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EXPERIMENTAL LITHIUM SYSTEM FINAL REPORT

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Hanford Engineering Development Laboratory

HANFORD ENGINEERING DEVELOPMENT LABORATORY

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P.O. Box 1970 Richland, WA 99352

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Hanford Engineering Development Laboratory

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April 1985

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EXPERIMENTAL LITHIUM SYSTEM

FINAL REPORT

R. Kolowitz
J. D. Berg
W. C. Miller

ABSTRACT

A full-scale mockup of the Fusion Materials Irradiation Test (FMIT) Facility lithium system was built at the Hanford Engineering Development Laboratory (HEDL). This isothermal mockup, called the Experimental Lithium System (ELS), was prototypic of FMIT, excluding the accelerator and dump heat exchanger. This 3.8 m³ lithium test loop achieved over 16,000 hours of safe and reliable operation. An extensive test program demonstrated satisfactory performance of the system components, including the HEDL-supplied electromagnetic lithium pump, the lithium jet target, the purification and characterization hardware, as well as the auxiliary argon and vacuum systems. Experience with the test loop provided important information on system operation, performance, and reliability. This report presents a complete overview of the entire Experimental Lithium System test program and also includes a summary of such areas as instrumentation, coolant chemistry, vapor/aerosol transport, and corrosion.

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ACRONYMS

7BELL	⁷ Beryllium Experimental Lithium Loop
ALIP	Annular Linear Induction Pump
ANL	Argonne National Laboratory
ATP	Acceptance Test Procedures
BPM	Beam Position Monitor
CCTV	Closed-Circuit Television
CRT	Cathode Ray Tube
EDL	Engineering Development Laboratory
ELF	Experimental Lithium Facility (at <u>W</u> -AESD)
ELS	Experimental Lithium System
EM	Electromagnetic
EOL	End of Life
FFTF	Fast Flux Test Facility
FMIT	Fusion Materials Irradiation Test (Facility)
FTTS	Flow-Through Tube Sampler
HAZ	Heat-Affected Zone
HEDL	Hanford Engineering Development Laboratory
HEPA	Highly Enriched Particulate Air (Filter)
IGA	Intergranular Attack
L/D	Length-to-Diameter (Ratio)
LANL	Los Alamos National Laboratory
LPTL	Lithium Processing Test Loop (at ANL)
NC	Normally Closed
NO	Normally Open

ACRONYMS (Cont'd)

MPS	Multipurpose Sampler
NPSH	Net Positive Suction Head
PTI	Plugging Temperature Indicator
RGA	Residual Gas Analyzer
RNA	Residual Nitrogen Analyzer
RWA	Rotating Window Assembly
SEM	Scanning Electron Microscope
SS	Stainless Steel
STCL	Source Term Control Loop
STP	Standard Temperature and Pressure
UNC	UNC Nuclear Industries, Division of UNC Resources Company
<u>W</u> -AESD	Westinghouse - Advanced Energy Systems Division
WHC	Westinghouse Hanford Company
wppm	Weight parts per million

EXPERIMENTAL LITHIUM SYSTEM FINAL REPORT

I. SUMMARY AND CONCLUSIONS

The Experimental Lithium System (ELS) is a test facility that was constructed to develop components and operating procedures for the Lithium System of the Fusion Materials Irradiation Test (FMIT) Facility. The ELS is located at the Hanford Engineering Development Laboratory (HEDL) and was operated by the Westinghouse Hanford Company for the U.S. Department of Energy. The ELS contains the largest known flowing lithium system in the world and includes unique features and operating capabilities, including vacuum operation, necessary for the development of the (FMIT) lithium target assembly and other key system components. This test facility was operated for nearly four years and achieved major success in the development of FMIT components. The facility operated safely and reliably from start of operation until it was shut down in January 1984.

This report summarizes the testing and operating experience of the ELS. Significant highlights of the development program include:

- Demonstration of the stability of the high-velocity lithium jet produced by the FMIT lithium target in a high-vacuum regime typical of the FMIT deuteron accelerator and verification of the suitability of the chosen design for use in FMIT.
- Confirmation of the predicted performance of a HEDL-designed, large electromagnetic lithium pump for use in FMIT.
- Development of equipment and procedures that provide for safe operation of a large liquid metal system with a vacuum replacing the normal cover gas used over the liquid metal surfaces.
- Demonstration of the inherent reliability of a low-temperature liquid lithium system by operating the facility for over 16,000 hours without any significant equipment failures or evidence of lithium corrosion attack.
- Development of lithium sampling and analytical chemistry techniques to monitor impurity levels in the liquid lithium.

- Demonstration of the ability of a cold trap to control the level of hydrogen, the most abundant impurity expected in the FMIT lithium system.
- Identification of the suitability of commercially available liquid metal valves for use in the FMIT lithium system.

Though the development program in the ELS was a major success, certain specific areas require further development before they can be implemented in the FMIT Facility. These include demonstration of a lithium hot trap to control nitrogen levels and demonstration of vacuum sensors less susceptible to liquid metal vapors.

This report documents the achievements from the ELS and identifies recommendations for further development activities that are needed to support the final FMIT Lithium System design. Due to the broad scope of this report, detailed recommendations are provided in the body of the report (see Sections V through X).

A. SYSTEM PERFORMANCE

The Experimental Lithium System (ELS) began circulating lithium on March 26, 1980 and was shut down on January 13, 1984. The ELS operated safely and reliably from startup to shutdown. The ELS, a full-size prototype of the Fusion Materials Irradiation Test (FMIT) Facility lithium system, was used to test critical components and demonstrated the safe and reliable operation of a large lithium system. Over the entire 46 months of operation, no major problems occurred. A small lithium spill occurred during lithium fill, prior to startup. The spill resulted from an elastomer seal failure on one of the black iron shipping drums supplied by the vendor. The spill was largely contained in a secondary containment vessel and was well controlled.

Component tests were performed on the main lithium pump, lithium target and purification hardware. In addition, operation of the ELS demonstrated

that a large lithium system can be operated under either an argon cover gas blanket or with a vacuum at the lithium free surfaces. Experience at the ELS was instrumental in identifying the need for a rapid vacuum break capability. Vacuum operation also demonstrated adequate air in-leakage detection instrumentation considered vital to the safe operation of this facility.

Operation of the ELS also demonstrated that several other critical components are within the state of technology for a large liquid lithium system, i.e., flowmeters, valves, plugging temperature indicator (PTI), and sampling hardware. Lithium impurity levels remained low throughout ELS operation, necessitating impurity additions of hydrogen and nitrogen to evaluate the cold and hot traps.

Lithium frost was observed early in ELS operation and became the object of a thorough investigation of vapor/aerosol transport. Some instrumentation used on the ELS suffered from frost deposition which impaired function (i.e., the beam position monitor and the high vacuum gauges). ELS corrosion studies were performed in conjunction with work on the ⁷Beryllium Experimental Lithium Loop (7BELL) at HEDL and work at the Colorado School of Mines and the Westinghouse Research and Development Center. More details in each of these areas follows.

B. COMPONENT TEST RESULTS

Electromagnetic (EM) Pumps -- Testing of the main pump on the ELS was successfully completed. The HEDL-designed and fabricated Annular Linear Induction Pump (ALIP) performed well, although cavitation was observed at very low Net Positive Suction Head (NPSH) levels. Pump performance was adequate to successfully evaluate the target hydraulics. The results of the Annular Linear Induction Pump (ALIP) test demonstrate that measured performance provides good correlation with predicted performance. The developed head at the design flow rate of $0.038 \text{ m}^3/\text{s}$ (600 gal/min) was 221 kPa. The cavitation inception NPSH at $0.038 \text{ m}^3/\text{s}$ was 39.3 kPa. These results confirm that the static head of lithium currently planned for FMIT is adequate. Pump coastdown tests were performed on the main pump. When power was interrupted,

pump flow typically dropped from $0.041 \text{ m}^3/\text{s}$ (647 gal/min) to zero in ~6 seconds. Pump internal temperatures were closely monitored during all phases of pump testing. The air-cooled pump design showed no heatup problems. Even with the pump operating at 480-volt and the ELS piping system throttled to a flow rate of $0.019 \text{ m}^3/\text{s}$ (300 gal/min), the pump coils maximum temperature was only about 38°C (100°F) higher than the bulk lithium temperature.

Two different control systems were tested with the main loop pump. Both solid-state and variac controllers were evaluated. No problems were encountered with either controller; however, the variac control system demonstrated greater rate and ramp control and was capable of supplying 540 volts. This additional voltage, above the 480-volt solid-state controller capability, produced a 244-kPa pump head at the design flow rate of $0.038 \text{ m}^3/\text{s}$.

The chemistry loop a-c electromagnetic conduction pump was removed for evaluation and found to be in excellent condition after 9500 hours in 270°C (518°F), low-nitrogen lithium. One half of the duct was cleaned, leak-tested and destructively examined; the other half was preserved for possible future investigation. No service-connected damage was found, nor was any indication of metallic or other deposits found in the lithium or the pump throat. Chemistry loop service conditions did not produce the problems encountered by others in higher-temperature, less-pure lithium. The decision to remove the chemistry loop pump was based on experience at Argonne National Laboratory, where a similar lithium pump failed after 9500 hours at 450°C (842°F).

Lithium Target -- Full-scale testing of two target assemblies for the Fusion Materials Irradiation Test (FMIT) Facility was completed on the ELS, using molten lithium at isothermal conditions. Since accelerator beam heating was not simulated at the ELS, this aspect of the design was not confirmed. This test program confirmed performance predictions and verified water modeling techniques. Test conditions included lithium temperatures to

$\sim 280^{\circ}\text{C}$ (540°F), flowrates to $0.033 \text{ m}^3/\text{s}$ (530 gal/min), and pressures ranging from $1.2 \times 10^5 \text{ Pa}$ (18 psia) to $\sim 1.3 \times 10^{-3} \text{ Pa}$ (10^{-5} torr). Results show that the lithium jet produced by the target is stable at all FMIT operating conditions. The contour of the jet free surface matches predictions within 1.5%.

The FMIT Mark I target test program confirmed the hydraulic viability of a free-wall lithium jet as an appropriate target concept for the FMIT. Tests confirmed the basic hydraulic stability of the free-wall lithium jet produced by this first generation lithium target design at both positive pressure and vacuum conditions. At steady-state operating conditions, little or no splashing or other gross flow anomalies were observed following modification of the drain region. Initial surface roughness and jet thickness measurements were within allowances. Although significant amounts of liquid metal frost were deposited very near the lithium jet, these deposits were reduced substantially a short distance away in the simulated accelerator beam tube.

