Design and Operation of a 1000°C Lithium–Cesium Test System

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DESIGN AND OPERATION OF A 1000 °C LITHIUM-CESIUM TEST SYSTEM

A 100 kW cesium-lithium test loop was fabricated of niobium-1% zirconium for experiments on erosion and two-phase system operation at temperatures of 980 °C and velocities of 150 m/s. Although operated at design temperature for 100 hours, flow instabilities in the two-phase separator interfered with the achievement of the desired mass flow rates. A modified separator was fabricated and installed in the loop to alleviate this problem. Because of program cancellation, the test system has been placed in standby condition for storage. This report documents the test system.
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PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.
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ABSTRACT

A 100 kWt cesium-lithium test loop was fabricated of niobium-1% zirconium for experiments on erosion and two-phase system operation at temperatures of 980°C and velocities of 150 m/s. Although operated at design temperature for 100 hours, flow instabilities in the two-phase separator interfered with the achievement of the desired mass flow rates. A modified separator was fabricated and installed in the loop to alleviate this problem. Because of program cancellation, the test system has been placed in standby condition for storage. This report documents the test system.
I. INTRODUCTION

Power generation for advanced space missions and central station power by a liquid metal magnetohydrodynamic cycle has been studied extensively (Refs. 1-4). A promising system for power levels above about 100 kW is based on the two-component separator cycle using lithium and cesium as working fluids (Refs. 5 and 6). Cesium is mixed with lithium at high temperature at the inlet of a nozzle as shown in Fig. 1. The cesium vaporizes and the mixture is accelerated in the nozzle to high velocity. Impingement on an inclined surface produces a low-void fraction stream that is predominantly liquid lithium. This stream is decelerated in an MHD generator, producing electric power, and is subsequently returned by its remaining kinetic energy through the heat source to the nozzle inlet. The other flow leaving the separator is a high-void fraction stream that consists of cesium vapor with carry-over of liquid and vaporous lithium. This mixture is condensed and returned by a pump to the nozzle inlet.

The characteristics of this system have been partially determined by analysis (Ref. 6), by component experiments using ambient water-nitrogen, NaK, and NaK-nitrogen mixtures (Refs. 7 and 8), in system experiments with water-nitrogen and NaK-nitrogen mixtures (Ref. 8), and through high-temperature, corrosion-erosion experiments with lithium (Refs. 9 and 10). However, information on the following subjects requires testing with cesium and lithium at the peak system temperatures:

(1) Erosion of surfaces by lithium impingement at the design velocity of 150 m/s.

(2) Performance of a two-phase nozzle with a cesium-lithium mixture.

(3) Condensation characteristics of cesium-lithium mixtures.
Nonequilibrium behavior of cesium-lithium flows where solution or dissolution are occurring.

In order to investigate these subjects a flow system was fabricated from niobium-1% zirconium alloy to operate with cesium-lithium at a peak temperature of 980°C. Erosion can be determined by measuring the depth of attack or deposit on a wedge with an optically flat surface which was located in the flow stream at the nozzle exit. Nozzle performance can be derived from the measured thrust produced by the flow on a target cone which was designed to turn the flow by 90 deg. Cesium condensation coefficients can be determined by measurements on the NaK-cooled compact condenser. Nonequilibrium behavior would be inferred by deviations from the thermodynamic cycle calculations.

The test system was operated with simultaneous cesium and lithium flow at the design temperature of 980°C for about 100 hours. Figure 2 is a photograph of operation at high temperature and low flow rates. Flow instability prevented attainment of the design mass flow rates and impingement velocities. Modifications to the separator component to eliminate the instability were nearly completed when the NASA liquid metal MHD project was cancelled. The test system has been placed in a standby condition pending further investigations oriented toward commercial power generation.

Appendixes A, B, C, and D present, respectively, loop operating procedures, test system schematics, fabrication drawings of the test system, and loop operating characteristics.

II. DESCRIPTION OF TEST SYSTEM

The two-component liquid metal MHD system being studied and the Cs-Li test system are most closely related to the Rankine cycle. The flow paths and processes can be illustrated by reference to Fig. 3, which is a schematic of the liquid metal circuits of the test system. Lithium is heated to the maximum temperature in the heater component and flows to the nozzle, where it is injected at point 1.

Cesium liquid is also injected in the nozzle at point 2. Part of the cesium vaporizes and the remainder goes into solution with the lithium, which remains mostly in the liquid state. The cesium vapor is accelerated
to high velocity and low pressure in the nozzle. As the pressure decreases, more cesium comes out of solution and vaporizes. Shear and pressure forces resulting from the expanding cesium vapor cause breakup and acceleration of the lithium droplets to high velocity. The mixture impinges on the target and on a mesh separator within the receiver component. The lithium pump increases the pressure to the maximum of the cycle and returns the flow to the heater. The cesium vapor leaves the receiver vessel and flows to the desuperheater. Subcooled liquid cesium is injected at that point to reduce the cesium vapor (which is highly superheated) to the saturated state. The vapor then enters the condenser, where the heat of vaporization is removed by flowing NaK, is condensed, and returns to the cesium pump. The pump pressurizes the cesium and returns it to the nozzle and through a cooler to the desuperheater.

Figure 4 is a photograph of the cesium and lithium circuits prior to testing. All components and piping were fabricated from Nb-1%Zr. All weldments were performed in a high-purity argon atmosphere. This part of the test system was mounted on the door of a getter-ion pumped vacuum chamber which was operated in the 10^-7 torr range to protect the refractory metals from oxidation during high-temperature operation. Description of the test system components and their performance is summarized below.

A. Two-Phase Nozzle

The two-phase nozzle for the test system was designed to provide cesium and lithium flow over a range of conditions. The design pressure gradient was established from the pressure variation measured on a larger nozzle, using water-nitrogen and freon-water flows. This gradient was used in the two-phase, two-component nozzle program to calculate the contour. The resulting geometry is summarized in Fig. 5. Figure 6 is a photograph of the nozzle prior to final welding.

The nozzle was calibrated with water and nitrogen to compare the exit velocity with that calculated by the computer program. The test setup is given in Fig. 7. As shown in Fig. 8, the agreement between the calculated and measured exit velocity was quite good. The computer program was then used to calculate the nozzle flow rates as a function of inlet temperature and mass ratio with the result shown in Fig. 9. At saturated Cs vapor conditions at the inlet, there is a unique relation between the cesium and...
lithium flow rates. The information from Fig. 9 was used to determine the flow rates and operating conditions of the test system for the desired values of mass ratio and nozzle inlet temperature.

