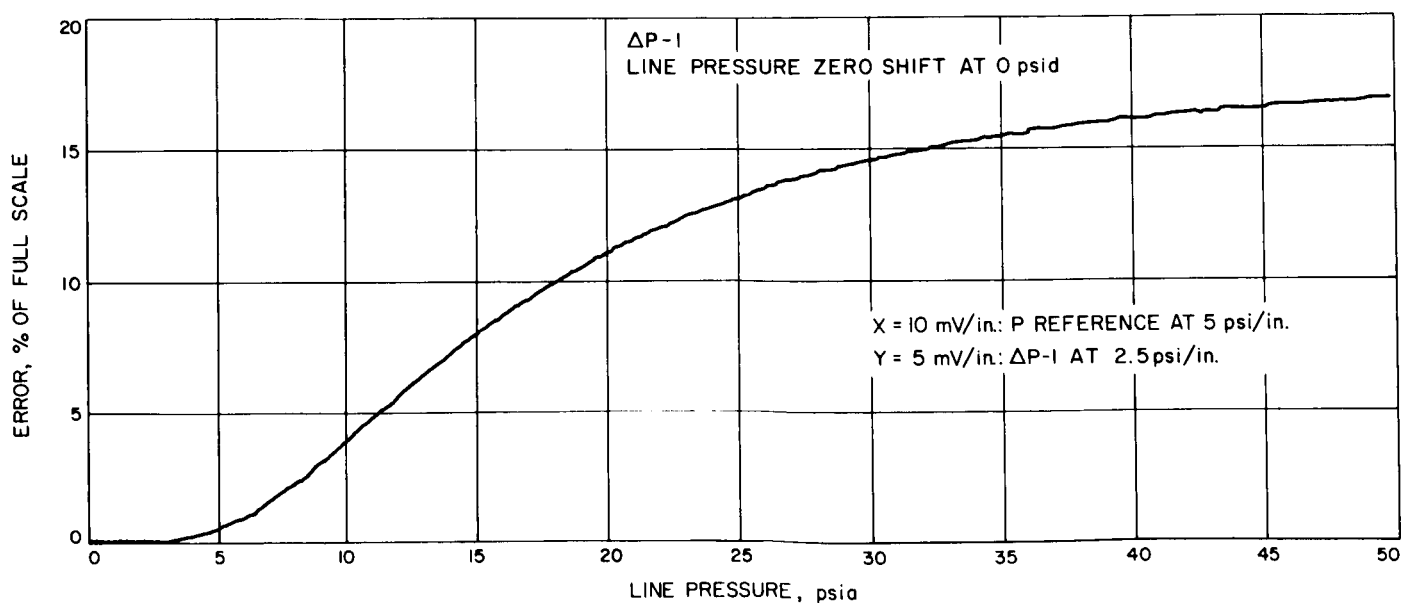


Fig. 64. Differential pressure transducer zero shift with line pressure

a low millivolt level signal. Voltage and current measurements use conventional voltage dividers and shunts to derive the required signal.

B. Cabling

The instrumentation cabling consists of three areas: inside the loop containment enclosure, feedthroughs through the enclosure wall, and between the feedthroughs and control room instrumentation.

1. Cabling inside enclosure. Cabling inside the enclosure uses conventional techniques. Aluminum oxide insulation is used on all thermocouples in high temperature zones; Teflon is used for all other insulation. The initial operation disclosed that some zones in the enclosure reached temperatures of 600°F. This damaged the Teflon insulation in several areas and required replacement of most of the cabling. Most connections have 500°F solder, or silver solder for connections close to the columbium loop, although mechanical and resistance welded connections are used in some cases.

2. Feedthroughs. Feedthroughs in the enclosure wall consist of three types: Pt-Rh and W-Re thermocouples, C-A thermocouples, and nonthermocouple signals.

a. W-Re and Pt-Rh thermocouples. The W-Re and Pt-Rh signals are sent through a 120-channel feedthrough. Both legs of a thermocouple are run through a single stainless steel tube having a 1/8-in. OD and a 0.012-in. wall. This tube is electrically isolated from the stainless steel flange. By electrically connecting the shields on these signal wires to this stainless steel tube on the inside and outside of the enclosure, a means is provided of running a completely shielded thermocouple signal through the enclosure wall. The actual thermocouple wires are vacuum-sealed to the stainless steel tube with a vacuum-sealing compound. This vacuum-sealing technique provides an excellent seal, and no leaks were detected when a helium leak check was run on the completed assembly. Figure 65 shows a typical feedthrough channel.

b. C-A thermocouples. The C-A thermocouple feedthrough uses a method similar to that for the Pt-Rh and W-Re thermocouples, but does not use a continuous shield because less accuracy is required on the C-A signals than on the others. A commercially available tubular feedthrough is used for the C-A signals. Each leg of the thermocouple pair is sent through an individual tube, and sealed to the tube with a solder connection.

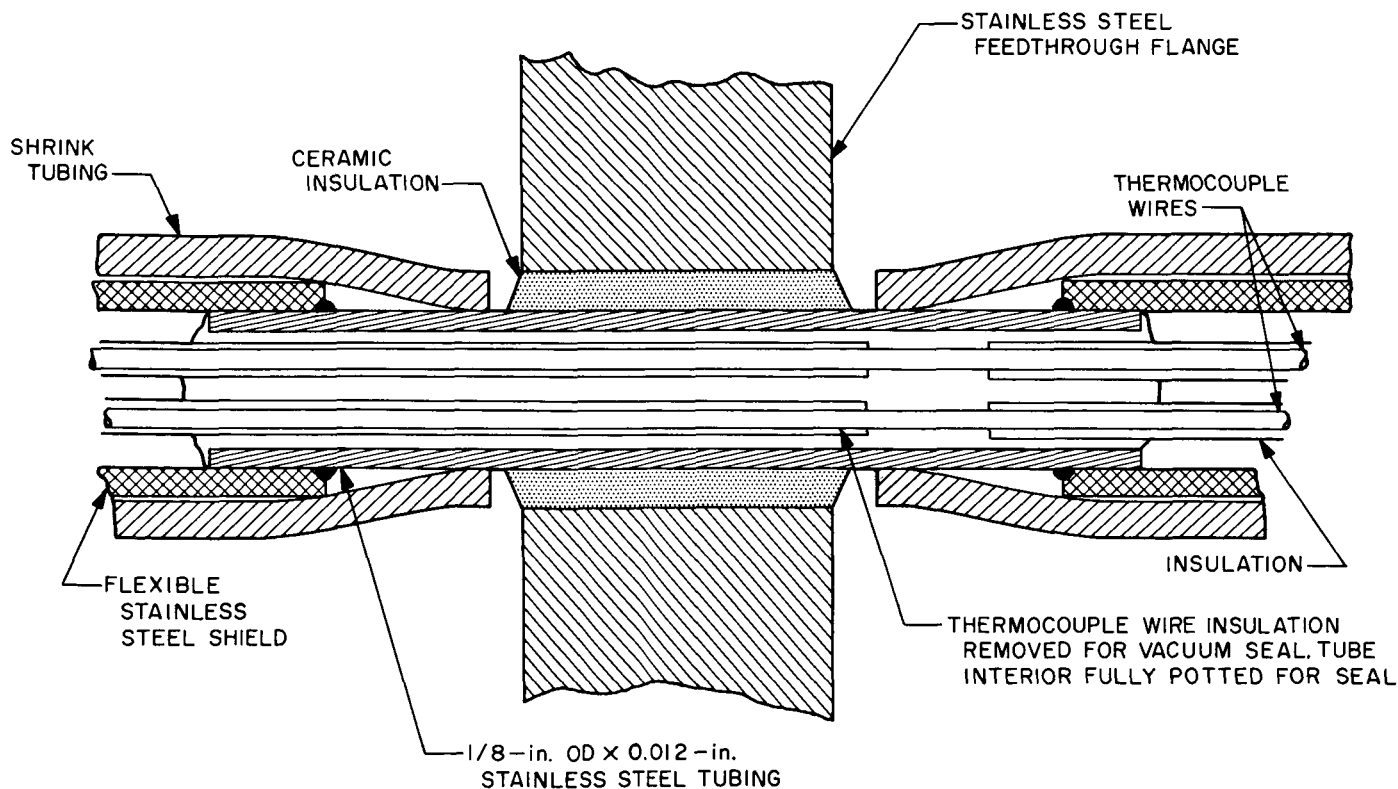


Fig. 65. Shielded thermocouple feedthrough

3. *Cable to control room.* Conventional cabling techniques are used from the vacuum tank to the control room. Junctions for all differential thermocouples are inserted in an aluminum block to assure no temperature gradients, thus eliminating any extraneous effects.

Cabling for all signals except for differential thermocouples is terminated in a patchboard in the instrumentation racks. The patchboard also serves as a parallel junction point for all signals to the control console. The shields and one signal line of all incoming signals are paralleled at the patchboard, to permit proper grounding arrangements.

C. Control Room Instrumentation

The control room instrumentation includes three main parts: signal conditioning, recording, and instrumentation associated with the control console. The signal conditioning consists of fairly conventional equipment. The record-

ing area is based on a digital data recording system which has some modifications to permit differential temperature measurements. Instrumentation associated with the control console consists of buffer amplifiers, and a switching and calibration module. Figure 66 shows an overall view of the instrumentation racks in the control room.

1. *Signal conditioning.* The signal conditioning equipment is primarily associated with the pressure transducers. Bridge supplies are used for all strain gage transducers. A balance and calibration unit supplied by the vendor of the differential pressure transducer is used for these transducers. Standard signal conditioning equipment and differential amplifiers are available for special measurements, although this equipment is not used extensively for routine measurements.

2. *Recording equipment.* The recording equipment is based on a digital data system. An 8-channel analog recorder and other analog recording instrumentation are also available.

a. *Digital data system.* The digital data system is based on a standard, commercially available 1962 system¹³ that has been modified to meet the measurement requirements of the liquid metal loop. Figure 67 shows a block diagram of the data system.

Scanners. The digital data system has four scanning modules. The first scanner is a 25-channel, 3-channel/s module that is standard equipment with this system. This scanner provides individual range programming on each channel. The other three scanners are 40-channel, 100-channels/s modules that have less than $1 \mu\text{V}$ error. These scanners are controlled by a special system that integrates them into the standard data system. Inputs to the 25-channel and first 40-channel scanner are available at the patchboard for multipurpose use, while the last two 40-channel scanners are hard-wired directly to the differential thermocouples. Figure 68 shows a block diagram of the differential temperature circuits. The control system scanners and amplifier control module are arranged so that the system automatically makes a differential temperature measurement for all signals in the last two scanners.