The FMIT Mark II prototype target performed as predicted in tests with lithium. This design incorporated a modified hydraulic geometry to allow improved access to high flux neutron test volume adjacent to the target. It also included a modified drain, which carried the lithium from the beam interaction region along a curved wall and into a mixing, or "quench," tank. The target produced a jet that is stable at steady-state FMIT operating conditions (excluding the deuteron beam) and remained stable at all expected transient flow conditions. Nominal jet thickness (1.9 cm) matched predictions within a few percent and was within allowable limits. Surface roughness was less than the limit of $\pm 0.1 \text{ cm}$ over the entire beam intercept region. Transport of the vapors of lithium and its impurities from the target is estimated to be $< 1 \text{ g/day}$ in FMIT based upon test results with this target. These results show that the Mark II target satisfies its design and operating conditions and provides necessary input to the final design of the FMIT target and facility.

Purification Hardware -- Testing of methods to control significant impurities in the FMIT lithium was completed with mixed results. An in-line, air-cooled, 304 SS wire-mesh-filled cold trap and an in-line, titanium-foil-filled hot trap were both subjected to thermal-hydraulic and purification testing. Thermal-hydraulic testing of the cold trap showed the economizer to be oversized but adequate for purification testing. The cold trap was later shown to be an effective control device for hydrogen. Hydrogen would be injected into the FMIT lithium by the deuteron beam. Thermal-hydraulic testing of the hot trap confirmed the design adequacy. However, limited purification testing of the hot trap as a means to control nitrogen impurities were inconclusive. Further testing of the hot trap for nitrogen control is recommended before procuring the FMIT lithium impurity traps. Based on the limited ELS hot trap test results, the selection of titanium for the getter material must be reconsidered.

C. CHEMISTRY

Analysis of lithium samples taken from the Experimental Lithium System (ELS) during the nearly four years of operation provided the first extensive chemical characterization of lithium in a large stainless steel system. Unexpectedly, nitrogen and oxygen, the primary impurities anticipated from air in-leakage, remained low throughout the life of ELS. Nitrogen stayed below 60 wppm, while oxygen stayed below 100 wppm. Several important reactions between lithium impurity species were observed in a large system for the first time. These reactions helped in maintaining these low levels of nitrogen and oxygen. Reactions between nitrogen and both aluminum and silicon in liquid lithium were found to control the dissolved (active) nitrogen concentration by precipitating insoluble nitrides. These precipitated nitrides tend to settle in quiescent areas of the loop; but over a long time, they can be expected to gradually dissolve from the relatively hot loop and redeposit in the cold trap. Reactions between oxygen and calcium in liquid lithium were found to control the dissolved (active) oxygen concentration by precipitating insoluble oxides.

Methods used for the sampling and analysis of lithium from the ELS were developed or modified specifically for use with lithium. The existing methods are considered to be satisfactory, although development work remains on methods for some additional lithium impurities, including oxygen, carbon species, and radioisotopes. Lithium from the FMIT will be intensely radioactive, primarily from ^7Be , and will require modification of techniques to allow remote analysis.

The program for surveillance of lithium purity in the ELS was adequate to monitor reactive impurities and corrosion products for both operations and safety purposes. More frequent sampling during operations and more extensive analysis during the fill would have aided in the interpretation of impurity interactions. More archive samples should have been preserved so that additional analyses could have been performed as the need was defined.

Argon cover gas was occasionally analyzed, but because liquid lithium is such an effective getter, impurities (other than hydrocarbons) were below the analytical detection limits during actual loop operation. The use of a residual gas analyzer at FMIT would seem to be desirable during vacuum operations when air leakage is most likely to occur.

D. VAPOR/AEROSOL TRANSPORT

Deposits of lithium, sodium and potassium vapors were measured at ELS as a function of distance from a source of flowing liquid lithium. Vapor transport rates from the Fusion Materials Irradiation Test (FMIT) Facility target were estimated using these data. A 12-cm diameter cylindrical simulated beam transport tube projected from the front face of the prototype target structure. Baffles restricted the flow of vapors to the beam tube from ~80% of the jet surface. Deposits were collected along the simulated beam tube for both vacuum and pressurized beam tube atmospheres.

The cumulative vapor deposits measured in the Experimental Lithium System (ELS) indicated mass transport rates to the beam tube of 0.241 g/day

lithium, 0.895 g/day sodium, and 7.3×10^{-4} g/day potassium for 270°C lithium with impurity levels of 2000 ppm sodium and 1 ppm potassium and vacuum conditions in the beam tube.

Expected deposition rates for FMIT based on ELS test information are as follows. The deposition rate at the FMIT vacuum pump port (located 4.3 m from the target) is 1.22×10^{-6} g/cm²·day. The approximate rate of deposition thickness increase is 1.0 cm/yr at the beam position monitors (BPMs) and halo feelers (located 8 to 26 cm from the target), 0.01 cm/yr at the BPMs and halo feelers (located 1 m from the target), 0.01 cm/yr at the in-cell beam viewing system (located 1.3 m from the target) and <1 μm/yr at the IR optical imaging device (located at the last bending magnet 8.7 m from the target). The design of the instrumentation mounted on the target beam tube will have to account for these relatively high deposition rates near the target.

It is highly unlikely that significant liquid metals will be transported to the accelerator tank because the liquid metals will tend to plate out on the long (15 m), cold (<90°C) beam tube between the vacuum pump and the accelerator. The two 45° bends between the target and the accelerator will also help prevent vapor migration into the accelerator. The ELS vapor deposits were measured to 14.5 ft (4.4 m) from the target (the distance to the nearest FMIT vacuum pumping port at the beam tube). The deposition rate at 14.5 ft (4.4 m) was found to be 1.22×10^{-6} g/cm²·day or 1 μm/yr thickness increase. These numbers represent the upper limit for deposits further away from the target than 14.5 ft (4.4 m). If vapor deposits are found to be more than can be tolerated in the beam tube away from the target, then the tube can be further cooled to trap the vapors before they enter either the vacuum system or the accelerator. The portion of the beam tube in which most of the deposition will take place is part of the target assembly that will be replaced every 6 to 9 months, so excessive buildup of vapors in the accelerator beam tube should not occur. Over a 20-yr facility life deposits in the last magnet module near the target will be ~2 mm.

E. CORROSION

Since ELS is a relatively low-temperature (270°C), low-nitrogen lithium system, no severe attack on piping or components was expected, nor was it found during testing. Several welds from the 10-cm main loop piping were examined after 6500 hours of lithium exposure at 270°C, with no evidence of attack. Also electron micro-probe scans of the surface showed no compositional changes.

A 2.5-cm bellows sealed Nupro valve, fabricated of 316 SS with a Stellite® 6B insert, was destructively examined after 5800 hours of lithium exposure and 10,000 open/close cycles. No evidence of corrosion or erosion was found. Similar results were obtained with a 2.5-cm bellows sealed Sargent valve containing a BNi₄ valve seat brazement and a 2.5-cm bellows sealed Hoke valve with a welded Stellite valve seat. Earlier results with a partial Sargent valve (body only) indicated some attack (~60 µm) on the brazement after 3500 hours of lithium exposure in ELS lithium service. These results are attributed to the formation of alpha-nickel phase in the brazement caused by too low a brazing temperature. Destructive examination of the complete Sargent valve assembly showed no sign of attack. This second Sargent valve was brazed using a previously qualified braze cycle (T = 2075°F maximum). The Hoke valve stuck in the open position after 5000 operating cycles and 3500 hours of lithium exposure. This valve was removed from service for interim examination. After cleaning in water and dilute acetic acid, the valve became operable. The bellows and seat were found to be in satisfactory condition, and the valve was reinstalled in the loop for additional cyclic testing. After 2000 more hours and 5000 additional cycles the valve was still functional. The earlier problem has been attributed to inadequate trace heat in the bellows region, which caused the formation of a solid lithium plug in the upper portion of the bellows. This plug prevented valve actuation.

*Stellite is a registered trademark of Cabot Corporation, Inc., Columbus, OH.

Overall results of the corrosion investigations confirm the absence of significant corrosion problems under conditions expected in FMIT. Based on this work, a corrosion allowance of $\sim 0.2 \mu\text{m/yr}$ has been established as the basis for design of the 304 SS FMIT lithium piping system. These data are based on low impurity concentrations ($<400 \text{ wppm of N}_2$) in lithium and low temperature exposure ($<270^\circ\text{C}$). For the hot trap, which will operate at temperatures to 540°C (1000°F), the corrosion rate has been estimated at $\sim 25 \mu\text{m/yr}$ while operating. However, hot trap operation is not expected to be continuous.

II. INTRODUCTION

The Experimental Lithium System (ELS) was designed and constructed at the Hanford Engineering Development Laboratory (HEDL) as a full-scale mockup of the Fusion Materials Irradiation Test (FMIT) Facility.⁽¹⁾ The FMIT is being developed to produce a fusion reactor-like environment of high-energy neutrons. FMIT will be used to irradiate potential fusion reactor materials and components to assess damage effects from the high-flux, 14-MeV neutrons generated in a deuterium-tritium fusion reaction. The intense neutron source will be produced through a stripping reaction of an impinging beam of 35-MeV deuterons on a 1.9-cm thick, flowing jet of molten lithium (target). The resulting neutron flux will produce damage in kind and rates typical of fusion reactor first wall projections.

Liquid lithium was selected as the target material and primary coolant for the FMIT. Lithium is ideally suited as a target material because of the high rate of neutrons produced when deuterons from the FMIT accelerator undergo a stripping reaction with the lithium. The high-heat capacity and low-vapor pressure of lithium are also advantageous properties for the primary coolant. This application requires a vacuum/lithium interface, but no experience with operating large lithium systems under vacuum has been previously reported.

New technology required to support FMIT design included a radio frequency quadrupole linear accelerator being developed at Los Alamos National Laboratory (LANL),⁽²⁾ a large lithium system capable of vacuum operation, and a target with a free surface jet of lithium.