B. Thrust Target and Separator

The relation of the nozzle and thrust target is given by Fig. 10. The two-phase lithium-cesium flow impinging on the thrust target is turned by 90 deg. The thrust produced is transmitted through a stainless-steel bellows which is joined to the Nb-1%Zr alloy by a coextruded joint. The measured thrust thus provides an indication of the nozzle exit velocity. The separated lithium falls to the bottom of the separator and is returned to the lithium pump. The cesium vapor is separated from the lithium by a mesh-type separator and flows to the desuperheater.

The thrust target with the erosion specimen mounted in place is shown in Figs. 11 and 12. The erosion specimen is an optically flat wedge which extends beyond the nozzle exit diameter. Erosion depth was to have been measured with a traversing microscope as was done on a previous test (Ref. 10). The basic wedge is Nb-1%Zr alloy; the insert, which was electron-beam-welded to the Nb-1%Zr, is T-111 alloy.

Figure 13 shows the thrust target mounted in the separator body. The Nb-1%Zr mesh was wrapped on the outside of the perforated annulus as shown in the assembly drawing of Fig. 14.

The entire unit was assembled and tested with water-nitrogen flows. The thrust measured by the thrust target agreed to within ±5% with the values measured for the nozzle alone. The nozzle exit velocity was varied from 90 to 155 m/s for these measurements. Liquid carryover in the gas exit ranged from 2-7% of the primary liquid flowrate, acceptable values for the high-temperature flow system. Complete separation of gas from the liquid outlet flow was made possible by adding baffles, as shown in Fig. 15. However, these same baffles resulted in excessive lithium holdup during the lithium-cesium tests.

In order to eliminate this holdup problem a cyclone separator was designed for the lithium-cesium test system. A model was tested (Fig. 16) with water and nitrogen with a liquid carryover in the gas outlet of less than
0.1% and gas-free flow at the liquid outlet. Figure 17 shows the cyclone separator fabricated of Nb-1%Zr ready for installation in the test system.

C. **Lithium Pump**

The lithium pump is a helical induction electromagnetic pump. The pumping element shown in Fig. 18 is a Nb-1%Zr structure that fits within a stainless-steel, thermally-insulated sleeve. The electromagnetic body forces are supplied through the stainless-steel sleeve by an air-cooled, three-phase motor stator shown in Fig. 19. The pump was operated for more than 1000 h at temperatures exceeding 1000°C and for more than 4000 h above 650°C.

The calculated performance curve is given in Fig. 20. Previous tests with lithium flow nozzles at 1100°C gave measured performance data which agreed quite closely with the calculated performance (Ref. 9). A serious limitation of the pump which became apparent during the testing was the tendency of vapor to accumulate within the pump body and cause flow oscillations. Extensive shakedown testing was required to evolve a startup procedure that minimized this problem. Although vapor accumulation was a problem, the pump was able to operate with a negative suction head. The most successful two-phase startup procedure consisted of injecting cesium while the pump operated with lithium flow at 980°C and zero pressure at the inlet.

D. **Lithium Heater**

The heater to raise the lithium to the maximum temperature of 980°C consisted of four "cal-rod" type elements welded in a Nb-1%Zr shell. Figures 21 and 22 are photographs of this unit before final welding. The heating elements are tantalum center conductors with beryllia insulation and swaged Nb-1%Zr sheaths. The beryllia was removed to a depth of 6 mm to enable the Nb-1%Zr sheaths to be TIG-welded to the Nb-1%Zr shell without degrading the ceramic insulation. As shown in Fig. 21, the body and elements are curved to provide flexibility to accommodate thermal stresses. The unit was operated for over 3000 h, heating lithium at temperatures ranging from 650-1000°C. After this time a small leak occurred at one of the sheath weldments. The leak was repaired and the unit was to have been used on succeeding tests. Electron-beam welding of the sheaths rather than TIG
welding would have enabled a greater depth of penetration, which probably would have eliminated this problem.

E. **Lithium Flowmeter**

The electromagnetic flowmeters used for the lithium and cesium are shown in Fig. 23. The calculated characteristics of the lithium flowmeter are given by Fig. 24. Calibration of this flowmeter with 1100°C lithium flow nozzles showed the measured flow to agree to within ±5% of the calculated values.

F. **Cesium Pump**

The cesium pump is of similar construction to the lithium pump. The stator is seen in Fig. 19, adjacent to the stator for the lithium pump. The flow was controllable with a throttling valve during the periods of operation at lower flow rates. Attempts to run the pump at higher pressure rise with a low inlet pressure and low flow rate resulted in excessive temperature rise and vaporization of the cesium at the pump inlet. A small jet pump was fabricated which should have eliminated this problem when installed.

G. **Cesium Flowmeter**

The cesium flowmeter of Fig. 23 was used only at very low flow rates. The calculated output curve is given in Fig. 25.

H. **Cesium Desuperheater**

The cesium vapor leaving the separator is highly superheated and has a very poor heat transfer coefficient. The desuperheater of Fig. 26 was designed to lower the temperature to saturated vapor conditions by injection of subcooled cesium liquid. The large surface area afforded by the small liquid metal droplets more than compensates for the poor coefficients.

An alternative method to desuperheat the Cs vapor is a heat exchanger with large internal surface area. A radiant heat exchanger with internal Nb-1%Zr fins was fabricated (Fig. 27) to replace the original desuperheater. This would enable the subcooled cesium bypass flow to be used for the cesium jet pump discussed previously.
I. **Cesium Condenser**

The condenser for the cesium was constructed of both Nb-1%Zr and stainless steel. The niobium alloy is required for the condensing cesium, while stainless steel is the material of construction for the NaK cooling system that rejects the latent heat of vaporization from the cesium.

The condenser assembly is shown in Fig. 28 before welding and in Fig. 29 after final assembly. The transition between the stainless-steel tees and center section and the niobium end pieces that weld to the Nb-1%Zr cesium tubing was achieved by brazing with a cobalt-nickel alloy. The condenser performed satisfactorily at the low Cs vapor flow rates tested.

J. **NaK Heat Rejection Loop**

The NaK heat rejection loop was constructed of type 316 stainless steel. NaK flow is produced by an electromagnetic AC conduction pump. The flow piping enters the vacuum chamber through a thermal sleeve. The entering NaK removes heat from the cesium subcooler and condenser and exits the vacuum chamber through another thermal sleeve. It flows through an expansion tank, heater, and air-blast heat exchanger (to reject the heat) back to the pump. The function of the heater was to control the NaK temperature during low-load operation and to heat the NaK during purification operations. A titanium-zirconium hot trap was provided for initial purification. The heat rejection system is shown in Fig. 30 before insulation.

K. **Vacuum Chamber**

The vacuum chamber and getter-ion pump are shown in Fig. 31. The chamber is heated so that the temperatures of all liquid metal lines can be maintained at at least 200°C to prevent solidification. All ports have bakeable metal seals. The main door seal is Viton-A cooled to less than 100°C. During testing the chamber operated in the 10⁻⁷ torr range, with the liquid metal system at 980°C and the chamber at 250°C.