Amplifiers. Two amplifiers are used with this digital data system. One is used in the normal manner to amplify all signals after the scanner. The other amplifier is used in conjunction with the first to make a differential

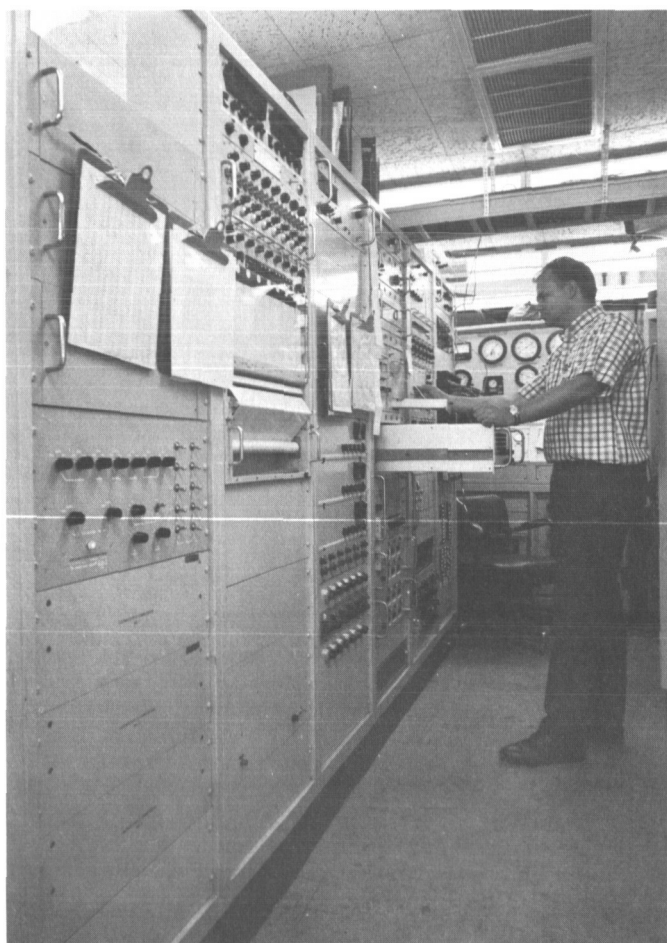


Fig. 66. Control room instrumentation

¹³Dymec Model 6087, Digital Data Acquisition System, Dymec Division, Hewlett-Packard Company, Palo Alto, Calif.

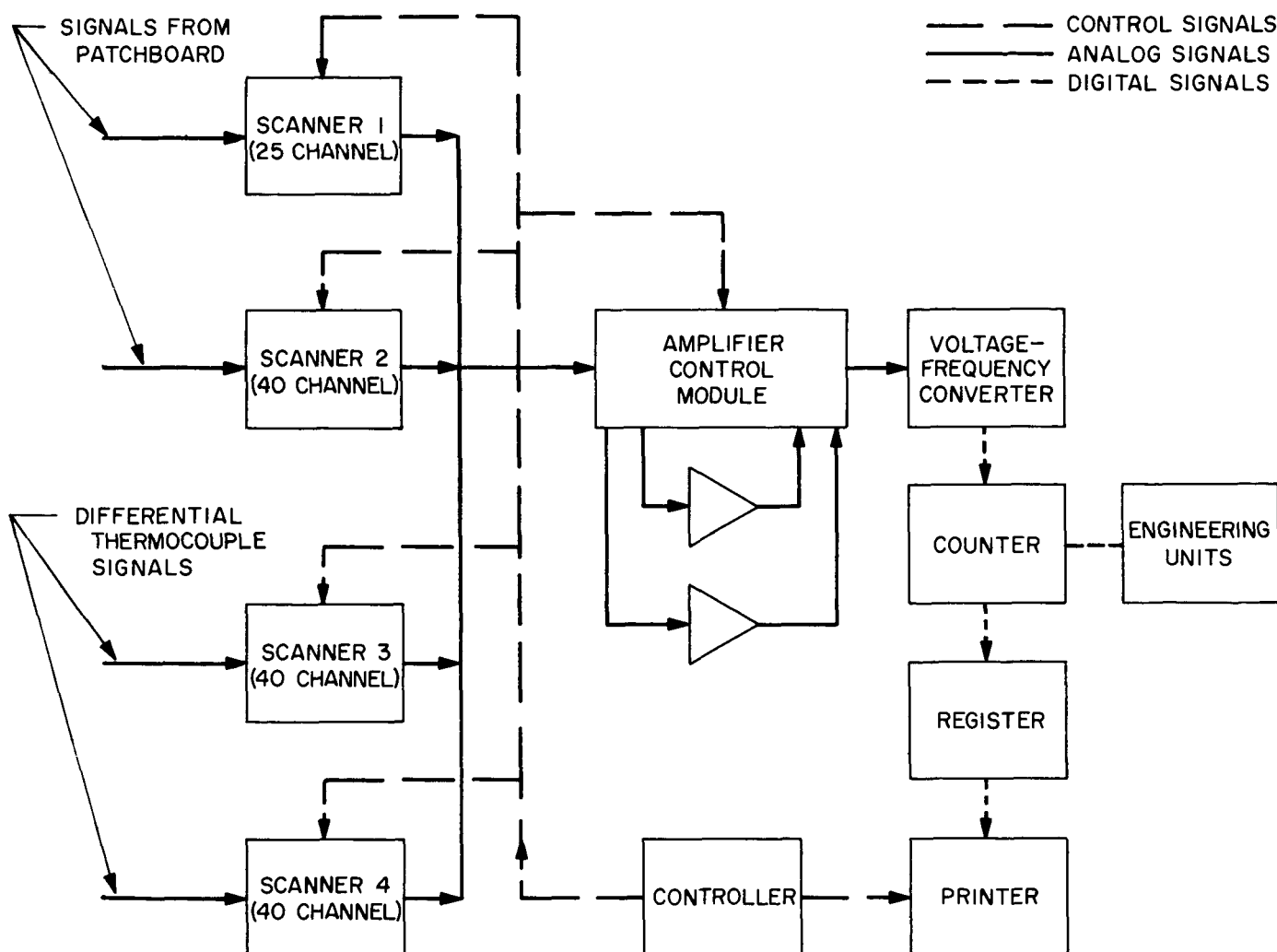


Fig. 67. Digital data system block diagram

temperature measurement. The use of two amplifiers electrically isolates any unintended grounds that may exist in the differential thermocouple installation. Control of these amplifiers according to the normal of differential temperature mode of operation is accomplished by the special control system.

Measurement. The digital data system uses the voltage-to-frequency technique to obtain digital data. The fully conditioned signal is presented to the input of the voltage-to-frequency converter, whose output is sent to a computing counter. This counter permits some measurements to be made in direct engineering units, although absolute temperature measurements cannot be displayed in engineering units because of the offset voltage associated with the reference junction. Output of the digital data system is a conventional digital-printed paper-tape recorder.

b. Analog recorders. The primary analog recording instrumentation is an 8-channel pen recorder. In addition to this recorder, an X-Y recorder and several strip chart recorders are available. Inputs for these recorders are available at the patchboard.

3. Control Console Meters. Signals for 50 control console meters are derived from the previously described transducers. The parallel connection dictated that the control console meters had to be completely buffered to avoid any loading effects on the other signals, since loading would interfere with data accuracy. Signals for the control console meters are paralleled at the back of the patchboard, then sent to a calibration and conditioning module. This module includes the switching necessary to set zeros, to offset thermocouples for 0–1000°F or 1000–2000°F operation, and to introduce calibration signals into

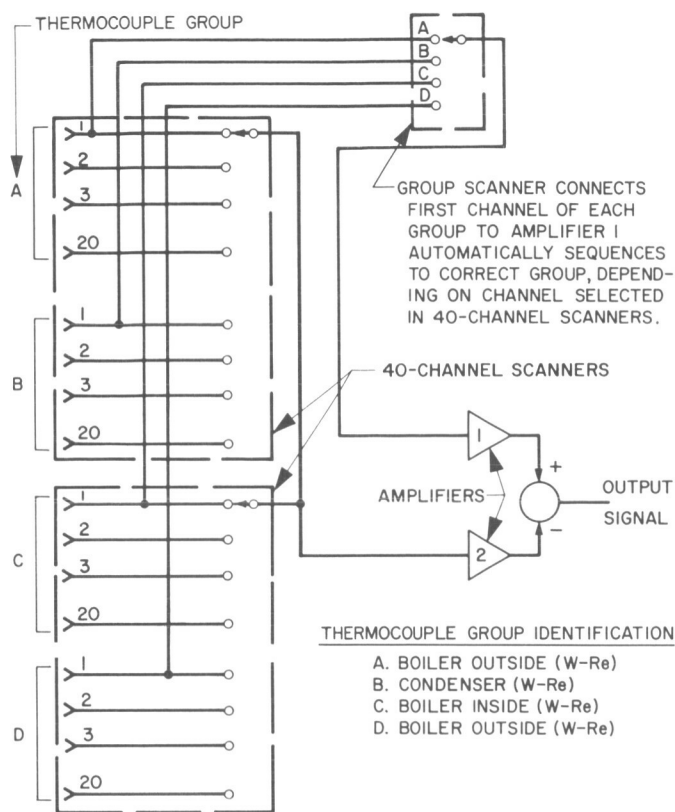


Fig. 68. Differential temperature measurement circuits

the meter circuits. The module also includes the switching that allows different thermocouples to be displayed on one meter. This switching includes stepping switches, which will multiplex from 7 to 40 thermocouples and display the output on a single meter. Outputs of the fully conditioned signals are sent to meter amplifiers which are based on an operational amplifier circuit. System gains are set at these amplifiers, which also present a high input impedance to the circuit. The actual meters provide the required current drive by being located in the feedback loop of the operational amplifier.

VI. Initial Operating Experiences

A. Initial Loop Operations

The lithium-boiling potassium test loop operations were begun January 11, 1966. Initial outgassing operations were accomplished by heating the loop and insulation with trace heaters at 400-500°F while maintaining a vacuum in the loop enclosure tank.

Following the outgassing procedures, the potassium loop was first filled completely ('hard-fill') with potassium.

Then the lithium loop was loaded with its nominal operating amount of lithium. Both loops were circulating in the 1000°F range, all-liquid nonboiling mode, for several hours, when the lithium centrifugal pump impeller suddenly seized and sheared the shaft which coupled it to the motor (January 29, 1966).

The loop was shut down and the pump dome and pump motor were removed. Examination showed that the pump shaft had sheared at a point where a deep keyway had been machined in the columbium shaft (Fig. 69). The break was readily accessible and a new coupling was bolted to the sheared impeller shaft.