The purpose of ELS was to develop and test critical components for FMIT and to give operators experience and confidence in safely operating a large lithium system. Critical components tested in this isothermal, nonradioactive, force-convection loop included a lithium free surface jet generating target, EM pumps, valves, instrumentation, and sampling and purification components. The engineering design and development required to safely operate

this 3.8-m³ capacity lithium test loop under high vacuum (10^{-3} Pa) at temperatures to 270°C and flow rates to 0.041m³/s included evaluation of vacuum pumping systems, vacuum sensors, air inleakage sensors, and a vacuum-break system. The early operation of the ELS has been reported.^(3,4) This document provides brief descriptions of ELS design and summarizes the results of the entire testing program.

III. ELS FACILITY DESCRIPTION

A. BUILDING AND STRUCTURAL

The ELS is located in work areas EDL-101, EDL-108, and an adjoining annex to the 324 Building (324C), as shown in Figure 1. The west half of EDL-101 and the 324C annex adjacent to EDL-101 contain the lithium tanks and piping. The east half of EDL-101 houses Source Term Control Loops (STCLs). Computers and operating controls are situated in the adjoining EDL-108 (see Figure 1).

High-bay work area EDL-101 (28 ft x 60 ft x 33 ft) exits to the outside through a 10 ft x 14 ft vertically sliding door with a conventional door built into it, and to an adjoining laboratory to the north through a similar door. A conventional door also allows access to work area EDL-108 and the east hall. A 4-ton overhead crane and hoist are located in the room. Storage is provided for one rollaway cabinet for tools and six cabinets for small replacement parts and monitoring equipment. Shipping and receiving areas are located elsewhere.

The adjoining pit (12 ft x 15 ft x 20 ft) is covered by a 16 ft x 18 ft x 10 ft enclosure, connected to EDL-101 by a personnel corridor. This adjoining room (Annex 324C) has an emergency exit door. Interconnecting piping between EDL-101 and the pit area is also enclosed.

The ELS lithium components are contained in two separate modules. The dump tank, main EM pump, throttle valve, drain valve and flowmeter are contained in the pit module. The pit module is 11.75 ft x 14.75 ft x 19.83 ft deep. The main surge tank and entire chemistry loop are contained in the EDL-101 module, which is 10 ft x 22.75 ft x 19 ft high. Both modules are covered with 11-gauge carbon steel sides and 0.19-in. carbon steel tops and bottoms. The bottom 12-in. of both modules are seal-welded catch pans with perforated, 11-gauge, carbon steel coverplates. The ELS target is contained in a 6 ft x 13 ft x 10 ft high penthouse located above the EDL-101 module.

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FIGURE 1. Graphic Isometric of ELS Facility Arrangement. Neg 8204197-1

This target penthouse has a 7-in. deep catch pan with a perforated, 11-gauge, carbon steel coverplate and a 2.5-in. retaining lip.

The controls for the ELS and STCLs are housed in EDL-108 (15 ft x 27 ft x 7 ft high) with access to EDL-101 and the 324 Building main corridor.

B. PIPED UTILITIES

Gaseous argon is available from two systems. Argon is piped from a two-bottle 440-ft³ capacity rack or from a 1300-gal liquid argon tank and evaporator system west of the 324 Building. The evaporator is sized for a 144-ft³, 35-psi maximum delivery. A 90-psig building air supply is also available in EDL-101. The control room (EDL-108) has an overhead wet sprinkler system for fire protection.

C. ELECTRICAL SERVICE

Special services include electrical power for loop operation, emergency battery power for fire alarm circuitry, and three battery-powered floodlight units. The main exhaust blower is also on the emergency power bus.

Electrical power distribution is divided among five mechanical and heater distribution panels. The ELS mechanical system has 225-A maximum power at 480 V, 3 ϕ , while the ELS heater system has 325-A maximum power at 120/208 V. Spare circuits available for ELS testing are:

<u>Panel</u>	<u>Voltage (V)</u>	<u>Phase (ϕ)</u>	<u>Spares</u>
DPNL-1	208	3	None
DPNL-2	480	3	1
DPNL-3	120/240	1	20
DPNL-4	120/240	1	None
DPNL-5	120/240	1, 3	15

D. FIRE PROTECTION

EDL-101 is equipped with smoke detectors plus large and small liquid metal fire extinguishers (carbon microspheres), but not sprinklers. To insure safety, no flammable cleaning agents are used or stored in EDL-101.

A heat-activated sprinkler system and smoke detectors below the false floor and at ceiling level provide EDL-108 fire protection. ELS module and pit area fire control features include smoke detectors, catch pans and localized argon inerting devices. A large supply of carbon microspheres is also on hand.

Two ionization smoke detectors on the ceiling of the dump tank pit module, two on the ceiling of the EDL-101 module, two in the target area enclosure, one in the ventilation exhaust ducting, two on the ceiling of 324C, two on the ceiling of the 324C hallway, two on the ceiling of the expansion room, and six on the ceiling of EDL-101 are all interlocked with an exhaust diverter valve, preventing smoke from venting into the normal exhaust system. On cue from a smoke detector, the diverter valve changes flow from normal ventilation exhaust to a venturi scrubber system, dump valves open, and the lithium system empties into the dump tank. In addition, EDL-108 has two smoke heads on the ceiling and three under the false floor. However, these detectors are not interlocked with ELS operations.

Mild steel catch pans lie within the EDL-101 module, the pit module, and the target penthouse. Perforated covers allow leaking lithium to drain into the pans, providing containment and limiting air available for reaction. Argon can be manually introduced into the pans if a fire is detected. A 304 SS catch pan is also provided under the transfer piping between the pit and EDL-101 module.

Alarm systems in EDL-101 and EDL-108 alert the 300 Area Hanford Fire Department, 325 Building power operators, and 324 Building personnel. These systems ensure the prompt action necessary for protection of personnel and property.

E. VENTILATION

Room EDL-101 has special ventilation independent of the 324 Building's system. Room exhaust is swept through the STCLs and ELS. During normal operation, exhaust from EDL-101 and the pit area is forced through the loop enclosures. STCL normal exhaust passes through two banks of high-efficiency particulate air (HEPA) filters before discharge from a 40-ft stack. ELS normal exhaust passes through three banks of HEPA filters before discharge to the atmosphere. Emergency conditions (smoke detector trip in any loop enclosure or in Room EDL-101) cause automatic diversion of exhaust flow via a three-way valve through a venturi air scrubber, moisture separator and two banks of HEPA filters. Exhaust then occurs from a 40-ft stack. Ventilation system flow is controlled by motor-operated butterfly valves on the inlet and exhaust.

F. ENGINEERED SAFETY FEATURES

Engineered safeguards and procedural controls used in EDL-101 and EDL-108 include built-in safety alarm circuitry for STCLs and ELS and a separate alarm system, independent of the computer, connected to a 24-hour call-in service in the 325 Building power operator station. Three conditions activate the alarm system:

- Condition I: Visual and audible annunciation in any of more than 200 computer channels occurs when deviation from normal operating conditions is noted.
- Condition II: Extreme deviation in any of more than 200 computer channels causes the ELS to assume a hold condition (deenergizing selected electrical components including vacuum and lithium pumps, heaters, blowers and breaks the vacuum).
- Condition III: Smoke detectors trip safety alarm circuitry. The effect of the Condition III is the same as the Condition II plus the system dumps. It diverts the exhaust system to the emergency scrubber train. The safety system circuitry is independent of the computer.

Safety systems are comprised of surge and dump tank level detectors, temperature detectors, smoke detectors, catch pans, an emergency ventilation system, liquid metal fire extinguishers and argon inerting devices. A water sump pump on the pit floor draws from the annulus between the concrete and steel pit module linings through a hole in the steel liner. Inspection is visual, with portable oxygen monitors provided for the pit and main loop modules to preclude accidental oxygen deficiency.

IV. EXPERIMENTAL LITHIUM SYSTEM DESCRIPTION

The ELS is designed to test lithium targets hydrodynamically for the Fusion Materials Irradiation Test (FMIT) Project using flowing lithium. The design also provides for testing of lithium purification and impurity characterization components and for development of a large EM pump and liquid lithium valves for FMIT. The ELS lithium inventory is about 3.8 m³ (1000 gallons). The ELS is designed to operate with the lithium free surfaces at vacuum or inerted with high-purity argon. The ELS typically operates at 270°C (520°F) (maximum design temperature, 800°F) with pressures varying from complete vacuum to 5 psig. System operation is controlled by a computer in Room 108.

A. LITHIUM SYSTEM

The lithium system has a main piping loop and a smaller chemistry piping loop that can be isolated from the main loop for independent testing. Both loops can also be operated in common. Both loops feature isothermal, forced circulation of the lithium, with independent pumping capabilities. The lithium system ELS design parameters are summarized in Table 1. An isometric view of the lithium piping is shown in Figure 2.

TABLE 1
SUMMARY OF ELS LITHIUM SYSTEM DESIGN PARAMETERS

<u>Component</u>	<u>Flow (gpm)</u>	<u>Temp (°F)</u>	<u>Pressure (psig)</u>	<u>Volume (gal)</u>
Dump Tank	---	800	50	1700
Main Surge Tank	600	800	50	500
Main Pump	600	800	150	Negligible
Chemistry Loop Pump	40	1000	50	Negligible
Main Loop Piping	600	800	50	210
Cold Trap	3	800	50	33
Hot Trap	3	1050	50	33
Chemistry Piping Loop	10	800	50	2.7
Chemistry Surge Tank	10	800	50	100

FIGURE 2. Experimental Lithium System. Neg 8202904-1

Commercially available components and hardware were used, wherever possible, during the design and construction of ELS. However, some of these items were not commercially available for the designs selected. All ELS piping systems were designed by Westinghouse Hanford Company (WHC). The lithium system was packaged in two large modules. These modules were fabricated by Wilkens & Associates of Tacoma, WA. The following lithium components were designed and fabricated by WHC and then were installed in the modules by Wilkens: main lithium pump, cold trap, plugging temperature indicator, and samplers. (Wilkens also fabricated all the piping within the modules.) The main surge and dump tanks were designed and fabricated by J. A. Jones Construction Co., Richland, WA, and were then installed in the modules by Wilkens. J. A. Jones installed the two modules and interconnecting piping in the 324 Building. A hot trap, impurity addition system, on-line resistivity meter, and valve test manifold were all designed and fabricated by WHC. These items were installed after startup, as modifications to ELS.