L. **Instrumentation and Controls**

Liquid metal pressure was measured directly with bonded strain gage transducers. The transducers and pressure lines were maintained at 230°C to prevent solidification. Installation of the transducers in the heated enclosure is shown in Fig. 32. Valving was provided to enable calibration during operation of the test system.
Chromel-alumel thermocouples were used for temperature measurement. Attachment to the Nb-1%Zr piping and components was made by welding the wires to a tantalum foil which, in turn, was welded to the niobium alloy. Only two thermocouples of 53 failed during more than 3000 hours of testing.

All instrumentation readout and control of the loop was accomplished remotely. Figure 33 shows the control console and alarm system which was used during the test. Schematic diagrams of the instrumentation and control circuits are given in Appendix B.

III. Operating Experience

The test system was operated for over 3000 h with liquid metal flow to determine the proper startup sequencing and flow characteristics with cesium and lithium. Achievement of stable flow with both liquid metals was very difficult and tedious. For proper functioning with cesium condensation in the condenser, no cover gas (argon) could be tolerated. Yet it was found that heating the evacuated system from ~200 to ~650°C while lithium was flowing always caused argon to evolve from the lithium. Attempts to reduce the pressure while circulating lithium produced instabilities and the loss of the pumping action unless extremely gradual reductions in pressure were used (~0.1 - 0.2 atm/day). Another problem which occurred early in the test sequence was lack of control of the cesium flow rate. Attempts to start the cesium pump at a low flow rate and without a control valve inevitably resulted in injection of a cesium flow which was too large for the conditions of lithium temperature and flow. The result was entrainment of cesium in the lithium circuit and the subsequent loss of the lithium pump due to cesium vaporization in the pump. This latter problem was eliminated by installation of a valve in the cesium line and an externally controlled cesium injection system for startup.

With these modifications, relatively stable cesium and lithium flow was obtained at lower flow rates (~0.1 kg/s). Attempting to further increase the lithium flow resulted in severe flow oscillations, cesium entrainment, and loss of the lithium pump. The reason for the flow oscillations is the holdup of lithium in the separator because of the baffles which were installed after hydraulic testing. Use of the centrifugal separator of Fig. 17 should
eliminate this problem and enable the attainment of higher flow rates. Figure 34 is a schematic of the test loop as it should appear after the above modifications are made.

IV. SUMMARY

The cesium-lithium test system proved to be a reliable installation for obtaining lithium and cesium flow at 980°C. However, stability problems were encountered as the flow rates were increased above about 0.1 kg/s. Minor modifications to the separator should enable attainment of the 0.4-kg/s design flow rate with stable operation.
REFERENCES


Fig. 1. Schematic diagram of cesium-lithium MHD power system

Fig. 2. Cesium-lithium erosion loop at 980°C
Fig. 3. 100-kW erosion loop liquid metal circuits schematic diagram
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Fig. 5. Cesium-lithium nozzle geometry

DIMENSIONS ARE IN INCHES
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Fig. 33. Control console for cesium-lithium test system
Fig. 34. Modified version of cesium-lithium erosion loop
APPENDIX A

LOOP OPERATING PROCEDURES

The startup and shutdown procedures used for the test loop are summarized below. The main modification required was installation of a cesium injection system and its actuation prior to starting the cesium pump (step 17). Full flow (steps 18-22) was not realized because of the problems discussed in the text. Values of temperatures, pressures, and flows are given in English units since the instrumentation and gauges are all in these units.
# STARTUP PROCEDURES FOR Cs-Li LOOP

<table>
<thead>
<tr>
<th>Startup Step</th>
<th>Values of Key Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Evacuate loop to less than 10 microns by opening manual valves HT-1 and HV-1. Evacuate chamber to less than 10 microns by opening vacuum valve MV-1 to roughing manifold. Turn on load cell and O-ring cooling air flange, and bus cooling water. Turn on makeup air in NaK room.</td>
<td>Pressure of chamber = $10^{-2}$ torr on multi-torr gauge.</td>
</tr>
<tr>
<td>2. Turn on the chamber heaters to 5 A in each leg. Increase by 5-A steps over 10-12 h time until current is 20 A. Continue pumping until pressure is below 10 microns again. Close all transducer valves to loop. Backfill with argon to 75 mm.</td>
<td>Final chamber temperature = 500°F. Loop temperature ≈ 450°F.</td>
</tr>
<tr>
<td>3. Start diffusion pump; open to chamber; close vacuum valve MV-1 to roughing manifold. Close manual valves HT-1 and HV-1.</td>
<td>Chamber pressure of $10^{-5}$ torr.</td>
</tr>
<tr>
<td>4. Adjust pressure on lithium sump to 15 psig. Heat to 500°F.</td>
<td>Current setting of 5 A on trace heater to obtain 500°F.</td>
</tr>
<tr>
<td>5. Actuate Li pump. Adjust voltage until $T-9$ reads 450°F. Shut off pump.</td>
<td>$T-9 = 450°F$. Li pump voltage ≈ 45 V.</td>
</tr>
<tr>
<td>6. Open lithium fill valve, V13, slowly. Monitor TC-3 to determine when receiver is filled to proper level. When TC-3 actuates, close V13.</td>
<td>$T-3$ should raise from 450 to 500°F in 2-3 s when lithium is at the proper level.</td>
</tr>
<tr>
<td>7. Adjust pressure on cesium sump to 15 psig. Heat to 200°F.</td>
<td>Current setting of 3 A on trace heater to obtain 200°F.</td>
</tr>
<tr>
<td>8. Actuate Cs pump. Adjust voltage until $T-21$ reads 300°F. Shut off pump.</td>
<td>$T-21 = 300°F$. Cs pump voltage ≈ 35 V.</td>
</tr>
<tr>
<td>9. Open cesium fill valve, V15, slowly. Monitor TC16 to determine when cesium leg is filled to proper level. Close V15 and V1.</td>
<td>$T-16$ should lower from 450 to 200°F in 2-3 s when Cs is at the proper level.</td>
</tr>
<tr>
<td>10. Evacuate NaK loop through HV5. Open V8, V9, and V17; continue evacuation while vacuum manifold is &lt;10 microns. Close HV5.</td>
<td>Manifold vacuum should be &lt; 10 μm at 4 h.</td>
</tr>
<tr>
<td>11. Increase the argon on the supply tank to 8 psig; open the auxiliary drain valves (V11 and V12), then the main drain valve (V7), slowly and only enough to insure flow. It is best to fill the system slowly. When the liquid level has reached the desired level in the expansion tank, close the drain valves (V7, V11, and V12), then the heat exchanger bypass valve (V5), the exit valve on the heat exchanger (V6), the hot trap bypass valve (V4), and the Cs-Li loop bypass valve (V10). Open the two loop valves V8 and V9. Listen for NaK flow in the loop lines. As a final step, adjust the level by adding or draining NaK to the predetermined level as discussed in a previous section. Set the pressure at 10 psig on the reservoir and supply tank.</td>
<td>Level indicator light on NaK reservoir will change from red to yellow at proper level.</td>
</tr>
<tr>
<td>12. Turn the NaK pump powerstat up slowly until the liquid metal is flowing in the loop. Keep a constant watch on the flowmeter. If there is no immediate indication of flow, stop the pump immediately and determine the trouble.</td>
<td>CAUTION: This is a high-capacity pump and cannot be operated without flow or liquid metal in the pumping section. In the event that there is no indication of flow, double-check the electrical connection on the flowmeter and pump, all valve settings, and the liquid level. If everything</td>
</tr>
</tbody>
</table>
### STARTUP PROCEDURES FOR Cs-Li LOOP (contd)