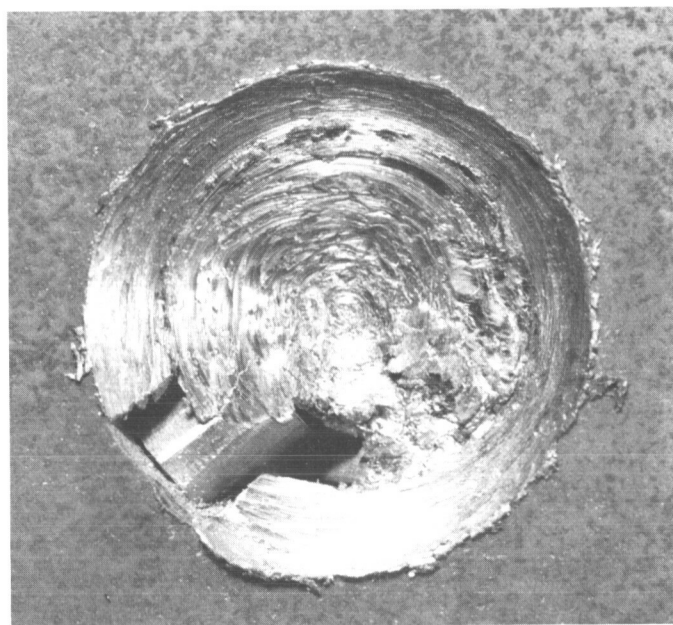


Fig. 69. Close-up photograph of sheared lithium pump shaft at keyway

The test loop was reheated and the lithium pump restarted. Potassium flow was then re-established. After about 170 hours of operation, the lithium pump seized again, at 1200°F. This seizure problem was alleviated by shimming the motor-and-impeller shaft up approximately 0.020 in. Operation of both loops in the liquid-liquid mode was then continued and calibrations of the lithium and potassium flowmeters were performed calorimetrically using the lithium heater and potassium pre-heater, respectively.

After initial liquid-liquid data were accumulated, the potassium level was slowly drained to its operating level with attendant commencement of boiling. The initial

boiling operations were stable; pressures, temperatures and potassium vapor quality were within expectations. Some boiling instabilities were first encountered at po-

tassium boiler temperatures of 1350-1400°F. These instabilities showed up mainly as periodic nondivergent oscillations in the potassium flow rate (see Fig. 70, which

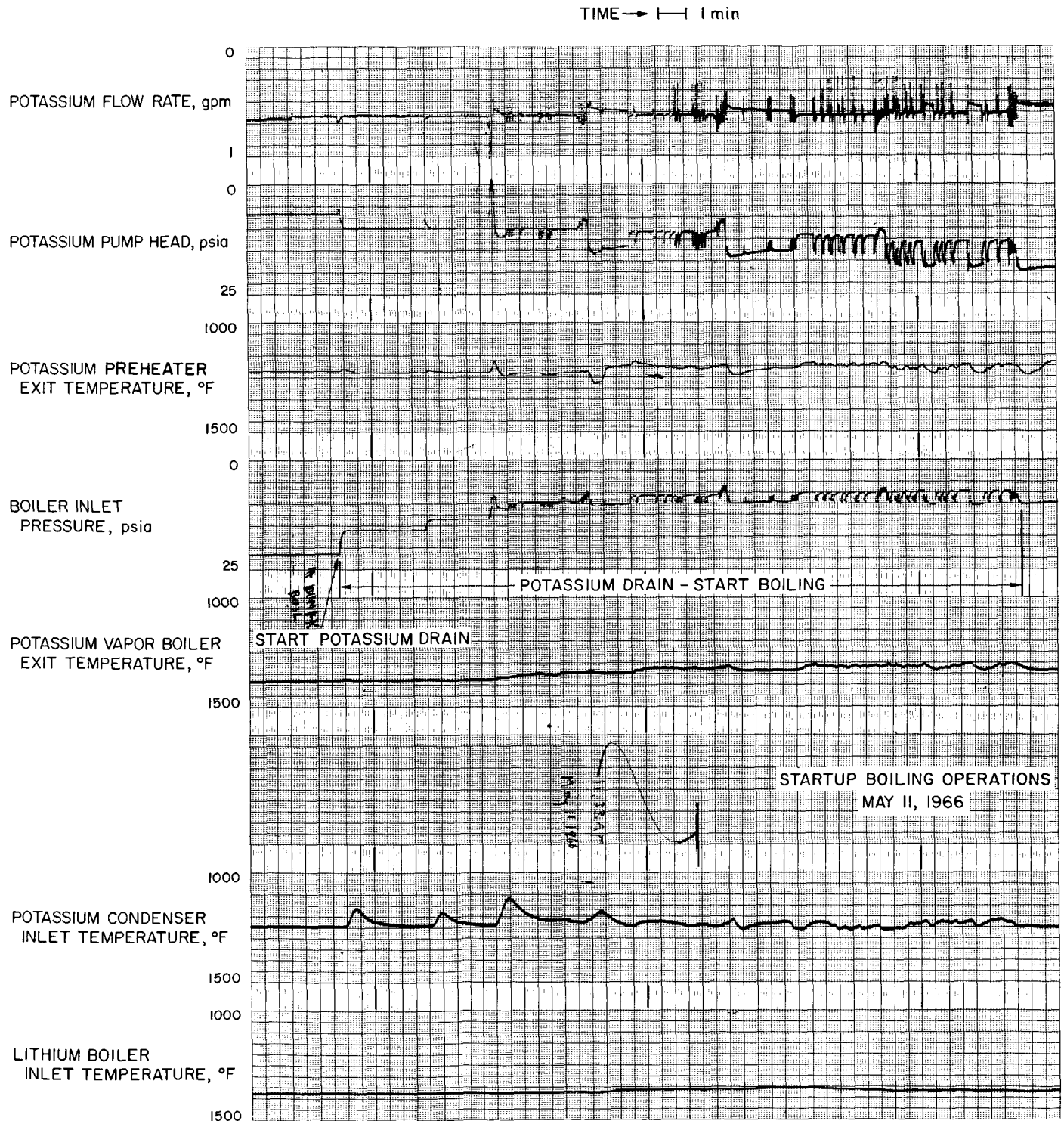


Fig. 70. Sanborn strip-chart recording of important loop parameters during initial boiling startup

is a Sanborn strip-chart recording of important loop parameters). The mean of the oscillatory potassium flow was greater than the previously observed flow rate under stable operating conditions. During this period of instabilities the potassium pump head was generally lower, indicating that the boiler pressure drop was lower because of the lower quality exit potassium vapor. These potassium hydraulic instabilities were readily controlled and removed by adjusting the potassium flow rate and lithium temperature by relatively small increments. Following this short period of unstable operation (~ 1 hour), stable boiling at $\sim 1500^\circ\text{F}$ (1700°F lithium temperature) proceeded for ~ 20 hours. The lithium pump then seized again but was successfully restarted after the pump shaft was reshimmed upward an additional 0.020 in.

At a power input of ~ 20 kW and at a boiler inlet lithium temperature of 1700°F , an overall JPL power failure occurred that resulted in a rapid loop cooldown to under 800°F .

After power was restored, temperatures were being returned to their previous level when another laboratory power failure occurred. Loop cooldown to $\sim 800^\circ\text{F}$ again occurred before power was restored. Approximately 20 hours later, with lithium temperatures back to $\sim 1600^\circ\text{F}$, a large reduction in the lithium flow signal initiated an automatic heater scram (May 14, 1966). Tests showed that the lithium pump was operating satisfactorily, but apparently a plug had formed somewhere in the loop that resulted in almost complete flow blockage. The system was cooled down to ambient and radiographs were taken of the loop to determine if the plug could be detected or to see if any significant mass transfer could be observed. Of particular concern was the possibility that the yttrium oxygen scavenger in the lithium hot trap had mass-transferred and precipitated in the boiler. However no such evidence could be seen in the radiographs.

Tests performed on the lithium loop to determine the location of the plug led to the conclusion that the plug was located in the lithium annulus at the bottom of the boiler.¹⁴ It was thought that the plug could be broken by pressurizing one side of the plug; or, by dumping the lithium from the loop, refilling with fresh clean lithium,

and reheating. Pressurization did not break the plug, so the old charge of lithium was dumped and a fresh charge loaded into the loop. Heating of the lithium loop and the boiler was accomplished by using trace heaters while circulating hot potassium through the boiler, the potassium loop having been previously hard-filled. Heating of the potassium was accomplished with the use of the preheater.

Raising the loop and boiler temperature to approximately 1200°F caused disintegration and dissolution of the plug.

With full lithium flow re-established, the hard-filled potassium loop, which was maintained at 1600°F , was slowly drained to its nominal, boiling-mode, potassium level of approximately two-thirds the height of the R-C. A plot of temperature vs R-C coil location before and after the draining and boiling operation reveals the height of potassium in the R-C (Fig. 34). This level was chosen to ensure against the possibility of pump cavitation.