1. Main Loop

The main loop includes an Annular Linear Induction Pump (ALIP), throttle valve, EM flowmeter, target, surge tank, air dump heat exchanger, and dump tank. The main lithium loop is constructed of 4-in. and 6-in. Schedule 40, 304 SS pipe. Lithium travels from the main pump to the target test stand through 4-in. pipe, but the return line from the target to the surge tank and pump inlet is 6-in. pipe. All lithium piping is heat-traced and insulated. The main loop has a 4-in. EM flowmeter on the discharge side of the main pump. The main loop has two 3-in., all-welded, bellows-sealed, sliding gate valves; one used as a drain valve to isolate the loop from the dump tank and the other used to throttle loop flow (Figure 2).

2. Chemistry Loop

The chemistry loop is a 1-in. Schedule 40, 304 SS circulation loop with a cold trap, a hot trap, and a Plugging Temperature Indicator (PTI)/Flow-Through Tube Sampler (FTTS) connected in parallel. The chemistry loop

includes a 1-in. EM pump, EM flowmeters, and a 100-gal surge tank with provisions for impurity addition and for thief sampling of the lithium.

B. ARGON AND VACUUM AUXILIARY SYSTEMS

The auxiliary systems at ELS include an argon system and a vacuum system. These are shown schematically in Figure 3. The lithium system normally operates in a vacuum because of the required vacuum interface with the deuteron accelerator. Operation in a vacuum also prevents a large gas load from entering the target beam tube, which normally operates at 10^{-4} to 10^{-5} kPa.

1. Argon System

The argon system consists of the following five subsystems:

- Liquid Argon Supply
- Argon Delivery or Makeup
- Argon Fire Suppression
- Argon Vacuum Break
- Argon Feed and Bleed

Figure 3 is a simplified schematic and does not show the Argon Fire Suppression Subsystem, the Argon Feed and Bleed Subsystem, or the Chemistry Loop. Design and operating criteria for these subsystems are presented in Table 2.

The liquid argon supply subsystem is vendor-leased equipment and consists of a liquid argon Dewar and vaporizer. The argon delivery or makeup subsystem routes the gaseous argon from the vaporizer to the various ELS pressure boundary functions, as required, and provides pressure regulation and pressure relief. The argon fire suppression subsystem provides additional pressure regulation and supplies argon to each of three covered catch pans. The argon vacuum break subsystem consists of an argon holding reservoir (cover gas space of the lithium dump tank) and 10.2-cm (4-in.) and 2.5-cm (1-in.) pressure equalization lines routed to the evacuated lithium

NEDL 0404-010

FIGURE 3. Simplified Schematic of ELS Argon and Vacuum Auxiliary Systems.

TABLE 2
ARGON SYSTEM DESIGN AND OPERATING CRITERIA

Criteria	Limit
<u>Liquid Argon Supply</u>	
Dewar Liquid Argon Capacity	150 in. (14,680 lb)
Equivalent Argon Gas Capacity at STP	142,000 ft ³
Dewar Relief Pressure	65 psig
Vaporizer Gaseous Argon Flow Capacity	144 ft ³ /min at 70°F
Gas Delivery Pressure	35 psig
Operating Temperature Range of Gas	~0 to ~110°F
Liquid Argon Reorder Alarm Level - Condition I Alarm*	50 in. (4,570 lb)
Equivalent Argon Gas Capacity at STP	44,200 ft ³
Minimum Operating Liquid Argon Level - Condition II Alarm**	35 in. (3,050 lb)
Equivalent Argon Gas Capacity at STP	29,500 ft ³
<u>Argon Delivery or Makeup</u>	
Design Temperature	150°F
Design Pressure	50 psig
Operating Temperature Range	~65 to ~110°F
Operating Pressure Range	0 to 13 psig
Gas Delivery Pressure	13 psig
Relief Pressure	14 psig
<u>Argon Fire Suppression</u>	
Design Temperature	150°F
Design Pressure	50 psig
Operating Temperature Range	~65 to ~110°F
Operating Pressure Range	0 to 25 psig

*A Condition I Alarm is a visual and audible alarm only.

**A Condition II Alarm is an automatic system shutdown.

TABLE 2 (Cont'd)

Criteria	Limit
<u>Argon Fire Suppression</u> (Cont'd)	
Initial Fire Suppression Delivery Pressure	25 psig
Maintaining Fire Suppression Delivery Pressure	2 psig
Minimum Argon Fire Suppression Flow (Initial)	21 ft ³ /min
Minimum Argon Fire Suppression Flow (Maintenance)	3.5 ft ³ /min
Minimum Argon Fire Suppression Flowtime	20 h
Maximum Allowable Time to Flood Catch Pans	8 min
Maximum Allowable Oxygen Level After Flooding	5%
<u>Argon Vacuum Break</u>	
Design Temperature	250°F
Design Pressure	50 psig*
Operating Temperature Range	~65 to ~110°F
Operating Pressure Range	0 to 13 psig
Minimum Acceptable System Pressure After Vacuum Break	1 psig
Required Emergency Vacuum Break Time	<10 s
Vacuum Break Reservoir Capacity**	173 ft ³
<u>Argon Feed and Bleed</u>	
Design Temperature	150°F
Design Pressure	50 psig*
Operating Temperature Range	~65 to ~110°F
Operating Pressure Range	0.5 to 8 psig
Control Band	±0.5 psig

*This subsystem was originally designed to 50 psig, but the first vacuum isolation valves were only rated for 14.7 psi.

**This gas storage volume does not include the dump tank volume occupied by the nominal 400-gal lithium heel in the tank during normal operation.

free surfaces. The argon pressure control (Feed and Bleed Subsystem) consists of additional pressure regulation, pressure relief, and an argon vent capability.

The argon system includes four separate argon supply paths to the lithium free surfaces. The first argon supply is a 2.5-cm (1-in.) argon delivery or makeup line connected directly from the vaporizer on the liquid argon tank to both the dump and the main surge tanks. The 2.5-cm (1-in.) argon supply also has equalization capabilities and can be used to slowly break vacuum during normal operation. Additional argon is required to break vacuum by equalization when the ELS is drained.

The second argon supply is a 1.3-cm (0.5-in.) argon feed line from the argon makeup supply to each of the lithium tanks for maintaining accurate pressure control. Corresponding regulated bleed lines allow controlled venting of each tank. The feed lines to both of the surge tanks have a hand-operated pneumatic regulator assembly (which also includes a pressure gauge and a manual block valve), a check valve, and double-pneumatic block valving (i.e., a vacuum-quality pneumatic block valve in series with a bellows-sealed pneumatic block valve). The dump tank has the same feed line design except that there is only one pneumatic block valve (i.e., a vacuum-quality valve). Bleed lines have the same double pneumatic block valving with a diaphragm-operated pneumatic throttle valve.

The third argon supply is a large standby argon reservoir (argon vacuum break) for rapid flooding of the vacuum system via a 10.2-cm (4-in.) equalization line, should air leak in during vacuum operation. The gas space of the ELS dump tank is used for this reservoir, and the equalization line connects the dump and the main surge tanks. When the ELS piping has been filled with lithium to operating level, the dump tank holds enough argon at a gauge pressure of 48 kPa (7 psig) to break the vacuum and pressurize the entire system to a gauge pressure of ~7 kPa (1 psig). When the ELS is drained and the dump tank is pressurized to a maximum allowable gauge pressure of 90 kPa (13 psig), makeup argon is required to reach a gauge pressure of ~7 kPa (1 psig) throughout the system.

The fourth argon supply is a 1.3-cm (0.5-in.) argon delivery line connected directly from the 2.5-cm (1-in.) argon line, just downstream of the vaporizer, to the main vacuum header. This line was installed as a temporary measure after the valve (POV-30) in the 2.5-cm (1-in.) argon line became nonoperational. During the last months of ELS operation, this line was used for all scheduled vacuum breaks because the flow blockage in the POV-30 line was not repaired.

The argon system also includes argon supply lines to each of three lithium catch pans for fire suppression, should an external lithium leak occur. These catch pans are covered with perforated steel plates. The argon, which is heavier than air, enters the pans below the cover and rapidly floods this space. The two larger catch pans (in the pit and Room 101 modules) are supplied with a 2.5-cm (1-in.) line, while the target penthouse is supplied with a 1.3-cm (0.5-in.) line. Flow to each of these lines is controlled by a common regulator. The argon shutoff valves to each of these lithium catch pans are pinned closed and must be manually opened to minimize the potential for accidental asphyxiation.

2. Vacuum System

The ELS vacuum system is designed to allow evacuation from two different locations. A main vacuum header (see Figure 4) is located on the 12-ft level of the EDL-101 module. Vacuum piping enables evacuation of the main surge tank, target, chemistry surge tank, and dump tank free surfaces with this single pumping package.

The main vacuum header includes a dual-stage mechanical roughing fore pump, Roots blower, traps, valves, pressure sensors, viewport, gas sampling apparatus, Residual Gas Analyzer (RGA), and Residual Nitrogen Analyzer (RNA). The RNA is a dual-function sensor to measure pressure and nitrogen partial-pressure levels. This dual-function sensor is used to detect and alarm air in-leakage in the ELS. The RGA, which can measure all impurities, was added to the chemistry surge tank vacuum system. This on-line quadrupole analyzer

FIGURE 4. ELS Main Vacuum Header. Neg 8104495-2cn

is also used to detect air in-leakage. The RGA and RNA both have additional vacuum pumping capabilities. More information on each of these pumps is provided in Table 3. The traps were installed to limit back-streaming.

At the second evacuation point, a cryopump is located on the target simulated beam tube for pulling a high-vacuum directly on the ELS target jet free surface. The cryopump was installed with provisions to permit regeneration. The ELS vacuum system was fabricated with stainless steel, whenever possible. Design and operating criteria for the vacuum system are presented in Table 4.

TABLE 3
VACUUM PUMPS USED ON ELS

<u>Pump Type</u>	<u>Manufacturer</u>	<u>Model No.</u>	<u>Free-Air Displacement (ℓ/s)</u>	<u>Location</u>
<u>Mechanical</u>				
Piston Pump	Leybold-Heraeus	Dk-45	50	Main Vacuum Header
Piston Pump	Welch	1405 H	0.6	Residual Nitrogen Analyzer
Piston Pump	Leybold-Heraeus	D2A	1.04	Residual Gas Analyzer
Piston Pump	Varian	EVAC-200	3.3	Residual Gas Analyzer
Roots Blower	Leybold-Heraeus	WS-400	104	Main Vacuum Header
Turbomolecular	Leybold-Heraeus	Turbovac 150	145 150*	Residual Gas Analyzer
<u>Cryopump</u>	CTI-Cryogenics	Cryo-Torr 7**	1000 850*	Target
<u>Diffusion</u>	Varian	HSA	60	Residual Nitrogen Analyzer

*Displacement with argon.