<table>
<thead>
<tr>
<th>Startup Step</th>
<th>Values of Key Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>12.</strong> (contd)</td>
<td>appears in order, try the pump again. Watch for a flow indication and also use an ammeter to check that the current is flowing to the pump. A humming or buzzing sound will be heard if power is reaching the pump. The above instructions may seem rather pessimistic, but the most important point to remember is that power must not be left on this pump for more than a few seconds without liquid metal flowing.</td>
</tr>
<tr>
<td><strong>13.</strong></td>
<td>Turn the NaK immersion heater on and set the temperature for 650°F. Close the valve (V4), isolating the hot trap from the system. Do not circulate cold liquid metal through the hot trap. By adjusting the flow through the heat exchanger, the desired temperature can be reached. Once the loop temperature has reached 650°F, operate at this point for an hour to ensure that the flowmeter is wet. Set the pump current at 19.5 A for a flow of 0.33 lb/s. The next step is to raise the loop temperature to 1000°F. Actuate the cooling blower for the pump when the loop temperature exceeds 850°F. Circulate at this temperature for a period of 24 h to ensure that oxides and impurities are absorbed in the liquid metal. Maintain as high flow in the heat exchanger as practical in order to ensure that the insides of these tubes are also cleaned.</td>
</tr>
<tr>
<td><strong>14.</strong></td>
<td>Operate the hot trap, starting the flow slowly, 1/4 - 1/2 gpm, through the hot trap by opening the valve (V4). The flow in the main loop should be 1 lb/s through the heat exchanger. All portions of the loop must be at a minimum of 1000°F while hot trapping to ensure that any oxide present is in solution. Maintain the temperature at a minimum of 1000°F and the flowrate through the loop at some reasonable rate (1/2 - 1 lb/s). The time required to reduce the oxide content to an acceptable level is dependent on the quantity present and the operating temperature of the hot trap. The oxide removal rate is greater at 1200 than 1000°F. Experience indicates for a system of this size that a minimum of 12 h would be necessary to initially clean the system. Reduce the heater voltage until the loop temperature is 800°F.</td>
</tr>
<tr>
<td><strong>15.</strong></td>
<td>Start Li pump at 25 V. Gradually increase until flow rate F1 is 0.3 lb/s. Start freeze stem flow at maximum flow rate. Remove insulation from Li pump duct port and Cs pump port.</td>
</tr>
<tr>
<td><strong>16.</strong></td>
<td>Actuate Li heater at 200 A. Increase current until Li inlet temperature TC-I is 1200°F (100°F/h).</td>
</tr>
<tr>
<td><strong>17.</strong></td>
<td>(a) Set Li pump at 90 V. (b) Start Li pump blower. (c) Start Cs pump at 80 V. (d) Actuate Cs pump blower. (e) Set heater at 9.1 V.</td>
</tr>
</tbody>
</table>

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STARTUP PROCEDURES FOR Cs-Li LOOP (contd)

17. (contd)
Open valves to transducers. Reduce freeze valve flow until T-26 = 450°F. Actuate load cell motor until the gap is reduced to 0.010 in.

18. Increase Li inlet temperature in 100°F steps by first increasing the heater voltage, then the lithium flow, then the cesium flow. Keep chamber pressure in the 10^-5 range. Actuate the ion pump when 1800°F is reached and pressure is declining. Valve off diffusion pump. When the Cs pump temperature TC21 reaches 1100°F, evacuate Cs expansion tank through manual valve HV2, close manual valve HT2, open the manual valve V18 to the expansion tank until the first level thermocouple TC-52 is actuated, close the manual valve V18. When Cs temperature TC-21 reaches 1300°F, drain loop through the Cs drain line V18 until the second level thermocouple TC-53 is actuated.

19. Adjust the separator gap until the NaK outlet temperature TC-33 is minimized. Change V1 until saturated vapor is obtained (compare TC14 and P11).

20. Adjust the Li pump and Cs pump, heater and NaK temperature until P1 = 137 psia at a value of F1/F2 = 10.

21. Measure nozzle thrust. Vary stem position by +0.010 in. in 0.002-in. increments to determine spring constant.

22. Freeze stem by increasing the Dowtherm flow to the full flow rate.

<table>
<thead>
<tr>
<th>T1</th>
<th>F1</th>
<th>E2</th>
<th>E3</th>
<th>n</th>
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<tr>
<td>1300</td>
<td>110</td>
<td>100</td>
<td>11.2</td>
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<tr>
<td>1400</td>
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<td>153</td>
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<tr>
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<tr>
<td>1800</td>
<td>283</td>
<td>277</td>
<td>16.4</td>
<td>0.509</td>
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The values under key parameters are for a lithium carryover fraction of 0.05. Different values will result in different heater settings to attain the required temperatures.
## Valve Positions for Erosion Loop Startup

<table>
<thead>
<tr>
<th>Startup Step</th>
<th>Valve No. V</th>
<th>Valve No. VA</th>
<th>Valve No. SV</th>
<th>HT</th>
<th>HV</th>
<th>MV</th>
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</tr>
<tr>
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<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

X: Closed
0: Open
NORMAL SHUTDOWN FOR EROSION LOOP

1. Decrease the Li pump and Cs pump voltages concurrently by 25-V steps until a Li pump flow rate of 0.3 lb/s is reached. Reduce flow to freeze valve and increase gap to 0.045 in.