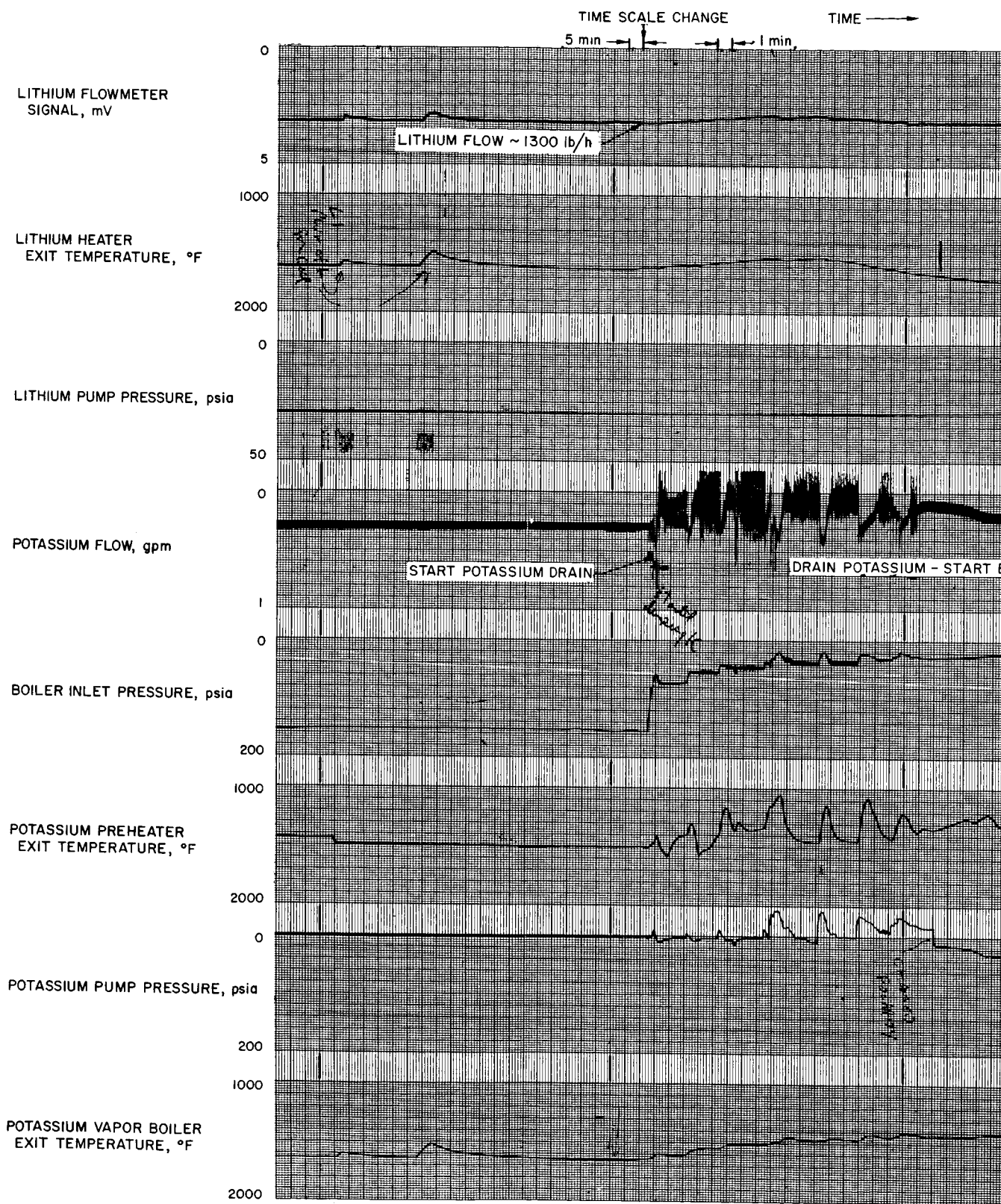
Figure 71 shows the Sanborn strip-chart recording during (a) startup, (b) steady state, and (c) shutdown operations. As the level was lowered in the potassium loop, boiling started and potassium flow fluctuations occurred for about 30 min (Fig. 71a).

Stable boiling was attained by increasing potassium pump power and operating at higher temperatures. Stable boiling of the potassium at about 1850°F continued for 8 h (Fig. 71b) with the lithium at 1900°F and at full-power operation of 30kW. Figure 72 is a plot of the boiler internal potassium temperatures (using internal Pt-Rh thermocouples) vs axial position in the boiler, based upon data taken during steady state boiling. The uppermost Pt-Rh thermocouple (measuring potassium exit-vapor temperature) is the reference thermocouple: potassium temperatures at other axial positions in the boiler are expressed as temperature differentials with respect to the reference temperature.

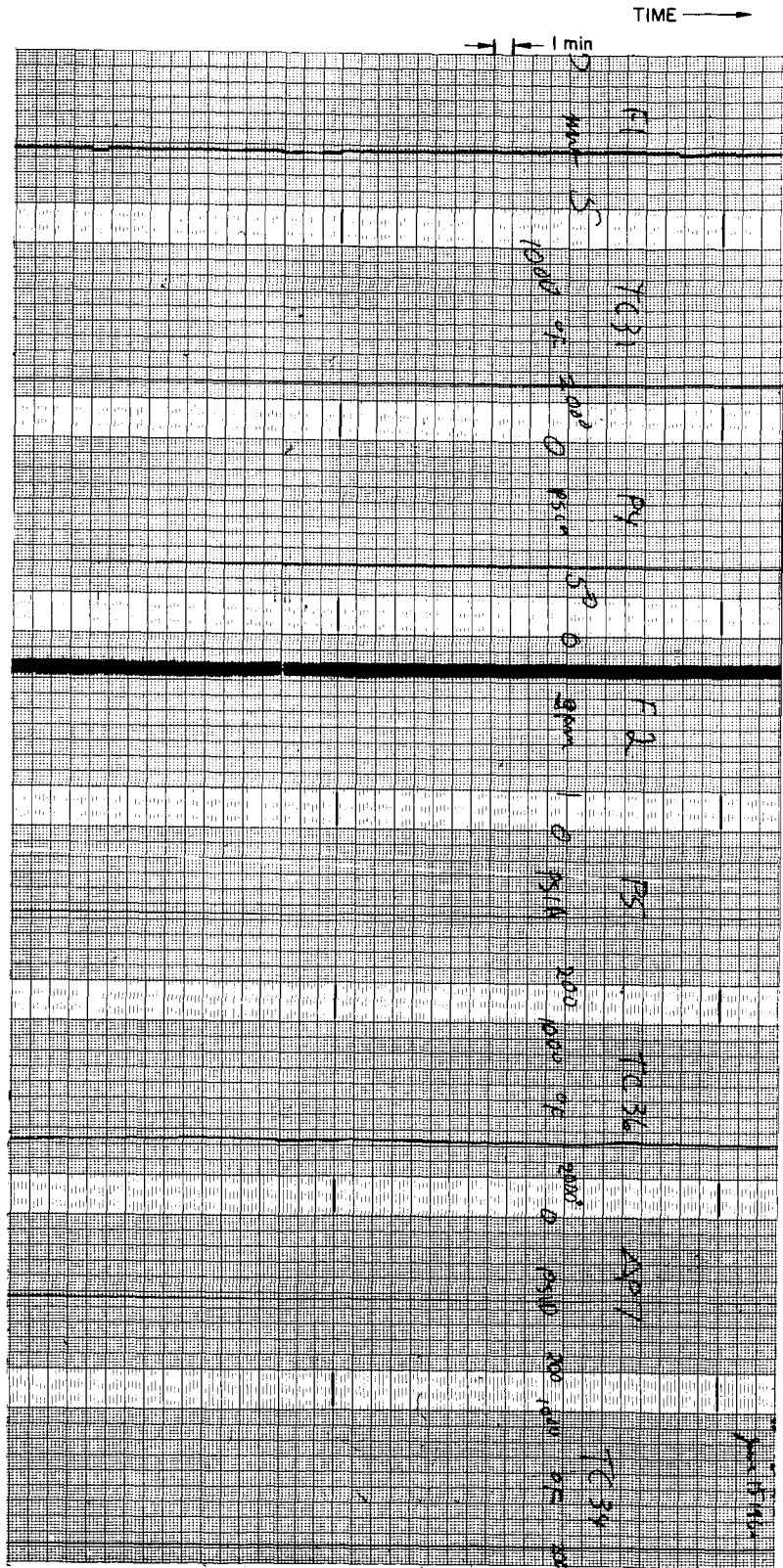
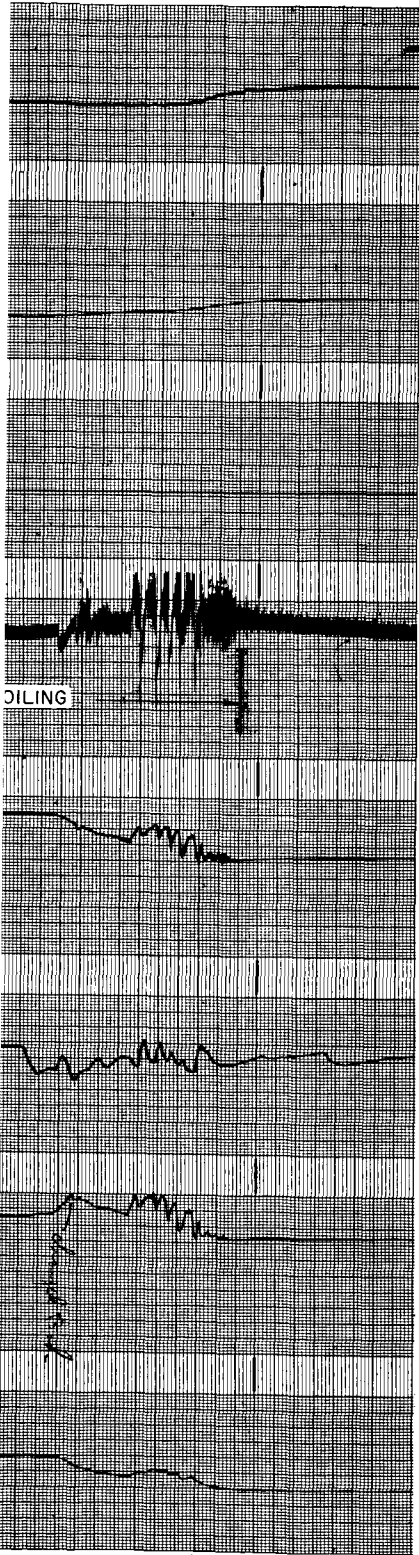
The overall potassium axial temperature difference in the boiler, as measured by the internal Pt-Rh thermocouples, agrees very well with the potassium inlet and outlet temperatures as measured by W-Re thermocouples which are positioned on the boiler inlet and outlet potassium piping.

Following this period of stable boiling, uncontrollable flow oscillations occurred which resulted in burnout and