**This pump has a standard 350-liter capacity for argon.

TABLE 4
VACUUM SYSTEM DESIGN AND OPERATING CRITERIA

Criteria	Limit
Vacuum System Design Temperature	250°F
Vacuum System Design Pressure	Vac to 14.7 psig*
Operating Temperature Range	~65 to ~110°F
Operating Pressure Range	0.5 psig to 10^{-7} torr
Nitrogen Partial Pressure Shutdown Level	10%
Design Pressure Range for Main Surge Tank	50 psig to 10^{-3} torr
Design Pressure Range for Target	50 psig to 10^{-3} torr**
Maximum Allowable Time to Pump Down System to 10^{-3} torr	60 min
Maximum Allowable Additional Time to Pump Down System to 10^{-6} torr	3 h

*Limited by valve design pressure.

**The required vacuum level was later revised to 10^{-6} torr.

C. TARGETS AND SUPPORTING TEST HARDWARE

Two target assemblies were fabricated and tested on the ELS. The first target (Mark I) used a nozzle with a symmetrical design; while the second target (Mark II) used a nozzle that was asymmetrical. The purpose of the target at FMIT will be to generate a high-velocity lithium jet that will intercept a beam of 35-MeV deuterons to generate high-energy neutrons for irradiation testing of fusion reactor materials. The principle of operation for FMIT can be seen in Figure 5. Both the Mark I and Mark II target designs were tested in water prior to lithium testing.

FIGURE 5. FMIT Principle of Operation: Provide a Fusion-Like High-Energy Environment for Irradiation Testing of Materials and Components in Development of Fusion Power Systems by the Interaction of a High-Powered Beam of Deuterons with a High-Velocity Jet of Flowing Liquid Lithium. Neg. 820539-2cn

1. Mark I Target

The ELS Mark I symmetrical target is shown in Figure 6. The target assembly mates to the ELS loop with metal seal mechanical connectors. Both inlet and outlet connectors have 100-mm (3.9-in.) diameter inner and 150-mm (5.9-in.) outer stainless steel seal rings with a flow-through gas space between seals. Lithium flow enters the inverted U-tube assembly and passes through the flow straightener [a series of four 4-mm (0.16-in.) thick stainless steel plates with a lattice of offset holes that smooth the skewed velocity profile introduced by the bend]. Flow then passes into a symmetrical nozzle that shapes the lithium into a high-speed (17 m/s) rectangular, free-wall jet, 100 mm wide x 20 mm thick. The 100-mm wide x 40-mm high region of the jet directly below the nozzle exit is the target area where, in FMIT, the deuteron beam would deposit 3.5 MW of power.

2. Mark II Target

The Mark II target is a hydraulic prototype of the FMIT asymmetric target assembly. It includes all critical hydraulic surfaces to shape the lithium jet and control its path through and beyond the region of interaction with the deuteron beam. It also includes other features, such as mechanical connectors, similar to those planned for use in FMIT. This device incorporates several improvements over the original design, including a revised configuration that provides improved access to the high-flux neutron test volume, reduced jet thickness for increased irradiation test volume, an extended drain region to smoothly transport the heated jet into a mixing or "quench" tank, and improved lithium connectors.

As depicted in Figure 7, the Mark II target assembly is shaped like an inverted 'U'. It is constructed of 300 series stainless steel consisting of 10-cm (4-in.) diameter pipe, rectangular sections, and precisely machined hydraulic surfaces. In FMIT the target will be installed inside a heavily shielded test cell where the material specimens will be irradiated. Mechanical connections are provided to allow periodic remote replacement of the assembly. Replacement is necessary due to the substantial radiation damage that will occur in the structure.

FIGURE 6. FMIT Lithium Target -- First Generation Design (Mark I).

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FIGURE 7. FMIT Lithium Target -- Second Generation Design (Mark II).
Neg 8308374-1cn

Lithium enters the assembly through a 10-cm (4-in.) inside diameter mechanical connector that is identical to one of the dual tapered seal connectors used on the first target (Mark I) tested with lithium. This connector is followed by a second 10-cm mechanical connector featuring a tapered, highload primary seal and a coated metal C-ring backup seal. A flow straightener section, consisting of an egg crate section followed by several plates perforated with progressively smaller holes, uniformly distributes the lithium flow into the nozzle. The nozzle develops the high-velocity (17 m/s), precisely shaped (average 1.9-cm thick by 10-cm wide) rectangular lithium jet that is the "target" for the deuteron beam. Earlier nozzle designs were symmetrical about their centerline along the direction of flow. That design resulted in a bulge that protruded directly above the high flux test volume and restricted access to this region. The prototype target (Mark II) nozzle is asymmetrically shaped. This design eliminates the bulge, allowing easy vertical access to the high flux test volume.

The lithium jet travels in a three-sided rectangular trough along a 25-cm (10-in.) radius curved wall. The jet free surface (concave side) is exposed to the accelerator vacuum. In FMIT the deuteron beam will deposit its 3.5 MW of energy in this region in a volume ~ 8 cm wide by 3 cm high by 1.6 cm thick. (No beam was used in the tests described here.) Most of the beam energy will be deposited ~ 1.5 cm into the depth of the jet because of the penetration of the high energy deuterons into the lithium. The curved wall centrifugally accelerates the lithium, building a pressure field within the jet sufficient to prevent superheating and, therefore, boiling of the lithium in the high vacuum environment of the accelerator.

3. Target Test Fixture and Rotating Window Assembly

A bolted flange welded to the face of the ELS Mark I and Mark II targets simulates the FMIT beam tube attachment and supports a test fixture with vacuum, lighting, instrumentation, and viewports (see Figure 8). The vacuum port interfaces with the ELS vacuum system. The light port supports a double sapphire window assembly behind which any variety of lamps can be mounted to

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FIGURE 8. Mark I Target with Test Fixture.

illuminate the jet free surface. Redundant windows separated by a monitored gas space are utilized for safe operation. The target pressure instrumentation (ion gauge, Pirani gauge, and positive pressure transducer) is supported on spoolpieces mounted to the instrumentation port.

For visual observations of jet performance, a 100-mm (4-in.) diameter vacuum valve is mounted to the test fixture, and a rotating window assembly (RWA) is mounted on the opposite side of the valve. The RWA (see Figure 9) can support a variety of cameras including closed-circuit television (CCTV), high-speed motion picture, and medium or small-format single-lens reflex cameras. The RWA incorporates a gear assembly with three 76-mm (3-in.) diameter sapphire viewports that can rotate into the line of sight to provide extended frost-free and splash-free viewing during testing. The sapphire ports are mounted in the gear using stainless steel O-rings. The O-rings provide a physical barrier to prevent lithium contact with rotating parts and instrumentation seals. Another set of redundant sapphire ports is situated in the line of sight between the camera and the jet free surface. These sapphire view ports form the pressure boundary of the target assembly.

To characterize the jet thickness and surface roughness, the RWA and vacuum valve are removed, and a conductivity probe assembly is mounted directly to the target test fixture. The sapphire window assembly is removed from the light port and an electrical feedthrough for probe operation is mounted in its place. Infrared imaging of the target free surface was also performed. The viewing system is shown mounted on the target in Figure 10.

D. SIMULATED ACCELERATOR BEAM TUBE

A schematic of the apparatus for collecting liquid metal deposition samples in ELS is shown in Figure 11. A 5-m (16.5-ft) long mock beam tube was attached to the ELS Mark II target at the beam tube flange. A 4.3-m (14-ft) long inner tube was inserted inside the outer tube. The inner tube was the same [12-cm (4.75-in.)] diameter as the FMIT beam tube. A foil liner to the

FIGURE 9. Rotating Window Assembly for Target Testing. Neg 8207526-10cn

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FIGURE 10. Viewing System with High-Speed Motion Picture Camera.
Neg 8308373-1cn

HEDL 8407-231.25

FIGURE 11. Schematic Diagram of Simulated Accelerator Beam Tube.

inside of the inner tube was used as the deposition surface. The 0.15-mm (0.006-in.) thick foil could be easily removed and cut to produce separate deposition samples.

The inner tube was heated using tubular resistance heaters to produce the desired temperature distribution along the beam tube length. Bearings on the outside of the inner tube allowed the tube to be pushed toward the target jet or retracted to behind a splash valve and a vacuum valve in the outer beam tube. The valves protected the test assembly from loop transients and permitted disassembly of the evaporation test apparatus without loop cooldown. A bellows in the outer beam tube prevented dead weight loading of the target from the mock beam tube. The outer beam tube was insulated to prevent heat loss from the apparatus. A cryopump was located at the end of the beam tube approximately 5.2 m from the target, which is 0.9 m farther away from the target than where the FMIT vacuum pump will be located. A photograph of the assembly on ELS is shown in Figure 12.

E. EM PUMPS

1. Main Loop Pump

The main loop pump (Figure 13) is an electromagnetic, annular, linear-induction-type suitable for moderate temperature operation. The pump consists of a pump duct, flux return inside the pump duct, stator assembly, outside case, temperature sensors, and power factor correction equipment. The pump power was computer controlled, and a computerized data acquisition system was used for data collection.

The cross-sectional flow area in the ALIP design is a circular annulus and can be made from standard tubing or piping, which adds to ease of fabrication and duct strength. The ALIP is the lightest in weight of the induction pump family and has the simplest duct. On an efficiency per pound basis, the ALIP is slightly more efficient than all other polyphase types.

FIGURE 12. Photograph of Simulated Beam Tube and Cryopump Installation. Neg W408196-1

FIGURE 13. Main Loop Pump. Neg 7913221-2

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In all EM pumps, a body force is produced on a conducting fluid by the interaction of an electric current, and the resulting magnetic field in the fluid reacts with the magnetic field of the stator. The body force results in a pressure rise in the fluid as it passes from the inlet to the outlet of the EM pump and is analogous to the familiar "motor" principle of force on a current-carrying conductor in a magnetic field.