2. Decrease the Cs pump voltage further until a setting of 25 V is reached.

3. Decrease the Li heater power until a lithium inlet temperature of 1000°F is reached (100°F/hr).

4. Turn off cesium pump.

5. Turn off Li heater.

6. Decrease Li pump voltage by 25-V increments until it is off.

7. Turn off NaK flow.


10. Heat both sumps to 400°F. Heat chamber and pumps to 800°F. Open V13 and V15. Monitor fill and dump line temperature TC-43. When TC-43 drops to ~400°F the loop is drained. Close V13 and V15. Turn off all heaters.
<table>
<thead>
<tr>
<th>Emergency</th>
<th>Function</th>
<th>Location of Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Liquid metal leak in chamber</td>
<td>a. Turn off Li, Cs, NaK pumps, Li heater, ion pump.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>b. Close manual dp valve (if open).</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>c. If O-ring temperature rises to 300°F, open argon flood for chamber, SA-8.</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>d. Increase cooling flow on chamber to limit temperature rise.</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>e. If NaK level drops, pressurize NaK reservoir to 10 psig, and drain through V7 to NaK sump. Watch chamber pressure.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>f. Keep system under observation as temperature cools.</td>
<td>CR/HB</td>
</tr>
<tr>
<td>2. Liquid metal leak in NaK room</td>
<td>a. Turn off Li, Cs, NaK pumps, Li heater, bus cooling water.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>b. Turn off heat exchanger blower and makeup air blower.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>c. Close heat exchanger damper by setting controller on 1400°F.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>d. Pressurize NaK reservoir to 10 psig, drain through V7 to NaK sump.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>e. When leak stops, extinguish fire if safe.</td>
<td>HB</td>
</tr>
<tr>
<td>3. Liquid metal leak in door area</td>
<td>a. Turn off Li, Cs, NaK pump, Li heater, bus cooling water.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>b. Turn off heat exchanger blower and makeup air blower.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>c. Close heat exchanger damper by setting controller on 1400°F.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>d. If safe, turn off flange water and transducer oven.</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>e. If NaK level drops, pressurize NaK reservoir to 10 psig and drain through V7 to NaK sump.</td>
<td>CR</td>
</tr>
<tr>
<td></td>
<td>f. If leak is from transducer box, valve off all transducers, if safe.</td>
<td>HB</td>
</tr>
<tr>
<td></td>
<td>g. When safe, extinguish fire.</td>
<td>HB</td>
</tr>
</tbody>
</table>

CR = control room
HB = high bay
APPENDIX B
TEST SYSTEM SCHEMATIC DIAGRAMS

All instrumentation, control, flow, argon and vacuum, and electrical schematics for the test system are contained in this appendix (see Figs. B-1 through B-30).

The following manufacturers' manuals are available at the Jet Propulsion Laboratory, care of Section 383 files, Mr. L. H. Huebner.


5. Miscellaneous instrumentation and auxiliary component calibration sheets and instruction manuals.
## INSTRUMENTATION FUNCTIONS

### Transducer Connections

<table>
<thead>
<tr>
<th>Inside Chamber</th>
<th>Outside Chamber</th>
<th>TC Panel 1</th>
<th>TC Panel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle inlet - lithium</td>
<td>NaK exit piping</td>
<td>1 &amp; 2</td>
<td>65 &amp; 66</td>
</tr>
<tr>
<td>Nozzle inlet - cesium</td>
<td>Expansion tank</td>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>Receiver lithium fill</td>
<td>Heater</td>
<td>5</td>
<td>69</td>
</tr>
<tr>
<td>Receiver cesium exit</td>
<td>Hot trap</td>
<td>7</td>
<td>71</td>
</tr>
<tr>
<td>Receiver lithium exit</td>
<td>Hot trap flowmeter</td>
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<td>73</td>
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<tr>
<td>Lithium pump return line</td>
<td>Heat exchanger out</td>
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<td>75</td>
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<td>Lithium pump exit</td>
<td>Main flowmeter</td>
<td>13</td>
<td>77</td>
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<td>Lithium pump duct A</td>
<td>Pump outlet</td>
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<td>NaK pump windings</td>
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<td>81</td>
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<td>Heater bus A</td>
<td>Pressure tap lines</td>
<td>19</td>
<td>83</td>
</tr>
<tr>
<td>Heater bus B</td>
<td>Fill and dump lines</td>
<td>21</td>
<td>84</td>
</tr>
<tr>
<td>Heater body</td>
<td>Lithium pump windings</td>
<td>23</td>
<td>85</td>
</tr>
<tr>
<td>Lithium flowmeter magnet</td>
<td>Cesium pump windings</td>
<td>25</td>
<td>86</td>
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<tr>
<td>Condenser, cesium inlet</td>
<td>Transducer oven</td>
<td>27</td>
<td>87</td>
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<tr>
<td>Condenser, cesium exit</td>
<td>Cesium pump windings</td>
<td>29</td>
<td>88</td>
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<tr>
<td>Condenser, cesium fill</td>
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<td>89</td>
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<td>Cesium pump windings</td>
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<td>Heater feedthru B</td>
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<td>91</td>
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<td>Chamber body</td>
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<td>Ambient</td>
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<td>Nozzle body</td>
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<tr>
<td>Sight glass, 3-1/4 in. high</td>
<td></td>
<td>61</td>
<td>104</td>
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<tr>
<td>Sight glass, 4-1/2 in. high</td>
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### Instrumentation Functions

**Transducer Connections (contd)**

#### Pressure Functions

<table>
<thead>
<tr>
<th>P-1</th>
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<tr>
<td>P-2</td>
<td>Nozzle, cesium inlet</td>
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<td>P-3</td>
<td>Receiver pressure</td>
</tr>
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<td>P-4</td>
<td>Nozzle tap A</td>
</tr>
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<td>P-5</td>
<td>Nozzle tap B</td>
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<td>P-6</td>
<td>Nozzle tap C</td>
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<td>P-7</td>
<td>Nozzle tap D</td>
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<td>P-8</td>
<td>Nozzle tap E</td>
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<td>P-9</td>
<td>Nozzle tap F</td>
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<td>P-10</td>
<td>Nozzle tap G</td>
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<td>P-11</td>
<td>Condenser cesium inlet</td>
</tr>
<tr>
<td>P-12</td>
<td>Cesium pump inlet</td>
</tr>
</tbody>
</table>

#### Pressure Panel Amp. Out Connections

- 1 to amplifier 105 & 106
- 2 to amplifier 107 & 108
- 8 to amplifier 109 & 110
- 9 to amplifier 111 & 112
- 10
- 11 to amplifier 139 & 140

#### Flowmeter Functions

<table>
<thead>
<tr>
<th>F-1</th>
<th>Lithium flow</th>
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</thead>
<tbody>
<tr>
<td>F-1a</td>
<td>Lithium flow (standby)</td>
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<tr>
<td>F-2</td>
<td>Cesium flow</td>
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<tr>
<td>F-2a</td>
<td>Cesium flow (standby)</td>
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<tr>
<td>F-3</td>
<td>Main NaK flow</td>
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<tr>
<td>F-4</td>
<td>Hot trap flow</td>
</tr>
<tr>
<td>F-5</td>
<td>NaK bypass flow</td>
</tr>
</tbody>
</table>