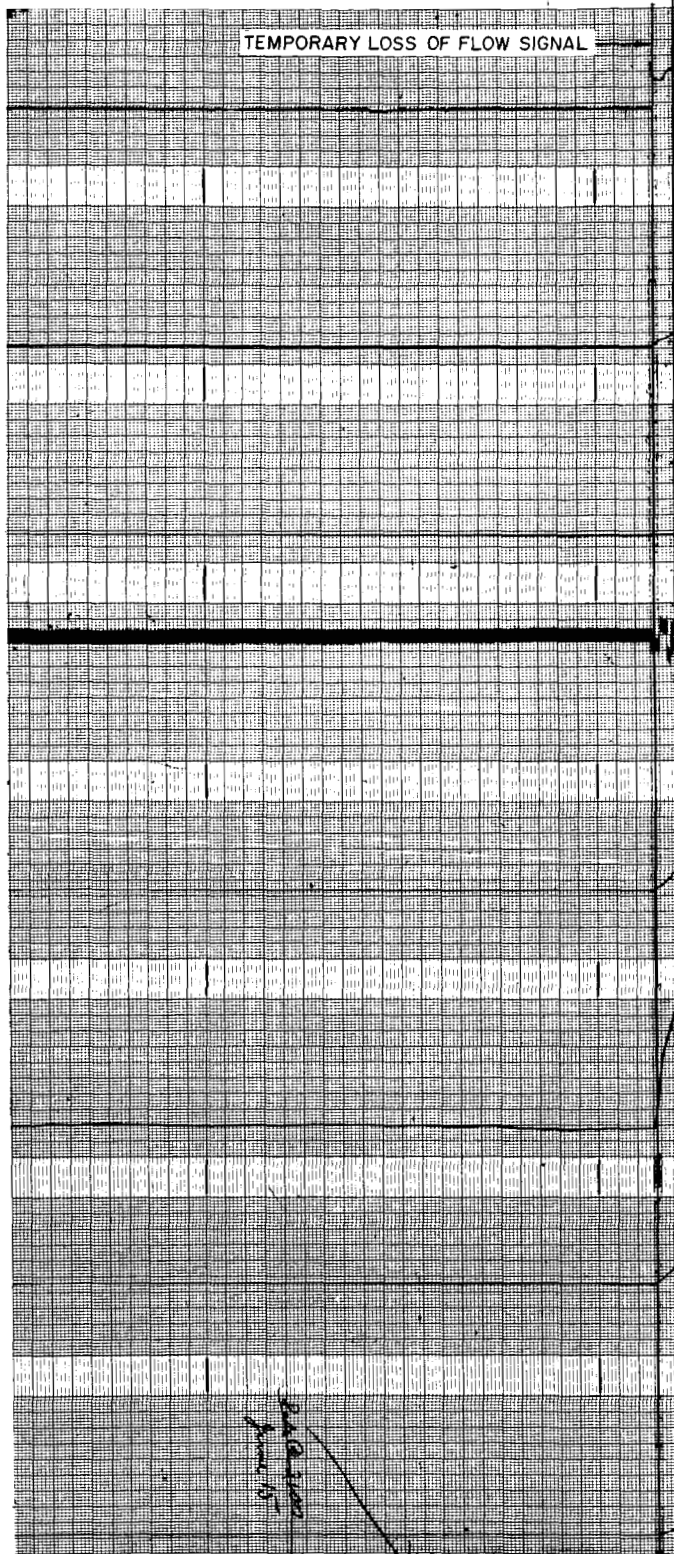
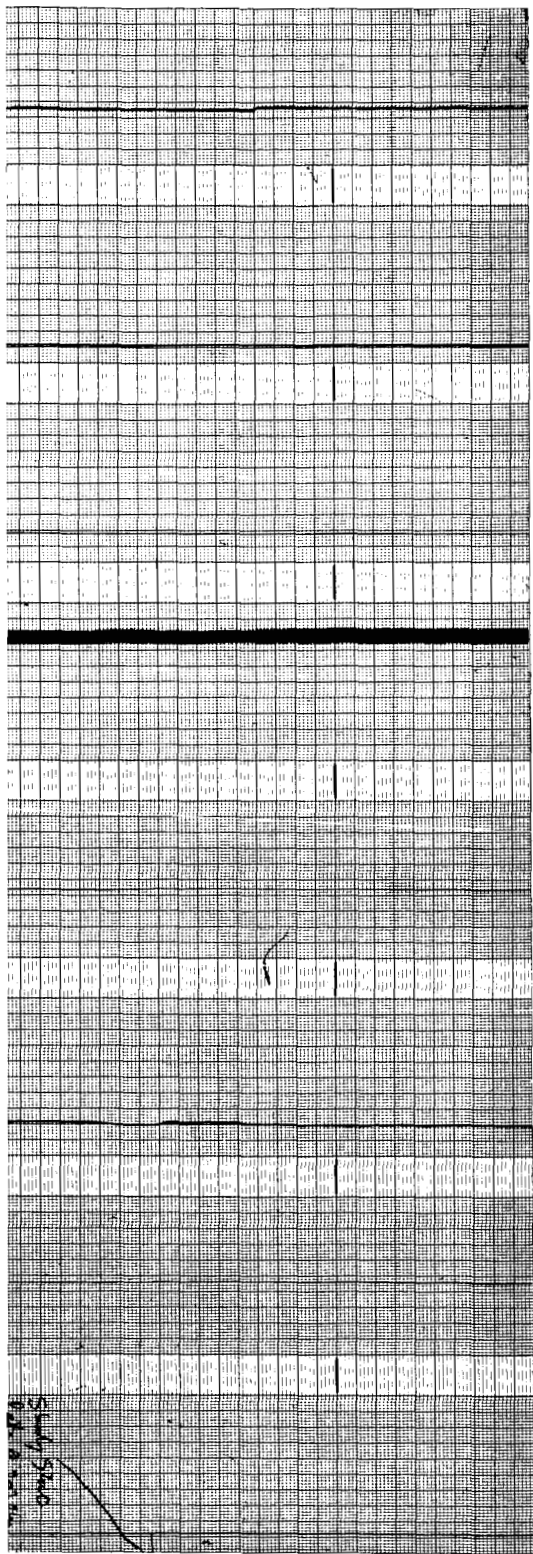
¹⁴This location of the plug explains why it was not visible on the radiographs. The lithium flow passage is annular, 0.875 in. OD by 0.062 in. wide. If the density of the plug material in this relatively thin annular passage (boiler OD 1.000 in.) is not greatly different from the surrounding fluid or not as dense as the columbium boiler structure, then it would not be visible on a radiograph.

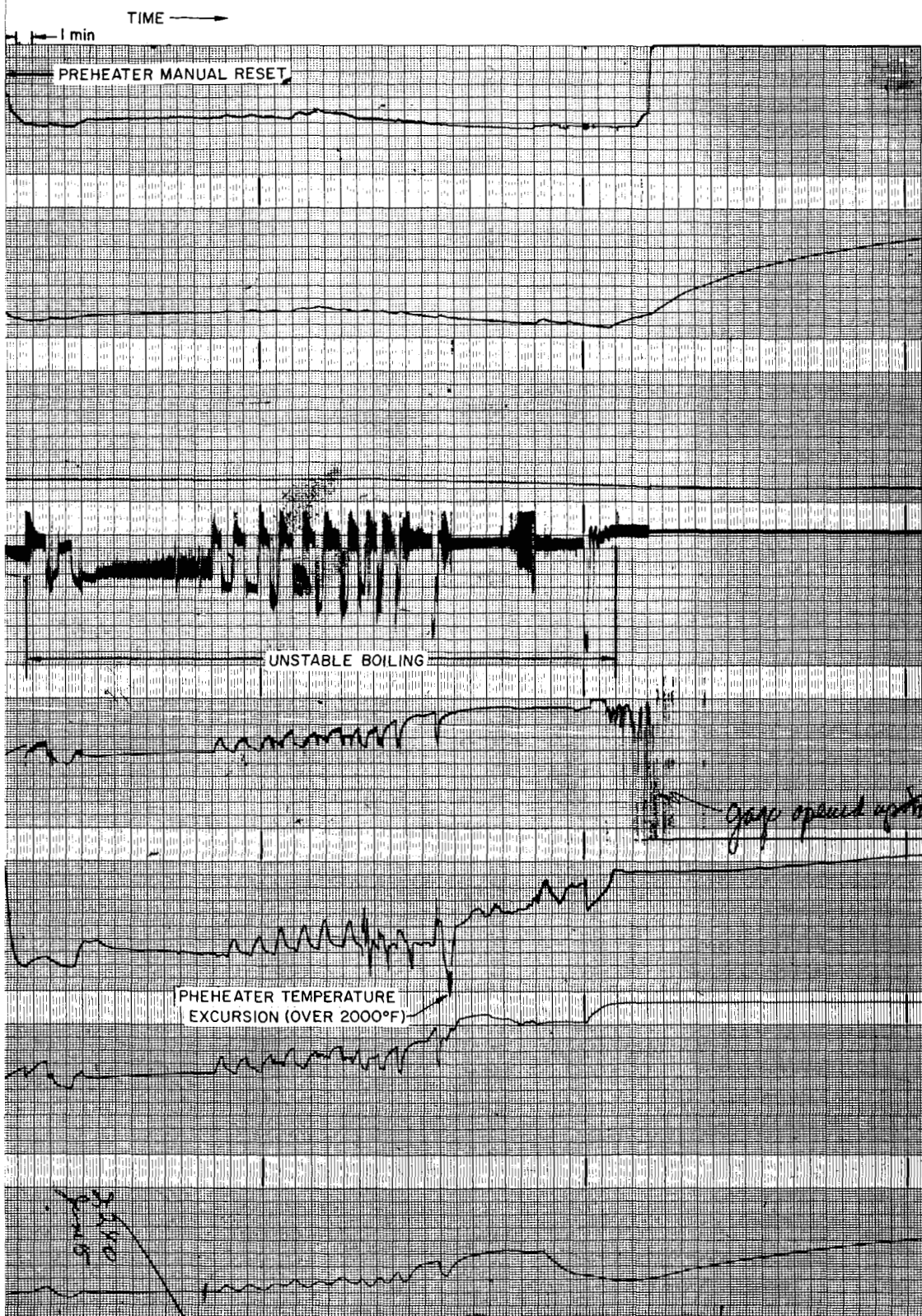


(a) BOILING STARTUP



(b) STABLE BOILING





(c) UNSTABLE SYSTEM BEHAVIOR

Fig. 71. Sanborn strip-chart recording - June 15, 1966

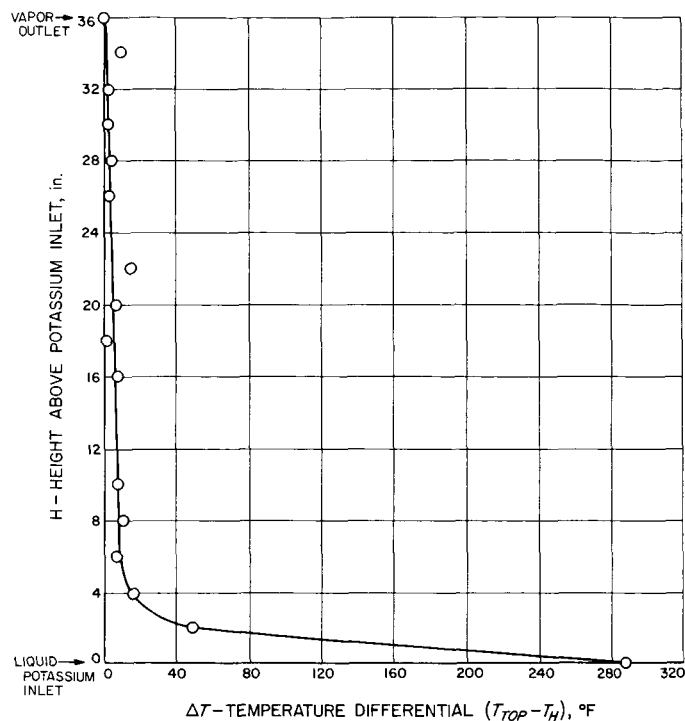


Fig. 72. Boiler axial potassium temperatures during stable boiling

meltdown of the potassium preheater. The explanation of this failure is as follows:

The oscillations started when an instantaneous reduction in lithium pump flow¹⁵ initiated an automatic shutdown of the lithium heater and potassium preheater power supplies. This automatic shutdown resulted in a very rapid drop of potassium boiler feed temperature which probably flooded the boiler. When the power supplies were manually reset, the temperatures rose very rapidly back to their nominal values. Flooding of the boiler and the cessation of the boiling process caused a large reduction in the net pressure drop through the loop, with an attendant rise in the potassium flow rate. After the power supplies were turned on again, the potassium in the boiler absorbed heat until it flashed and started boiling again in a very explosive manner. This sudden explosive boiling evidently caused not only a *reduction* in flow because of the much greater loop pressure drop during the vaporization mode, but also *reversals* in flow. This *chugging* effect on the potassium flow is seen on the Sanborn strip chart recording in

¹⁵This sudden reduction in lithium flow is thought to be due to either a momentary pump seizure, or a momentary formation and freeing-up of a plug in a lithium flow passage.