The basic ALIP concept is illustrated in Figure 14 and operates similarly to a polyphase-induction motor. The pump contains an EM stator subassembly and an annular duct subassembly. When power is applied to the 3-phase stator winding, a traveling wave is produced in the liquid metal annulus by the magnetic field from the stator. This magnetic field induces voltage in the conducting fluid contained in the duct. As a result of this induced voltage (Lenz's Law), currents will flow in the fluid. These currents interact with the magnetic field of the stator to produce a body force on the fluid, which causes it to move through the annular duct, thereby developing pressure. The pressure gradient at any point in the fluid is proportional to the product of magnetic field strength and the component of current density perpendicular to the magnetic field strength. The total pressure rise developed by the pump is the integral of this pressure gradient over the axial length of flow passages in the pump duct.

No external heating or auxiliary cooling systems are required for the pump. Outer case natural convection, radiation in air, and heat transfer to the pumped liquid provide cooling throughout the operating envelope. The inlet and outlet nozzles are butt-welded to 6-in. Schedule 40 pipe. Mounted horizontally, the pump weighs 1130 lb, is 60 in. long, and is 16 in. in diameter.

Overpressure protection of the pump duct was unnecessary because the pump cannot develop pressures in excess of the design pressure (150 psig). Pump over-temperature protection and electrical coil conductor insulation suitable for 1000°F operation are provided.

FIGURE 14. Basic Annular Linear Induction Pump Concept.

All pump electrical power requirements are satisfied by a three-phase, 480-V ($\pm 5\%$) power source with a normal frequency of 60 Hz. The controls can operate with a line frequency variation of $\pm 5\%$ from 60 Hz. The pump has remotely controlled stepless output over the liquid metal flow range. Protective devices:

- Prevent overload on loss of a single phase of the multiphase pump, or any other overload.
- Shut down the pump at high stator winding temperature.
- Shut down the pump at high pump duct temperature.

A panel is provided for pump power control and instrumentation. Ungrounded thermocouples are mounted on the duct, case, coils and laminations.

Pump performance requirements are given in Table 5 and the calculated performance envelope is shown in Figure 15.

2. Chemistry Loop Pump

The chemistry loop is an MSA Style V a-c electromagnetic pump. The electromagnetic pump operates on the principle of the "left-hand rule." This describes the direction of a force produced on a conductor by a current and a magnetic flux. In a conduction-type electromagnetic pump, the liquid metal is a conductor of electricity. When current passes through the pumping section perpendicular to the magnetic field, a force is produced in the liquid metal within the pumping section that is at right angles to the current and magnetic field.

A schematic diagram of the pump is shown in Figure 16. Two current transformers connected additively supply the current in the secondary conductor (bus bars). The current flows through the pumping section wall to the liquid metal and out the other wall. This forms a continuous current path across one flattened portion of the pumping section and a return through

TABLE 5
PERFORMANCE REQUIREMENTS FOR MAIN LOOP PUMP

Item	Parameter	Data
1	Design Flow Rate	600 gpm (See Figure 15)
2	Pressure Delivered at Design Flow Rate	33 psi (see Figure 15)
3	Minimum Cutoff Pressure	59 psi
4	Operating Temperature (Lithium at Pump Inlet)	400°F to 800°F
5	Duct Design Pressure	150 psig
6	Duct Design Temperature	800°F
7	Power Consumption	40 kW (max), 480 V, 60 Hz
8	Pump Cooling	Natural convection and radiation in air, or heat transfer to the pumped liquid
9	Service Life	50,000 h (or 20 yr)
10	Type of Service	Continuous
11	Minimum Acceptable Efficiency at 600 gpm	20%
12	Maximum Velocity of Lithium Through Pump Duct	40 ft/s

the other flattened portion. The bus bars are attached to the pumping section using high-temperature microbrazing compound in a dry hydrogen atmosphere.

The flux in the pumping sections is produced by coils on each leg of two U-shaped laminated magnetic iron cores. The cores are positioned so that the two flattened portions of the pumping section are in the air gaps.

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FIGURE 15. Calculated Performance Envelope for ELS Annular Linear Induction Pump.

FIGURE 16. Schematic Diagram of a Two-Stage a-c Electromagnetic Conduction Pump.

The pump duct is a 0.91-m (36-in.) long section of 25.4-mm (1-in.) OD 316 SS tube with a wall thickness of 0.049 in. In the actual pumping section this duct tube is deformed to produce a roughly rectangular shape. The region of the duct between the opposing bus bar brazed joints has been further flattened to make this area as flat as possible. The magnet pole pieces rest against these flat areas. Typical performance curves for this Style V pump are shown in Figure 17. The curves shown are for NaK, the only fluid for which data are available, but the curves would not be greatly different for lithium.

F. PURIFICATION HARDWARE

The lithium purification hardware removes impurities (primarily hydrogen, nitrogen, and oxygen) from lithium and maintains their concentrations at or below their saturation levels at 400°F. A forced-convection, in-line cold trap and a titanium-foil-filled, in-line hot trap have been proposed

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FIGURE 17. Performance Curves for MSA Style V Pump.

for implementation on the Fusion Materials Irradiation Test (FMIT) Facility. Prototypes of each of these traps were fabricated and permanently installed on the Experimental Lithium System (ELS). Trap tests were deemed necessary because of a lack of data on hydrogen and nitrogen removal rates by in-line trapping of lithium systems operated at FMIT temperature conditions. In addition, in-line lithium trapping has been plagued by short trap life.⁽⁵⁻⁷⁾

1. Cold Trap

The FMIT cold trap is an in-line design featuring a single 38.1-cm (14-in.) diameter tank with built-in economizer and crystallizer sections. Figure 18 shows a cutaway view of this trap design. The physical characteristics of the trap are given in Table 6. The coiled economizer tube has lithium crossflow on the shell side. The crystallizer section is filled with woven stainless steel wire mesh packing. The cold trap is forced-air-cooled. The design and operating criteria for the cold trap are presented in Table 7.

The air cooling system includes a direct-drive centrifugal blower, a 15.2-cm (6-in.) pressure-operated butterfly valve and an in-line resistance-type duct heater (10,000 W) connected with 6-in. ducting. The remainder of the air cooling system consists of a 500 ft³/min blower and a variable-speed controller.

The cold trap is electrically trace-heated and insulated with three 1-in. layers of flexible-blanket, refractory-fiber insulation around both the economizer and the crystallizer cooling shroud. The cold trap trace heat system is divided into two zones. One zone is provided for the economizer and one for the crystallizer. The economizer zone is composed of seven band heaters (7000 W total), while the crystallizer has four U-bend heaters (2300 W total).

2. Hot Trap

The FMIT hot trap is an in-line design featuring an economizer, pre-heater, getter tank, and filter in a series arrangement. Figure 19 shows a cutaway view of this trap design. The physical characteristics of the trap are given in Table 8. The 16-in. diameter getter tank is filled with two vertically stacked rolls of 0.005-in. thick x 17-in. wide titanium foil. Rolls are fabricated with alternate rows of corrugated and flat titanium sheet. The top and bottom of the getter section are covered with screens

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FIGURE 18. Cold Trap - Cutaway View.

TABLE 6
COLD TRAP ASSEMBLY PHYSICAL CHARACTERISTICS

ECONOMIZER (Tube in Shell)

Tube OD (in.)	1.315
Tube Wall (in.)	0.133
No. of Coils	13.66
Helical Coil Diameter (in.)	11.70
Pitch (in.)	1.7
Shell Active Height (in.)	22.12
Shell ID (in.)	13.25
Shell Wall Thickness (in.)	0.375
Flow Director Can OD (in.)	10.06
Flow Director Can Thickness (in.)	0.25

CRYSTALLIZER

Flow Separator Mean Diameter (in.)	9.0
Flow Separator Thickness (in.)	0.25
Shell ID (in.)	13.25
Shell Wall Thickness (in.)	0.375
Active Height (in.)	27.0
Active Volume (gal)	15.0
304 Stainless Steel Mesh Density (lb/ft ³)	26.0

COOLING SHROUD

Shroud OD (in.)	14.87
Shroud ID (in.)	14.75
Air Gap (in.)	0.375
Active Height (in.)	38.0

TABLE 7
COLD TRAP DESIGN AND OPERATING CRITERIA

Design Temperature for Lithium Side (°F)	800
Lithium Inlet Temperature Operating Range (°F)	393 to 752
Nominal Lithium Inlet Temperature (°F)	518
Design Pressure for Lithium Side (psig)	Vacuum to 50
Operating Pressure Range for Lithium Side (torr/psig)	$10^{-7}/20$
Lithium Design Flow (gpm)	3
Lithium Operating Flow Range (gpm)	0 to 3
Total Internal Volume (gal)	~35
Minimum Crystallizer Residence Time (min)	5
Maximum Allowable Cold Trap ΔT (°F)	<u>± 50</u>
Maximum Allowable Cold Trap ΔP - Clean (psi)	5
Maximum Allowable Cold Trap ΔP - End of Life (psi)	20
Trap Life (yr)	20
Predicted LiH Impurity Burden (lb)	13
Minimum Cold Trapping Temperature (°F)	360
Maximum Allowable Cold Trap Temperature Control Band (°F)	<u>± 10</u>
Nominal Air Inlet Temperature (°F)	80
Nominal Air Outlet Temperature (°F)	140
Maximum Air Side ΔP (in. H ₂ O)	6
Required Air Flow at 4.7 in. H ₂ O (ft ³ /min)	500

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FIGURE 19. Hot Trap - Cutaway View.

TABLE 8
HOT TRAP ASSEMBLY PHYSICAL CHARACTERISTICS

ECONOMIZER (Concentric Tube)

Outer Tube OD (in.)	1.315
Outer Tube ID (in.)	1.049
Inner Tube OD (in.)	0.625
Inner Tube ID (in.)	0.555
No. of Coils	9.75
Helical Coil Diameter (in.)	24.0
Pitch (in.)	3.0

PREHEATER

Tube OD (in.)	1.315
Tube ID (in.)	1.049
No. of Coils	2
Helical Coil Diameter (in.)	24.0
Pitch (in.)	3.0

GETTER TANK

Tank OD (in.)	16.0
Tank ID (in.)	15.0
Overall Length (in.)	50.0
Active Length (in.)	34.0
Screen Mesh Size	8
Screen Wire Diameter (in.)	0.047
Titanium Foil Thickness (in.)	0.005
Titanium Weight (lb)	112
Titanium Surface Area (ft ²)	930

(No. 8 mesh x 0.047 in. diameter stainless steel wire) and retainer assemblies. The economizer is a concentric tube design. The 25- μ m filter has a flow area of 2.25 ft² and was installed to prevent passage of getter material back into the loop. The design and operating criteria for the hot trap are presented in Table 9.