#### Flowmeter and Feedthru

- 85 & 86 95 & 96
- 87 | 88 97 | 98
- 89 | 90 99 | 100
- 91 | 92 101 | 102
- 93 | 94 103 | 104
- 113 | 114 (outside)
- 115 | 116 (outside)
- 117 | 118 (outside)
Instrumentation Functions

<table>
<thead>
<tr>
<th>Cable No. 71 to Main Control Panel (CBA)</th>
<th>Meter No.</th>
<th>Cable No. 71 to Controllers</th>
<th>Controller No.</th>
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<td>Subcable 6</td>
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<td>Subcable 7</td>
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### Instrumentation Functions

**Meter - Relays (contd)**

**Cable No. 45**  
Multi-Point Recorder 1

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<td>8-33</td>
<td>P12</td>
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<td>9-34</td>
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<td>139 &amp; 140 - 34 amp 6</td>
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**Cable No. 46**  
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Fig. B-1. 100-kW erosion loop liquid metal circuits schematic diagram
Fig. B-2. 100-kW erosion loop electrical schematic diagram
Fig. B-3. 100-kW erosion loop argon, vacuum, and air circuits schematic diagram
Fig. B-4. 100-kW erosion loop cooling circuits schematic diagram
Fig. B-5. 100-kW erosion loop Cs injection and separation circuit schematic diagram
Fig. B-6. Building 148 panel CBA wiring diagram
Fig. B-7. Building 148 junction box JA interconnection diagram
Fig. B-8. Building 148 panel CBB wiring diagram
Fig. B-9. Building 148 panels CBE and CBF wiring diagram
Fig. B-10. Magnetohydrodynamic facility panel CBH wiring diagram
Fig. B-11. Magnetohydrodynamic facility panel CBJ wiring diagram
Fig. B-12. Magnetohydrodynamic facility panel CBK wiring diagram
Fig. B-13. Building 148 panel CBP wiring diagram

Fig. B-14. Building 148 panel CBQ wiring diagram
Fig. B-15. Building 148 100-kW test valves schematic diagram
Fig. B-16. Magnetohydrodynamic facility type WSH welder 1000 A, unit 1, wiring and schematic
Fig. B-17. Magnetohydrodynamic facility type WSH welder 1000 A, unit 2, wiring and schematic
Fig. B-18. Magnetohydrodynamic facility type WSH welder 1000 A, unit 3, wiring and schematic
Fig. B-19. Magnetohydrodynamic facility type WSH welder 1000 A, unit 4, wiring and schematic
Fig. B-20. Building 148 NaK pump blower schematic diagram
Fig. B-21. Building 148 heat exchanger blower schematic diagram
Fig. B-22. Building 148 vacuum vessel heater schematic diagram

Fig. B-23. Building 148 damper control schematic diagram
Fig. B-24. Building 148 100-kW test, NaK heater schematic diagram
Fig. B-25. Building 148 NaK pump schematic diagram
Fig. B-26. Building 148 hot trap schematic diagram

Fig. B-27. Magnetohydrodynamic facility 15-hp blower schematic diagram
Fig. B-28. Magnetohydrodynamic facility 1-1/2-hp blower schematic diagram
Fig. B-29. Magnetohydrodynamic facility lithium pump schematic diagram
Fig. B-30. Magnetohydrodynamic facility cesium pump schematic diagram
APPENDIX C

FABRICATION DRAWINGS OF TEST SYSTEM

The fabrication drawings of the cesium-lithium test system are included in this appendix (see Figs. C-1 through C-53). In some cases minor deviations and/or modifications have been made for the reasons discussed in the text. However, the essential features of the components and piping arrangement are identical to the drawings.
Fig. C-1. Layout and installation - 100-kW MHD ac generator erosion loop
REMOVE APERTURE PLATE FROM NEEDLE ASSY. & WELD IN POSITION. THEN INSTALL NEEDLE ASSY & WELD.

ALL WELDS TO BE ELECTRON BEAM.

Fig. C-2. Weldment injector assembly

Fig. C-3. Plug, housing injector assembly
WELD ALL AROUND △

△ INSTALL 1 TO LOO, GRIND TO LOO AFTER TUBE WELDING.
△ ELECTRON BEAM WELDING TO BE USED THROUGHOUT.

Fig. C-4. Needle assembly
Fig. C-5. Aperture plate

1. CLEAN & DEBURR TUBE ENDS.
   MEASURE & RECORD I.D. & WALL ON ALL TUBES.

<table>
<thead>
<tr>
<th>TUBING</th>
<th>$D_{935}$ OD, $0.014$ wall</th>
<th>Cu-17, Zr</th>
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<tbody>
<tr>
<td>DESCRIPTION</td>
<td>SPECIFICATION</td>
<td>MATERIAL</td>
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<tr>
<td>$D_{935}$</td>
<td>$0.014$ wall</td>
<td>Cu-17, Zr</td>
</tr>
</tbody>
</table>

Fig. C-6. Tube, needle assembly
Fig. C-7. Holder, tube
ASSEMBLY INSTRUCTIONS

STEP NO. 1. INSERT O INTO 1 AS SHOWN. THE DIMENSION SHOWN IN
DETAIL A IS DESIGN DIMENSION AND MUST BE HELD
TO ±0.005 (USE .010 SHIM STOCK, REMOVE AFTER WELDING)
WELD 1 & 2 AS SHOWN.

STEP NO. 2. INSTALL O INTO 1 AND WELD AS SHOWN.
NOTE: PRESS 0 LIGHTLY UNTIL IT BOTTOMS OUT ON THE
STEP OF 1. THIS WILL ESTABLISH THE ±005 WELD DIM.

STEP NO. 3. COVER OR PLUG ALL PORTS, ETC.

ALIGN INDEX MARKS; USE FITTING JOINT -005 & JOINT -1.
1. AFTER WELDING STORE IN PROPER CONTAINER TO PREVENT DAMAGE.

SPEC TIG WELD JPL 20035
SPEC IDENTIFICATION JPL20002

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<tr>
<th>CODE</th>
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<tr>
<td>CH1753</td>
<td>BODY</td>
<td>1 1</td>
</tr>
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</table>

Fig. C-8. Separator – 100-kW erosion loop
**ASSEMBLY PROCEDURE**

**STEP NO. 1**
Weld Item 1 & 8 together as shown.
Weld Items 2 & 5 to Weld 10 to 6.

**STEP NO. 2**
Insert Step No. 3. Align the steps of (3-8) that receive 9. Then weld as shown. Item 5 may be used for positioning but do not weld on this time.