Fig. 71(c). With zero flow or a flow reversal, there is effectively no heat being removed by the potassium in the preheater, and within a short period of time (< one-half minute) it is possible to have a meltdown of the columbium tubing in the preheater when a large amount of power is being fed into the preheater (in this case ~ 6 kW before failure). Figure 73 shows the opened loop enclosure with the preheater that failed (*lower right*). The hot potassium leaking out of the preheater reacted with the Glasrock foamed silica insulation as seen in Fig. 74. The preheater melted at two points approximately midway between the center power-feed bus-bar and the outer ground straps. The remaining center section is shown in Fig. 75.

Following this failure, which occurred on June 16, 1966, the system was shutdown for repairs. All necessary repairs have been made and a new preheater (Fig. 76) has been installed and welded in place with the field welder described in Section VI-B.

A boiler feed valve (Fig. 77) had been included in the system at the boiler inlet for the specific purpose of varying inlet pressure drop to quantitatively study the effect of this important parameter on boiling stability. The valve has tungsten insert discs on both faces of the swinging gate. One of these discs that was not properly captured, dislodged and prohibited the valve from closing. Total liquid pressure drop from pump discharge to boiler inlet was thus less than 1 psi and a substantial stabilizing influence was unavailable for subsequent loop operations. However, even under these unfavorable conditions, stable boiling was achieved most of the time during the boiling runs.

It can be seen that this valve, after being cleaned of liquid metals, has a bright appearance, indicating very little, if any, oxygen contamination of the columbium during the total operating time of the potassium loop.

It is felt that stability in the boiling potassium loop will be greatly enhanced by providing a high pressure drop through the boiler feed valve when operating properly.

B. Field Repair Techniques—TIG Field Welder

Changes are being made (primarily, installation of a new preheater) in the lithium-boiling potassium heat-transfer loop, now that the first phase of operations has been completed. Any such changes of columbium components necessitates inert atmosphere TIG welding in a confined area. Techniques have been developed at ORNL

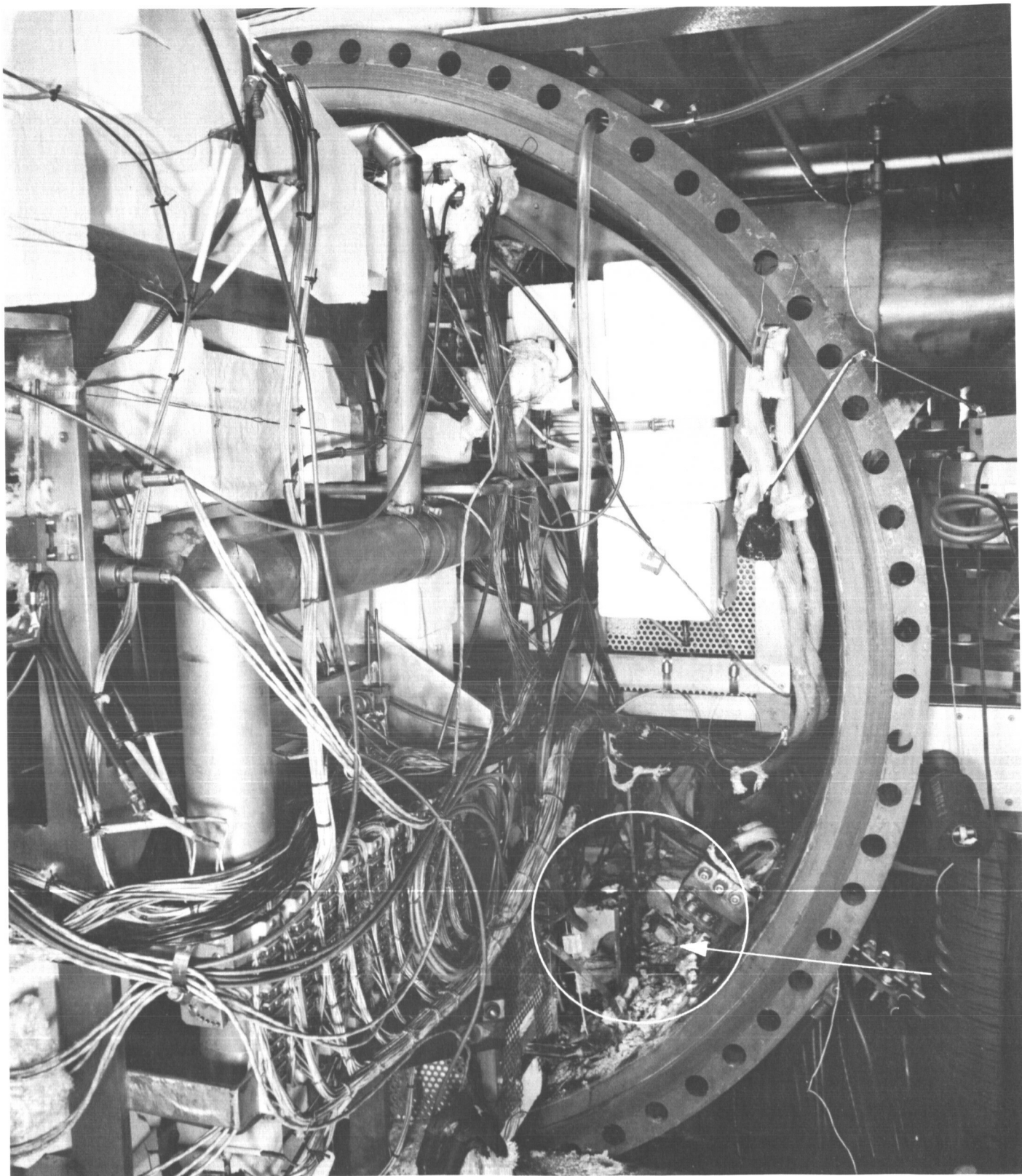


Fig. 73. View inside test loop containment vessel showing damaged preheater (arrow)

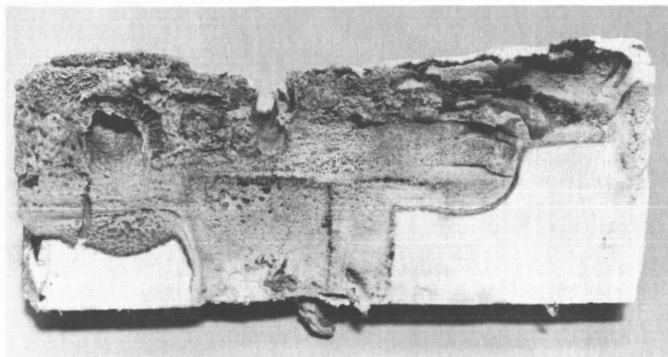


Fig. 74. Glasrock insulation after reaction with potassium during preheater failure

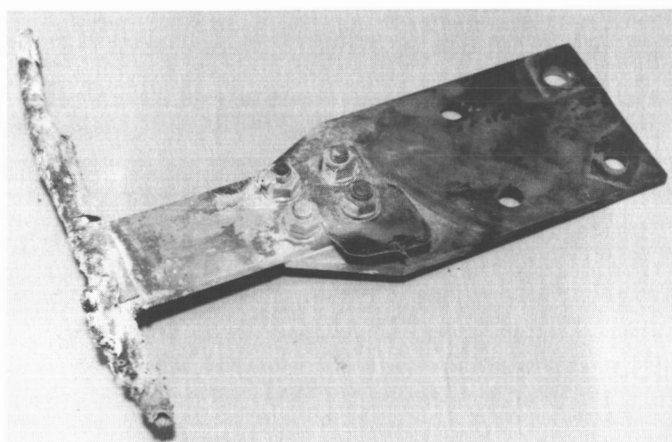


Fig. 75. Center section and positive power terminal of damaged preheater

(Ref. 3) to facilitate this type of welding operation. The methods developed there use equipment which is still too large to be used in the available space in the JPL test loop.

A refinement of the ORNL method was evolved at JPL to meet space restrictions. Components of the weld jig are shown in Fig. 78. The standard ceramic tip was removed from a TIG weld-torch. The torch was then bolted through a hole in a length of pyrex tubing using an O-ring for a seal. The pyrex-tubing torch assembly rotates on split water-cooled copper blocks which are bolted to the columbium tube ends. Sealing between the pyrex and the copper chill blocks is accomplished by double O-ring seals. A combination vent and atmosphere sampling line was placed in one of the copper chill blocks. Argon was purged through the columbium tubing and through the TIG torch argon line. The assembled jig is shown in Fig. 79.