TABLE 9
HOT TRAP DESIGN AND OPERATING CRITERIA

Design Temperature (°F)	1050
Lithium Inlet Temperature Operating Range (°F)	393 to 752
Nominal Lithium Inlet Temperature (°F)	518
Design Pressure (psig)	Vacuum to 50
Operating Pressure Range (torr/psig)	10 ⁻⁷ /20
Lithium Design Flow (gpm)	3
Lithium Operating Flow Range (gpm)	0 to 3
Total Internal Volume (gal)	~35
Minimum Residence Time (min)	10
Maximum Allowable Trap ΔT (°F)	+50
Trap Life (yr)	20
Predicted Nitrogen Impurity Burden - Formula Weight 14 (lb)	2.3 to 7.9
Nominal Hot Trapping Temperature (°F)	1025
Maximum Allowable Hot Trap Temperature Control Band (°F)	+10
Maximum Allowable Hot Trap ΔP - Clean (psi)	5
Nominal Air Inlet Temperature (°F)	80
Nominal Air Outlet Temperature (°F)	140
Maximum Air Side ΔP (in. H ₂ O)	6
Required Air Flow at 4.7 in. H ₂ O (ft ³ /min)	1500

The hot trap is electrically trace-heated and insulated with six 1-in. layers of flexible blanket, refractory fiber insulation around the entire trap assembly. The hot trap trace heat system is divided into seven zones, excluding inlet, outlet and filter piping. Two zones are provided for the getter tank, one zone for the preheater and four zones for the economizer. The upper getter tank zone is composed of four band heaters (8800 W total at 208 V). The lower getter tank zone has only one band heater (2200 W total at 208 V). The preheater zone includes two tubular resistance heaters (3000 W at 220 V). The upper two zones on the economizer each have a single tubular resistance heater rated at 750 W at 120 V and 650 W at 120 V, respectively. The lower two zones on the economizer each have two tubular resistance heaters rated at 2600 W (total for each zone) at 240 V.

After initial operation of the hot trap, it was apparent that an air-cooler was going to be required on the chemistry loop to dump the excess heat produced by the hot trap when the chemistry loop is isolated from the main loop. A 5-ft long x 6-in. diameter cooling shroud was installed on the hot trap outlet piping. A 920 ft³/min blower (Model PB-14, manufactured by Cincinnati Fan and Ventilator Co., Cincinnati, OH) forced EDL-101 module air through the cooling shroud. This fan was smaller than the 1500 ft³/min blower predicted from heat balance calculations but was used because it was available. Blower speed control provided air flow control.

G. IMPURITY SAMPLING HARDWARE

A flow-through tube lithium sampler, cover gas sampler, and on-line chromatography have been proposed for FMIT to monitor lithium, and argon cover gas chemistry. The flow-through tube lithium sampler provides a means of removing a small bulk lithium sample from the loop for chemical analysis. The gas sample cylinder provides a means of removing a small volume of cover gas from the system for chemical analysis with a laboratory gas chromatograph. Based on these proposals, a prototype of the flow-through tube sampler was fabricated and installed on ELS. In addition, a lithium thief

sampler was fabricated and installed on ELS for the special purpose of impurity addition testing. This impurity information provides data for operation of lithium purification equipment (cold or hot traps) and ensures that lithium purity meets materials corrosion, activity control, and impurity deposition standards.

1. Flow-Through Tube Sampler

Grab samples of lithium were taken with a Flow-Through Tube Sampler (FTTS), a 0.5-in. OD x 0.035-in. wall, 304 SS tube removed periodically for definitive chemical analysis. The FTTS went through several design evolutions on ELS. Both filtered and unfiltered samplers were used for sampling ELS lithium. The unfiltered sampler design is shown schematically in Figure 20 while the filtered sampler design is shown in Figure 21. The lithium sample is taken in a hairpin section of thin-wall stainless steel tubing. The overall length of the sample tube is limited to 18 in., since the sample tube has to be transferred through an airlock into an inert glovebox for chemical analyses. Early ELS samples were taken without filtering. To investigate particulates in the ELS, sintered metallic 10- μ m filters, with $\sim 7 \text{ in}^2$ of filter area, were used satisfactorily in a modified sample tube design.

2. Thief Sampler

The second type of lithium sampler used on ELS was the vacuum thief sampler as shown in Figure 22. A thief sampling concept was used on ELS so that lithium samples could be taken at a faster rate than achievable with the flow-through tube sampler alone. The thief sampler tube consists of a 12-in. section of 0.5-in. OD tubing with a 1/8-in. inlet tube and a 1/8-in. freeze-seal outlet tube. The 0.5-in. tubing section has a 5- μ m sintered filter disc near the inlet end. The thief sampler tube is used in conjunction with a charging mechanism that maintains an inert atmosphere around the sample tube, while the sample is taken and until it is frozen. The lithium is drawn into the sampler tube by the pull of vacuum.

FIGURE 20. Unfiltered Flow-Through Tube Sampler.

HEDL 8503-071.1

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FIGURE 21. Filtered Flow-Through Tube Sampler.

HEDL 8408-146.1

HEDL 8408-214 1

*Swagelok is a registered trademark of Crawford Fitting Co., Solon, OH.

FIGURE 22. Thief Sampler.

3. Gas Sampler

Standard sample cylinders were used to sample the ELS argon cover gas. These cylinders were then transported to the 325 Building laboratory gas chromatograph for analysis. The cylinders were normally pressurized at 3 to 5 psig.

H. VALVES

1. Lithium Valves

Several different types of liquid metal valves were used on ELS. A summary description of each of these valves is presented in the ELS Valve List found in Appendix A. Two 3-in. (7.5 cm) valves (manufactured by Valcor Engineering Corp., Kenilworth, NJ) are used on the main loop. This type, a modified gate valve developed for FFTF sodium service, is shown schematically in Figure 23. The second type of liquid metal valve used extensively on ELS was the commercially available Nupro valve in 0.5-in. (1.2-cm) and 1-in. (2.5-cm) sizes.

In addition to these system valves, two other valves were installed on the valve test manifold for test and evaluation. These test valves were 1-in. (2.5-cm) Sargent and Hoke pneumatic block valves. The Sargent valve was identical to the valves developed for FFTF sodium service, while the Hoke valve was a modified FFTF gas valve with a single-ply 321 stainless steel bellows. All of the liquid metal valves were bellows sealed. Also, all valves used for lithium service were commercial designs or modifications of same.

2. Gas and Vacuum Valves

A large number of different gas and vacuum valve types and sizes were used on the ELS auxiliary systems. A summary description of each of these valves is presented in the ELS Valve List in Appendix A. The types of valves

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FIGURE 23. Modified Gate Valve.

used on these two systems included check, safety relief, pressure control, metering, and block. Sizes ranged from 0.625 cm (0.25 in.) to 15 cm (6 in.) All valves used for argon and vacuum service were commercial designs, unmodified for the ELS application, except for the target splash valves.

I. STATIC MECHANICAL SEALS

A number of different types of static mechanical seals were used on the ELS lithium and auxiliary systems. Summary descriptions of each of the seals used on the lithium system are presented in Table 10. Similar information on each of the seals used on the argon and vacuum auxiliary systems is presented in Table 11.

J. TRACE HEAT AND INSULATION

The entire lithium system was trace-heated and insulated with multiple layers of 1-in. flexible blanket, refractory fiber insulation. Five different types of electrical heaters were used in the ELS trace heat system. Summary descriptions of each of the heaters used on ELS are shown in Table 12.

The tubular resistance heaters were the predominant heater used on the piping. These circular-cross-section, metal-sheathed, mineral-insulated heaters were clamped to the piping every few feet in the orientation shown in Figure 24. Standard adjustable hose clamps were used to clamp both heaters and thermocouples to the pipe. The thermocouples used were 1/8-in. diameter x 12-in. long, 304 SS sheathed, MgO insulated, ungrounded junction, Type K units. After clamping, the entire length of pipe was spiral wrapped (50% overlap) with a layer of 0.005-in. thick stainless steel shim stock. All heater and thermocouple connections were wrapped with glass tape. The 1-in. layers of flexible-blanket, refractory-fiber (Kaowool®) insulation was installed over the shim stock and anchored in place with 22 gauge

•Kaowool is a registered trademark of Babcock & Wilcox, Refractories Division, Augusta, GA.

stainless steel wire. All lithium piping was insulated with 3 in. of insulation, while the lithium traps and tanks had 6 in. of insulation. Heater cold ends were specified to place heater terminations outside the insulation.

The larger diameter lithium components, such as the lithium traps and tanks, were trace-heated with banded resistance heaters. These Inconel-sheathed heaters had a triangular cross section and were bent in a hair-pin shape. Each banded heater assembly consisted of two of these hair-pin heaters attached to a flexible support clamp. The heaters and clamp assembly were pre-bent at the factory to the diameter of the component to be heated.

The flexible tape heaters were only used on special short-term applications or where frequent heater removal was necessary. The plate heaters were used to preheat all valve bodies except the 1-in. Sargent test valve. Each Nupro valve body was sandwiched between two plate heaters. Small cartridge heaters were only used to correct cold spots in the lithium system. These cold spots were identified during pre-operational testing of the trace heat system. After this testing a number of the cartridge heaters were installed.

K. INSTRUMENTATION

Since the ELS was an experimental facility, it was highly instrumented. This instrumentation can be divided into two major types: Process Instrumentation and Test Instrumentation. Process Instrumentation, which is essential to the operation of ELS, consisted of both standard, commercially available equipment and instrumentation systems specially developed at HEDL for the needs of the facility and its operation. Standard pressure transducers were purchased to measure the pressure of liquid metal, gas, and vacuums in the systems, and standard thermocouples were used to indicate temperatures for process control. Flowmeters were either purchased as complete assemblies or as component parts for assembly to measure gas and liquid metal flows. To indicate the levels of liquid argon and liquid metal, level sensors were both purchased and developed, depending on the precise use.