**STEP NO. 3**
Install 9. Weld Items 3 & 8 as shown. Press 2 until it bottoms.

**STEP NO. 4**
Insert and weld 4 into 5. Install and weld 3 onto 5. Weld as shown.

**SPECIFICATION**
- **IDENTIFICATION**: JPL 20035
- **TIG WELD**: JP 20035

**Fig. C-9. Assembly, body, separator — 100 kW erosion loop**
4. All diameters to be concentric within .005, except .09 dia.

3. Machined fillet radius .005R
2. Remove all burrs and sharp edges .010 R
1. Machine finish G Y

<table>
<thead>
<tr>
<th>SPEC</th>
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<tr>
<td></td>
<td>COLLAR</td>
<td>3/4 x 4 1/8 DIA</td>
<td>Cr-IX RF</td>
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</tbody>
</table>

Fig. C-10. Collar separator - 100-kW erosion loop
TO BE CONCENTRIC WITHIN 0.001 AFTER WELDING.

1. MACHINE FILLET RADIUS.
2. REMOVE ALL BURRS AND SHARP EDGES 0.015 R MAX.
   MACHINE FINISH G3

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Fig. C-11. Baffle 1, separator – 100-kW erosion loop
Fig. C-12. Baffle 2, separator - 100-kW erosion loop
Fig. C-13. Cylinder screen, separator — 100-kW erosion loop
Fig. C-14. Body, separator - 100-kW erosion loop
Fig. C-15. Band, separator — 100-kW erosion loop
Fig. C-16. Plate, top, separator – 100-kW erosion loop
Fig. C-17. Nozzle assembly, separator - 100-kW erosion loop
Fig. C-18. Ring, nozzle, separator - 100-kW erosion loop
4. The removed core will be used to produce C9117762.

3. Machined fillet radius:
2. Remove all burrs and sharp edges .030 in. max.
1. Machine finish .0005 max.

Fig. C-19. Plate, bottom, separator – 100-kW erosion loop
Fig. C-20. Ring, separator - 100-kW erosion loop
Fig. C-21. Assembly, cone and support, separator – 100-kW erosion loop
Fig. C-22. Cone assembly, separator - 100-kW erosion loop
Fig. C-23. Support, tube, separator – 100-kW erosion loop
Fig. C-24. Plug, tube support—100-kW erosion loop separator
Bellows to have a No. 6 end cuff termination, reduced diameter as shown. Material: 005; 1 ply, 100 psi at 800°F. Max deflection: 0.25; spring rate 68 lb/in.; effective area 1.68 sq in.

Similar to Arrowhead No. 21012, Arrowhead Products, 4411 Katella Ave., Los Alamitos, Calif., or equal. (Bulletin No. 501-R)

Fig. C-25. Bellows, separator - 100-kW erosion loop
3. MACHINED FILLET RADIUS: .010 MAX
2. REMOVE ALL BURRS AND SHARP EDGES .015 R MAX
1. MACHINE FINISH .6/

Fig. C-26. Coupling, separator – 100-kW erosion loop
**Fig. C-27.** Tubing, separator - 100-kW erosion loop

**Fig. C-28.** Pin ring, separator - 100-kW erosion loop
4. Material to be determined by the COG, ENG.
2. Remove all burrs and sharp edges
1. Machine finish 48

Fig. C-29. Nose cone, separator - 100-kW erosion loop
Fig. C-30. Heater assembly - 100-kW erosion loop
Fig. C-31. Shell, lithium heater - 100-kW erosion loop
Fig. 32. Element assembly, lithium heater

Fig. C-33. Bulkhead, lithium heater
PROCURE FROM NUCLEAR METALS INC., CONCORD, MASS., OR EQUAL.

DIFFUSION BOND LIMITS.
1. MACHINE FILLET RADIUS.
2. REMOVE ALL BURRS AND SHARP EDGES
3. MACHINED FILLET RADIUS

Fig. C-35. Joint, coextruded - erosion loop cesium condenser
Fig. C-36. Bracket, bus support, inner (LH and RH)
PERFORM THESE FUNCTIONS AFTER A

1. MACHINE FINISH
2. REMOVE ALL BURRS AND SHARP EDGES .030 R.
3. MACHINED FILLET RADIUS .030 R.

Determine length at next assembly.

Fig. C-37. Bar, bus, lead-in (RH)

DRILL \( \frac{3}{16} \) (.483-.003) DEPTH SHOWN 90° CSK .875 DIA.

Fig. C-38. Adapter, aft
Fig. C-39. Bar, bus, lead-in (LH)
Fig. C-40. Bracket, bus support, outer
Fig. C-41. Housing, injector assembly
Fig. C-42. Bar, bus transition (LH)
Fig. C-43. Bar, bus transition (RH)

- ALL MACHINED SURFACES.
- BRAKE ALL EDGES & CORNERS .015 IN.
- VIEW AA
- SPECIFICATION: 250K AL A44 L4 - BAR WOLFBENUM 2

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Fig. C-44. Door assembly - 100-kW erosion loop
Fig. C-46. Frame, weldment, vacuum tank support
Fig. G-47. Frame, assembly
Fig. C-48. Transition pieces, columbium separator
Fig. C-49. Sump weldment – cesium, lithium and NaK (tabulated)
.062 DIA (44) PLACES

.020 DIA (48) HOLES SPACED 90° AROUND CIRCUMFERENCE.

1. 1.125 O.D. X .062 W. X 3.1 LG. TUBE
   MAT'L. - COLUMBIUM 1% ZIRCONIUM.

2. 1.125 O.D. X .03 W. X 13.0 LG. TUBE
   MAT'L. - COLUMBIUM 1% ZIRCONIUM.

3. .062 X .75 DIA DOUBLER
   MAT'L. - COLUMBIUM 1% ZIRCONIUM.