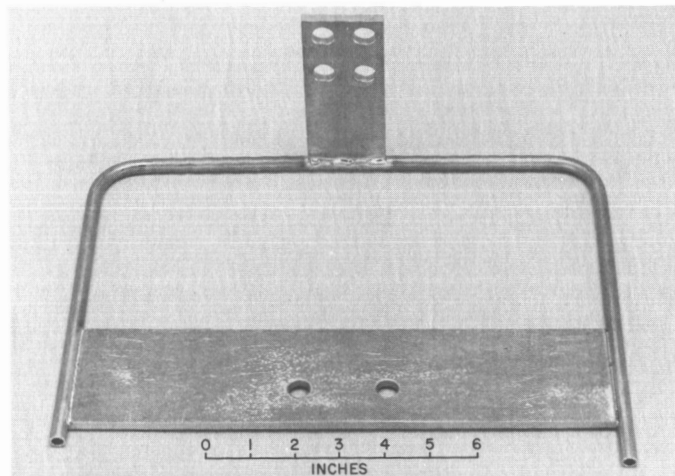


Fig. 76. New potassium preheater

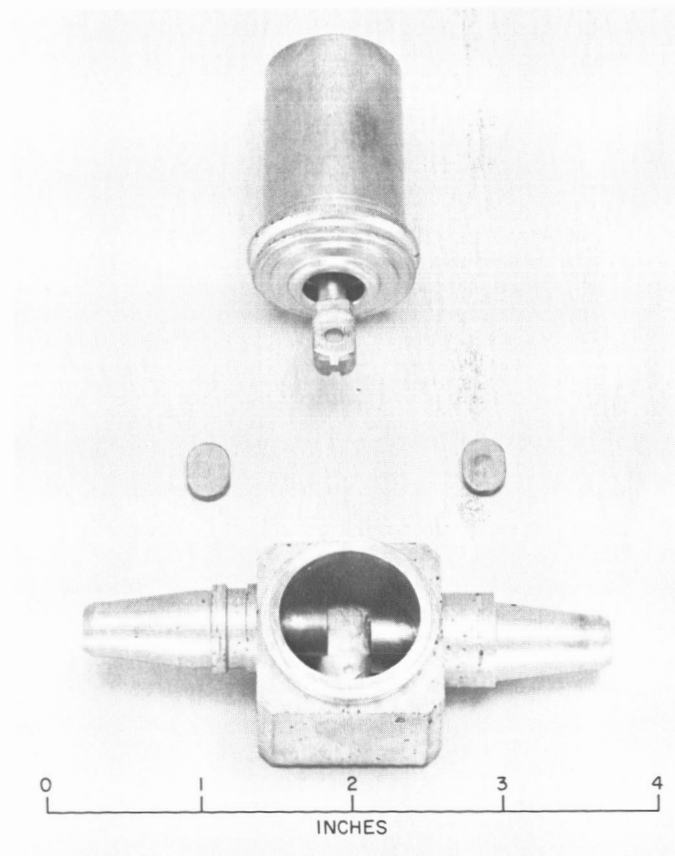


Fig. 77. Disassembled potassium boiler feed-throttle valve

A photomicrograph is shown in Fig. 80 of the fusion weld pass. A filler ring was made from Cb-1Zr wire which was then fused into place. A photomicrograph of this

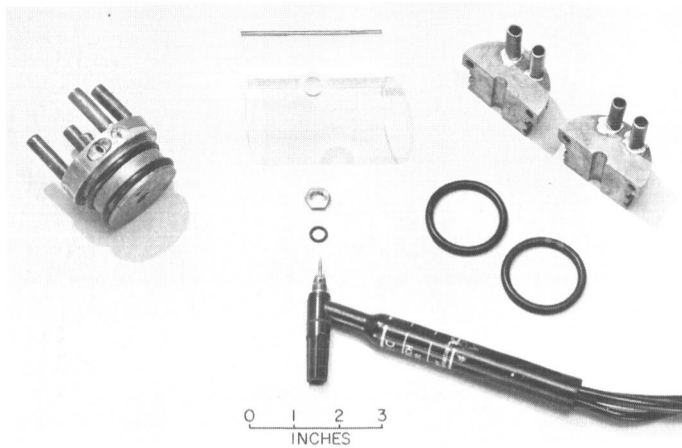


Fig. 78. TIG field-welder components

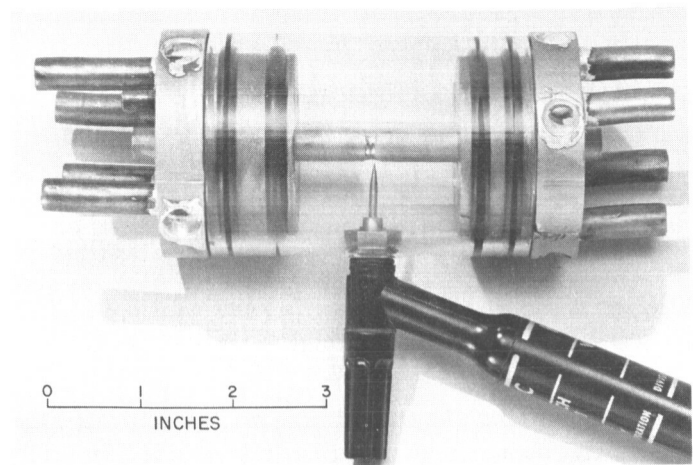


Fig. 79. TIG field-welder, assembled

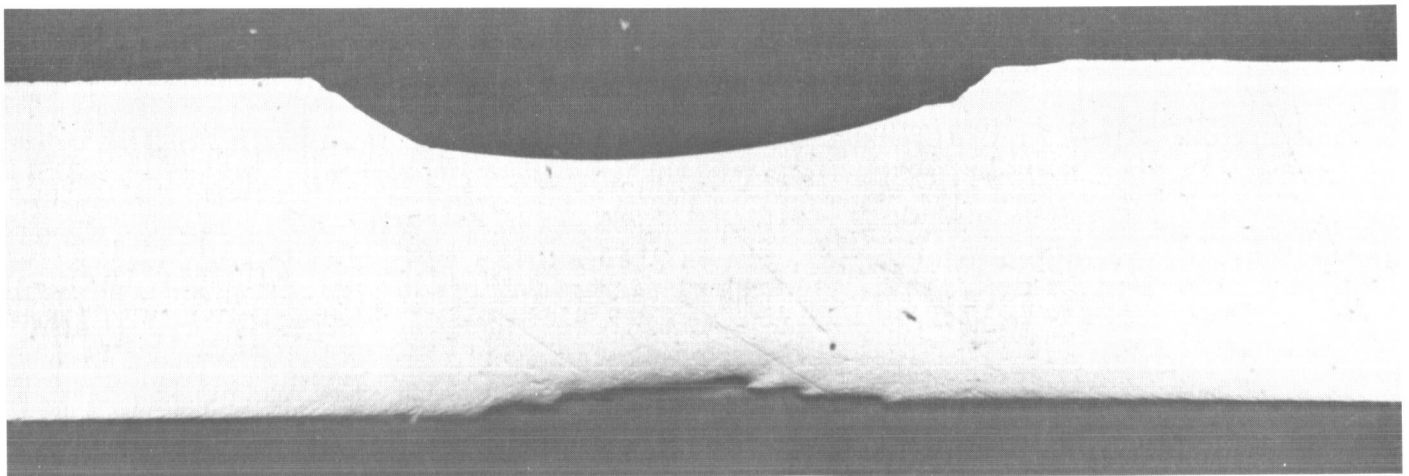


Fig. 80. Photomicrograph of cross section of fusion weld pass

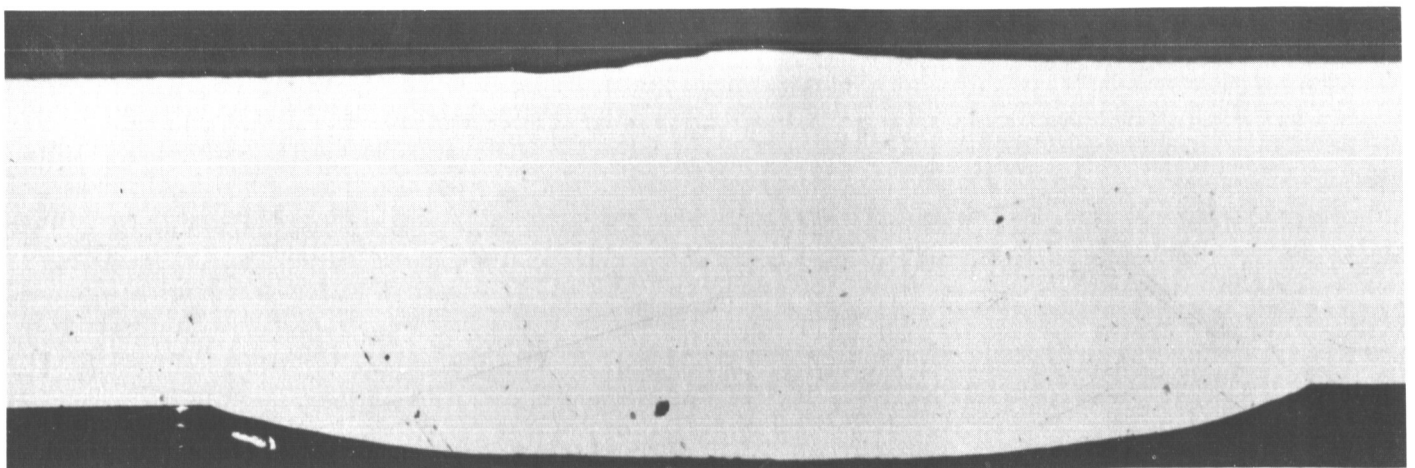


Fig. 81. Photomicrograph of cross section of filler-wire insert weld pass

Table 4. Analyses of weld samples

	PPM		
	H	O	N
Tubing	9	330	50
Fusion Pass	5	450	40
Filler Pass	6	500	260

cross section is shown in Fig. 81. Analyses of the weldments are shown in Table 4.

C. Summary of Pertinent Loop Component and Behavioral Experiences

1. Outgassing. Shakedown of the loop took about three months with a great portion of that time spent for instrumentation checkout and calibration. Outgassing of the loop and attainment of satisfactory moisture and hydrogen levels was successfully achieved following application of the argon purifier for on-stream purification.

2. Lithium pump. Prevention of further lithium pump impeller seizures was successfully accomplished by shimming the impeller up a total of 0.040 in. This compensated for the differences in impeller and pump casing growth during heat up.

3. Electromagnetic potassium pump. The MSA EM potassium pump operation was quite satisfactory. Potassium wetting of the columbium pump coils resulted in increasing the pump performance to a level which was apparently ~5% greater than its nominal design head-flow characteristic.

4. Valves. Experience has shown that considerable attention must be given to liquid-metal valve design and manufacture, including operating mechanisms. A malfunction of the boiler feed valve is being corrected and subsequent reliable valve operation will assist in the suppression of unstable boiling by creating a large liquid pressure drop before entrance of the potassium into the boiler.

5. Radiator-condenser. Radiator-condenser heat rejection was greater than expected. This is being compensated for by installing additional R-C heaters and blanking off the coolant argon flow to the portion of the loop enclosure that houses the R-C. Also, a tantalum foil heat shield will be placed about the lowermost coils of the R-C.

6. Potassium preheater. The original installation of the potassium preheater was upstream of the boiler feed

valve and the potassium hot trap, and at some distance from the boiler inlet. The heat losses through this portion of the system resulted in a large drop in temperature (as much as ~150°F) between the preheater outlet and the boiler inlet. Thus the liquid potassium entered the boiler with a large amount of subcooling because the operation of the preheater at temperatures close to or actually greater than the saturation temperatures in the boiler would result in unwanted boiling in the preheater. Actually it was just such a condition which caused preheater failure. A new, longer preheater will be installed immediately upstream of the boiler inlet between the boiler feed valve and the potassium hot trap.

7. Tantalum foil. Examination of the inner protective wraps of tantalum foil indicate that they are still ductile; therefore, oxygen contamination of the columbium through this period of operation was not a problem. A total of about 750 hours of loop operation in excess of 500°F has been accumulated in the argon cover gas environment of the test chamber.

A great amount of valuable experience has been gained in liquid-metal loading, startup, and shutdown, and steady- and unsteady-state operations of a two-loop lithium-boiling potassium system.

Boiling of potassium, in stable and unstable modes, has been carried on for a total accumulated time of ~40 h at power levels of 20-30 kW and at temperatures of 1600-1900°F. Further loop operations will be concerned with accumulation of boiler heat transfer data, operation of the turboalternator and further experimental investigations of stable, unstable, and transient system performance.

The results of these experiments will be used to guide the modifications necessary for refinement of the formulated analytical models describing the dynamic behavior of the system.

D. Instrumentation Operating Experience

The two-month period of initial operation provided valuable experience in the instrumentation area. Certain parts of the system, primarily the digital data recording system, gave good performance. This experience also pointed out certain modifications that should be made to provide more efficient operation and more accurate data.

1. Problems. The initial operation showed that many problems existed in the instrumentation. These problems are described briefly below.

- (a) W-Re thermocouple breakage. One of the primary problems associated with the transducer installation was breakage of the W-Re thermocouple wires during the foil wrapping and insulation procedures which had to be done after installation of the thermocouples. The breakage would occur, typically during the final insulation operation, and would cause a very difficult replacement problem. It appears that a fairly expensive thermocouple wire protection device would be required to assure complete reliability of all thermocouples.
- (b) Checkout and documentation. Stringent time limitations during the first installation did not permit thorough checkout and documentation of each channel. Only the C-A thermocouples were completely checked for continuity and polarity. The W-Re thermocouples were connected, and the enclosure was closed before a thorough checkout could be made. It became apparent soon after heat was applied to the loop that problems would be encountered with the W-Re thermocouples. The C-A thermocouples appeared to be functioning well. Problems with the W-Re thermocouples were traced to shorts in the feedthrough, misconnections, and similar wiring errors that could have been determined with a thorough checkout. To be valid, this checkout must include a complete end-to-end determination of signal polarity and approximate sensitivity. Some preliminary checkouts determined polarity properly, but did not disclose amplitude discrepancies because the checks were not sufficiently detailed.
- (c) Pressure transducer failures. All differential pressure data became questionable shortly after operation of the loop reached high temperature. As stated previously, these transducers had a 350°F rating. Some transducers were undoubtedly subjected to temperatures of 400–500°F, so this failure is explainable. Absolute pressure measurements were subject to doubt, and required frequent calibration. Pressure measurement redundancy will be attained by installation of stainless steel Bourdon-type pressure gages at three critical locations.
- (d) Pressure lead line temperatures. Some of the lead lines from the columbium pipe to the pressure transducer did not have a sufficient number of thermocouples installed to completely define the temperature of the entire line. This caused some doubt as to the fluidity of the liquid metal. Because of this uncertainty, about half of the absolute pressure transducer data was questionable.
- (e) Insufficient thermocouple channels. Time and funds limitations dictated that the number of thermocouple channels be held to a minimum. After the loop was in operation, it became evident that many more thermocouples would be required to assist in troubleshooting and accurate determination of the conditions existing inside the tank. The majority of these thermocouples could be C-A, since the temperatures were generally related to heaters, controls, and other components rather than to the loop itself.
- (f) Noise pickup. The heavy currents from the lithium heater, potassium preheater, and EM pump power supplies caused large amounts of magnetic pickup. This pickup was primarily noticed on the Pt-Rh thermocouples on the inside of the boiler, one of the prime measurements on the loop. The leads extending from this thermocouple assembly were accidentally damaged during the loop fabrication and had to be significantly shortened. This placed a physical limitation on the routing of the cable leads. The only place that signal leads could be routed was immediately adjacent to the common bus of the two prime power supplies, and also close to the EM pump power. This pickup caused approximately 4 mV of noise on a signal of approximately 100 μ V. Noise pickup inside the enclosure is primarily electromagnetic, and so can be reduced only through thorough twisting of all signal leads. The combination of coaxial boiler thermocouples and the normal parallel leads through alumina insulation on the high-temperature W-Re thermocouples does not permit twisting. Magnetic shielding techniques are not feasible because of space limitations.
- (g) Thermocouple calibrations. Some unforeseen troubleshooting required that comparisons of the difference between two absolute thermocouples be made. This proved to be impossible in practically all cases, since errors of ± 20 μ V can be accumulated with individual errors in the thermocouple wire calibration, lead-wire to thermocouple-junction errors, and noise pickup. The necessity for these comparisons cannot be predicted, since they are typically the result of a partial failure or some other trouble. It appears that the only way that this problem can be resolved is by careful and thorough

calibration of all errors which can enter into the temperature measurement.

- (h) Temperature conversion. The conversion from millivolts to temperature in degrees Fahrenheit consumed a great deal of time. This conversion can be automatically provided with a modification to the digital data system, but time limitations have not made this possible.
- (i) Meter amplifier drift. Drift in the meter amplifiers has required continuous adjustment of the sensitivity and zero of these amplifiers. This created some uncertainty in the meter readings, although no major failures occurred.
- (j) Cross talk. Cross talk between the meter amplifiers and the digital data system was evident. Both input circuits are high impedance and are floating, so proper grounding should eliminate cross talk. The problem was caused by input current requirements of the operational amplifiers used in the meter amplifiers, and can be eliminated by circuit modifications to the meter amplifiers.

2. Successful operation. Three areas of good performance were obtained during initial operation.

- (a) Data system resolution. The resolution of the data system was $1 \mu\text{V}$. This resolution, plus ± 1 count stability, provided an excellent means of determining slight changes in low level signals. This technique is suited to the steady state signals inherent in the operation of this loop. This capability would also be very useful to determine relative temperatures, if the errors mentioned in item (g) were eliminated.
- (b) Engineering units readout. The data system permitted all nonabsolute thermocouple parameters to be read directly in engineering units. This saved a great deal of conversion of time. It also showed the value of a possible modification to permit engineering units readout on absolute thermocouples.
- (c) Noise performance. The basic noise performance of the signals, except for electromagnetic pickup in the loop containment enclosure, is approximately $10 \mu\text{V}$. The basic grounding and shielding of the instrumentation system provides good performance from normal noise sources.

3. Future modifications. The initial performance indicated that the following modifications should be made to the instrumentation system:

- (a) Digital system. The engineering units for absolute temperatures should be added to simplify operational procedures. In addition, the basic counter in this system is an obsolete tube design. It should be replaced with a solid state up-down counter, which can eliminate the zero crossover error inherent in the signal-to-noise levels now seen on many temperature channels.
- (b) Thermocouples. More thermocouples, especially C-A thermocouples, should be added to the loop to permit better troubleshooting in case of failures. These failures are typically associated with temperatures below 1500°F . Drift of the C-A thermocouples is a problem, but can be defined by comparison to a W-Re thermocouple.

VII. Future Experiments

The primary experiments to be conducted in this facility are as follows:

Transient response to load perturbations. Load changes will be made on the turboalternator, and overall system response will be determined using secondary system constant flow control or constant pressure control. The primary system will be controlled by negative temperature coefficient reactor simulator programming.

Regimes of boiling stability. Variation in boiler inlet throttling and subcooling will be made to determine effects on boiling stability.

Startup. Both injection and liquid-drain startups will be attempted.

Steady state operational characteristics. Steady state thermal-hydraulic performance will be determined for all system components.

Cross-flow boiler. A shell-side boiling cross-flow boiler will be inserted in the loop to determine effects on steady state operation and boiling stability.

VIII. Some Design Recommendations

Our experiences during this phase of operation may be of general interest to others contemplating or constructing refractory metal systems that have some characteristics similar to this loop. The following is a list of recommendations, some of which may be applicable to operation only in an inert atmosphere environment.

1. **Argon supply.** Liquid argon has consistently been available at oxygen levels less than 1 ppm.
2. **Argon purification.** Continuous catalytic side-stream purification has made it possible to maintain oxygen levels around 0.1 ppm and moisture below 1 ppm.
3. **Insulation.** Microquartz, Q-felt, has demonstrated satisfactory out-gassing characteristics and is much more convenient for fitting to irregular shapes than solid types of insulation such as Glasrock.
4. **Protective foil wraps.** Duplex wraps consisting of two outer layers of tantalum over an inner layer of zirconium has proved effective in protecting the base columbium from trace amounts of oxygen and moisture that are found in the experimental, argon atmosphere.
5. **Field Repairs.** The simple gas-purge pyrex-tube type has proved totally satisfactory for tube-to-tube field repair welds.
6. **Dry box practice.** Use of sulphur-free butyl rubber gloves at least 0.020 thick is indicated.
7. **Loop hot trapping.** Use of full flow or side-stream continuous hot trapping employing yttrium for

lithium and zirconium for potassium appears satisfactory. Materials should be located in the coldest portion of the loop to minimize any mass transfer.

8. **Thermocouple reliability.** Use of three thermocouples at critical points of measurement is indicated. As a consequence of their higher output the W-5% Re:W-26% Re couples have much lower relative noise problems than the Pt-Rh couples. The low output level of the Pt-Rh has resulted in significant noise discrimination problems.
9. **Pressure transducers.** Transducers employed require frequent recalibration. Response times are more than adequate for following fast transients of significance. Selected introduction of Bourdon gages for reliable absolute-pressure readings are recommended.
10. **Mechanical actuators.** Activation of valves and shutters through vacuum feedthroughs have generally been satisfactory. Significant torques have been required for valve manipulation after high-temperature operation.

We recognize, of course, that other facilities may have had different experiences from the ones we have listed. The experiences presented here are our own with this particular facility.

References

1. Davis, J. P., Kikin, G. M., Phillips, W. M., Wolfson, L. S., *Lithium-Boiling Potassium Refractory Metal Loop Facility*, Technical Report 32-508, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 31, 1963.
2. Phillips, W. M., *Evaluation of Oxidation Resistant Coatings for Inert Atmospheric Applications*, Technical Report 32-1014, Jet Propulsion Laboratory, Pasadena, Calif. (in press).
3. Thurber, W. C., Long-range applied research, p. 83. In *Metals and Ceramics Division annual progress report for period ending June 30, 1964*. ORNL-3670. Oak Ridge (Tenn.) National Laboratory.