Fig. C-50. Sketch, desuperheater, erosion loop
Fig. C-51. Cooler, 100-kW erosion loop
Fig. C-52. Flowmeter FM-14

Flow Tube — 1" O.D. x ½" Wall, Columbian-Titan
End Preparation — Square
Thermocouple — Chromel-Alumel
Estimated Height — 150 lbs.
Fig. C-53. Flowmeter FM-12
APPENDIX D

CESIUM-LITHIUM LOOP OPERATING CHARACTERISTICS

The operating characteristics of the Cs-Li loop were determined by modeling the performance of the major components (Li pump, Cs pump, Li heater, Cs condenser, Cs subcooler, bypass valve) and combining the relations together with the hydraulic and heat loss characteristics of the system. The CAL program resulting from this effort is given in this appendix. The results of variation of key parameters over a range of interest is summarized in Fig. D-1. The independent variables are taken to be the pump voltages $E_1$ and $E_2$, the heat rejection rate $Q$, the NaK pump current $I$, the lithium heater voltage $E_3$, and the number of turns opening of the bypass valve $N$. The variations of the condenser temperature $T_2$, mass ratio $r_c$, NaK temperature $T_3$, and lithium temperature $T_1$ are shown for individual variations in the independent parameters. At the design point of:

- $T_1 = 1800^\circ F$
- $T_2 = 1300^\circ F$
- $T_3 = 900^\circ F$
- $C_1 = 0.02$
- $r_c = 10$

the control variables should have the following settings (from the figure):

- $E_1 = 304 V$
- $E_2 = 283 V$
- $E_3 = 11.3 V$
- $Q = 24.3 kW$
- $T = 18.3 A$
- $N = 0.45$ turns

The effect of variations of the control parameters from the design point can be determined by following the appropriate curve.
NOMENCLATURE

A1 \( \sigma_B \)  fraction of cesium in lithium at nozzle exit

A2 \( A \)  area of loop at highest temperature, \( \text{ft}^2 \)

B1 \( \beta_B \)  fraction of lithium vapor in cesium at nozzle outlet

*C1 \( C_0 \)  fractional lithium carryover

C2 \( \rho_{cs10} \) specific heat of cesium liquid and vapor at \( T_{10} \), Btu/lb \(^\circ\)F

C3 \( \rho_{Li} \) specific heat of lithium at \( T_{12} \)

C4 \( \rho_{Li9} \) specific heat of lithium and cesium mixture into desuperheater

*D1 \( \Delta p_{f1} \) frictional drop in lithium lines, psi

*D2 \( \Delta p_{f2} \) frictional drop in cesium lines, psi

D3 \( \Delta T_B \) drop in bulk temperature in nozzle, \(^\circ\)F

E1 \( E_1 \) lithium pump voltage

E2 \( E_2 \) cesium pump voltage

E3 \( E_3 \) lithium heater voltage

E4 \( E \) emissivity of foil insulation

L1 \( L_{Li} \) latent heat of lithium vapor, cal/g

L2 \( L_{Li} \) latent heat of lithium vapor, B/lb

L3 \( L_{cs} \) latent heat of cesium vapor, cal/g

L4 \( L_{cs} \) latent heat of cesium vapor, B/lb

M1 \( \dot{m}_{T} \) total nozzle flowrate, lb/s

M2 \( \dot{m}_{Li} \) lithium flowrate in nozzle, lb/s

M3 \( \dot{m}_{p} \) lithium flowrate in pump, lb/s
NOMENCLATURE (contd)

M4 $\dot{m}_{csN}$ cesium flow in nozzle, lb/s
M5 $\dot{m}_{csI9}$ mass flowrate of dissolved cesium, lb/s
M6 $\dot{m}_{Li_v9}$ mass flowrate of lithium vapor, lb/s
M7 $\dot{m}_{csD_8}$ desuperheater flowrate, lb/s
M8 $\dot{m}_{p2}$ cesium pump flowrate, lb/s
N1 n number of layers of radiation shielding
P0 $p_0$ inlet pressure of lithium, psi
P1 $p_1$ nozzle inlet pressure, psi
P2 $p_{12}$ condenser pressure, atm
P3 $p_{12}$ condenser pressure, psi
Q1 $Q_1$ heat input from lithium pump, kW
Q2 $Q_2$ heat input from cesium pump, kW
Q3 $Q_3$ heat input from lithium heater, kW
Q4 $Q_4$ radiant heat loss, Btu/hr
Q5 $Q_5$ heat transfer in subcooler
Q6 $Q_4$ radiant heat loss, kW
Q7 $Q_R$ heat rejection date required, kW
R1 $\rho_{Li}$ lithium density, lb/ft$^3$
*R2 $r_c$ mass ratio of lithium to cesium in nozzle
R3 $\rho_{cs}$ cesium density, B/ft$^3$
R4 $\rho_{Li}$ lithium density, g/cm$^3$
NOMENCLATURE (contd)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5</td>
<td>$\rho_{cs}$ cesium density, g/cm$^3$</td>
</tr>
<tr>
<td>*T1</td>
<td>$T_1$ nozzle inlet temperature of lithium, °F</td>
</tr>
<tr>
<td>*T2</td>
<td>$T_{12}$ condenser temperature, °F</td>
</tr>
<tr>
<td>T3</td>
<td>$T_{34}$ potassium low temperature, °F</td>
</tr>
<tr>
<td>T4</td>
<td>$T_{12}$ condenser temperature, °K</td>
</tr>
<tr>
<td>T5</td>
<td>$T_1$ nozzle inlet temperature, °F, °C</td>
</tr>
<tr>
<td>T6</td>
<td>$T_{19}$ temperature into desuperheater, °F</td>
</tr>
<tr>
<td>T7</td>
<td>$T_{10}$ nozzle exit temperature, °C</td>
</tr>
<tr>
<td>T8</td>
<td>$T_{12}$ condenser temperature, °C</td>
</tr>
<tr>
<td>T9</td>
<td>$T_{10}$ nozzle exit temperature, °K</td>
</tr>
<tr>
<td>X1</td>
<td>$T_c$ temperature of vacuum chamber</td>
</tr>
<tr>
<td>X2</td>
<td>temperature factor</td>
</tr>
<tr>
<td>X3</td>
<td>temperature factor</td>
</tr>
<tr>
<td>X4</td>
<td>temperature factor</td>
</tr>
<tr>
<td>X5</td>
<td>$T_{10}$ nozzle exit temperature, °F</td>
</tr>
</tbody>
</table>
Cs-Li LOOP PERFORMANCE PROGRAM (contd)

1:433 M8=1
1:434 X7=(Q7+Q5)/(Q4+Q7+Q5)
1:435 X8=(Q5+Q7)/(Q4+Q5)

1:436 X9=(X7)\LOG(1/(1-(X7)/(T2-T3+X8)))
1:437 M9= IF ABS((X9-X6)/X6) < 0.1 THEN M9 ELSE M9
1:438 TO STEP 1:434 IF ABS((X9-X6)/X6) > 0.1
1:439 I=4+7xM9+74
1:440 TYPE E1,E2,E3,P0,P3,T1,T2,D3,C2,M4,L2
1:441 TYPE X6
1:442 V7=29230xM7/23
1:443 X9=(P0/P3)/(R3xV7/2)
1:444 N=3x6+X4+5
1:445 TYPE N,M9,X7,X9,1
1:446 TYPE M1,M2,M3,M4,M5,M6,M7,M8
1:447 TYPE C1,C2,C3,C5,C6,C7
1:448 TYPE D1,D2
1:449 TO STEP 1:00
Fig. D-1. Cs-Li loop characteristics