TABLE 10

STATIC MECHANICAL SEALS USED ON ELS LITHIUM SYSTEM

Seal Type	Manufacturer	Model No.	Nominal Flange Size (in.)	Material	Recommended Torque	
					(ft-lb)	(Joule)
High Compression (Grayloc®)	Gray Tool Co.		1/2, 1, 4 & 6	17-4PH Stain- less Steel	240	
High Compression Primary Seal with Backup C-Ring	Rocky Mountain Nuclear	S 4063	4	17-4PH Stain- less Steel & Silver-Plated Backup	160	
Swage (Swagelok®)	Crawford Fitting	C-1072	1/2	316 Stainless Steel	1-1/4 Turns from Finger Tight	

®Grayloc is a registered trademark of Gray Tool Company, Houston, TX.

Swagelok is a registered trademark of Crawford Fitting Company, Solon, OH.

TABLE 11

STATIC MECHANICAL SEALS USED ON ELS AUXILIARY SYSTEMS

Seal Type	Manufacturer	Model No.	Nominal Flange Size (in.)	Material	Recommended Torque	
					(ft-lb)	(Joule)
Flat Metal Gasket (Conflat)*	Varian, Huntington or MDC	*	Mini	Copper	3.5	4.8
			2-3/4		16	21.8
			3-3/8, 4-1/2,		16	21.8
			6, 8 & 10		26	35.4
Flat Metal Gasket (for Conflat Flange)	HEDL	N/A	2-3/4, 3-3/8, 6 & 8	Annealed 316 SS	20	27.2
Flat Metal Gasket (for Conflat Flange)	HEDL	N/A	4 1/2, 8 & 10	Soft Iron	20	27.2
Double C-Ring with Helical Spring	Helicoflex	HND200	12	Inconel* 750 Spring with Soft Iron Jacket	320	435.2
High Compression (Grayloc®)	Gray Tool	51273	2	17-4PH Stain- less Steel	55	74.4
O-Ring (ISO Quick Coupling)	Leybold-Heraeus, Varian & MDC	*	1/2, 1-1/2 & 2	Viton® with Stainless Steel Centering Ring	Finger Tight	
Flat Gasket	Leybold-Heraeus	910-181-606	4	Buna - N	Not Available	
O-Ring (Ultra Torr Feed Thru)	Cajon Company	SS-8-UT-128T	1/2	Viton	Finger Tight	
Swage (Swagelok®)	Crawford Fitting	C-1072	1/8, 1/4, 1/2 & 1	316 Stainless Steel	1/8 in. = 3/4 Turn from Finger Tight >1/8 in. = 1-1/4 Turns from Finger Tight	

*Vendor parts are interchangeable.

®Conflat is a registered trademark of Varian Associates, Palo Alto, CA.

Grayloc is a registered trademark of Gray Tool Company, Houston, TX.

Inconel is a registered trademark of Huntington Alloys, Inc., a division of International Nickel Inc., Huntington, WV.

Swagelok is a registered trademark of Crawford Fitting Company, Solon, OH.

Viton is a registered trademark of E. I. duPont de Nemours & Co., Wilmington, DE.

TABLE 12

HEATERS USED ON ELS TRACE HEAT SYSTEM

Heater Type	Manufacturer	Model No.	Nominal Size (in.)	Material	Power Rating
Tubular Resistance (Rigid)	Chromalox	TRI	0.246 & 0.315 diam	Inconel® Sheath	75 W/ft at 120 V
Banded Resistance (Rigid)	Chromalox	HBT	7.5 diam	Inconel Sheath	600 W/ft at 120 V
			14 diam	Inconel Sheath	1150 W/ft at 240 V
			16 diam	Inconel Sheath	1150 W/ft at 240 V
			18 diam	Inconel Sheath	1150 W/ft at 240 V
			36 diam	Inconel Sheath	1250 W/ft at 240 V
			60 diam	Inconel Sheath	2170 W/ft at 240 V
Tubular Resistance (Flexible)	Aerorod	BXA	0.125	Inconel Sheath	125 W/ft at 120 V
Flexible Tape	Briscoe	BIH	0.5 & 1.1 wide	Glass Cloth	90 W/ft at 120 V
Plate	Electro-Applications	SK-1	6 x 6 x 0.5	Ceramic	200 W/ft at 120 V
Cartridge	GE	7C813-A101	0.375 x 3 long	Inconel Sheath	90 W/ft at 120 V

*Inconel is a registered trademark of Huntington Alloys, Inc., Division of International Nickel Inc., Huntington, WV.

FIGURE 24. Pipe Heater/Thermocouple Orientation. Neg 7913081-1

Test Instrumentation was needed to support particular experiments for the use or adaptation of various designs for the FMIT Facility. Standard cameras and lighting equipment, including closed-circuit television, motion picture and still-life cameras, were used for target jet documentation. Standard acoustic monitors were important in evaluating pump cavitation and demonstrating a potential for target loss-of-flow detection. A standard infrared imaging system aided in accelerator beam tube diagnostics. Special ultrasonic sensors, developed at HEDL, were evaluated for measuring target jet thickness and roughness. Impurity monitors, including an on-line plugging temperature indicator and a resistivity meter, were specially designed to monitor lithium impurity trends. A conductivity probe was developed to measure jet thickness and map the contour of the jet surface. A prototype beam position monitor was also fabricated and installed on the ELS for lithium vapor compatibility studies. In the following sections these types of instrumentation are described in greater detail.

1. Pressure Transducers

Pressure transducers were used on ELS to measure the pressure of the lithium, argon, and vacuum systems. There were two types of NaK-filled pressure transducers used to monitor lithium. Both individual and differential-type units were employed. Individual transducers (manufactured by Taylor Instruments Process Control Division, Sybron Corporation, Rochester, NY) were used on the main loop pump inlet and outlet; while a differential transducer (manufactured by ITT Barton, Monterey Park, CA) was used on the cold trap inlet and outlet.

A number of different types of pressure transducers were used on the argon and vacuum auxiliary systems. Summary descriptions of each of these units and their locations are shown in Tables 13 and 14, respectively. These tables also show two different instruments used to detect air in-leakage, i.e., a Residual Gas Analyzer (RGA) and a Residual Nitrogen Analyzer (RNA).

The Inficon 200 Residual Gas Analyzer* was purchased as a package with its supporting vacuum components: a Leybold-Heraeus D2A fore pump* and a Leybold-Heraeus 150 turbomolecular pump,* which together provide the vacuum required for the quadrupole mass spectrometer. Also included is a DW-2 pressure converter with its manifold and support vacuum pump (D2A fore pump). The DW-2 sample system allows sampling of a gas system that ranges in pressure from 760 torr to 10^{-4} torr. The DW-2 accomplishes this through a system of capillaries (optional flow paths), so that the pressure of the sample stream is adjusted to $\sim 10^{-4}$ torr when it enters the mass spectrometer analyzer section. Consequently, when sampling a system that is near atmospheric pressure, the D2A pump must exhaust relatively large quantities of gas to adjust the inlet pressure to meet the requirement for operation of the quadrupole (10^{-4} torr). The Inficon 200, as the name implies, can scan the mass range of 1 to 200 amu. The advertised minimum detectable partial pressure (N_2) for the electron multiplier mode is 5×10^{-14} torr.

*Distributed by Inficon Leybold-Heraeus, East Syracuse, NY.

TABLE 13

PRESSURE SENSORS AND AIR IN-LEAKAGE DEVICES

Sensor Type	Manufacturer	Sensor Model No.	Controller Model No.	Range*	Accuracy (%)
Manometer - Compound Gauge	Matheson	63-3704	N/A	30 in. Hg to 30 psig (1.33×10^3 to 2.07×10^5 Pa)	1 (of full scale)
Manometer - Flexible Diaphragm (Kuflex)	Kulite Semiconductor	KF1074-3	KF1074-3	0 to 50 psia (1.33×10^3 to 3.45×10^5 Pa)	0.25
Thermal Conductivity - Thermocouple Gauge	Varian Assoc	531	801 & 810-2	2 to 10^{-3} torr (2.66×10^2 to 1.33×10^{-1} Pa)	**
Thermal Conductivity - Pirani Gauge	Granville/Phillips	275	275	1000 torr to 1 mtorr (1.33×10^5 to 1.33×10^{-1} Pa)	**
Manometer - Capacitance	MKS Instruments	310BHS-1SP	170M-6C	10^{-1} to 10^{-5} torr (1.33×10^1 to 1.33×10^{-3} Pa)	0.08
Ionization - Millitorr	Varian Assoc	971-5009	971-1008	10^{-1} to 10^{-6} torr (1.33×10^1 to 1.33×10^{-4} Pa)	**
Ionization - Cold Cathode	Varian Assoc	524-2	860	10^{-2} to 10^{-7} torr (1.33 to 1.33×10^{-5} Pa)	**
Ionization - Ultra High Vacuum (UHV-24)	Varian Assoc	971-5008	971-1008 971-0015	10^{-3} to 10^{-11} torr (1.33×10^{-1} to 1.33×10^{-9} Pa)	**
Residual Nitrogen Analyzer (RNA) - Pressure - N ₂	Varian Assoc	973-5025	973-5028	10^{-4} to 10^{-8} torr (1.33×10^{-2} to 1.33×10^{-6} Pa) 1 to 100% Nitrogen Partial Pressure	**
Residual Gas Analyzer (RGA) with DW-2 Pressure Converter	Inficon Leybold-Heraeus	155-37	IQ200	Atm to 10^{-14} torr (10^5 to 1.33×10^{-4} Pa)	**

*Vendor-supplied values.

**Vendor data not available.

TABLE 14

PRESSURE SENSOR, AIR IN-LEAKAGE DEVICES, AND SCREENING ELBOW LOCATIONS

Sensor	No.	Location							
		Mark I Target	Mark II Target	Chemistry Surge Tank	Main Surge Tank	Dump Tank	Vacuum Header	Cryo System	RNA Pumping System
Manometer - Compound Gauge	4			X	X	X		X	
Manometer - Flexible Diaphragm (Kuflex)	5	X	X	X	X	X			
Thermal Conductivity - Thermocouple Gauge	4		X*		X		X		X
72 Thermal Conductivity - Pirani Gauge	5	X	X		X		X	X	
Manometer - Capacitance	1		X*						
Ionization - Millitorr	5	X	X*		X		X	X	
- Cold Cathode	2						X		X
- UHV	5		X*,**		X		X	X*	
Residual Nitrogen Analyzer - Pressure	3		X				X		X
- N ₂	3		X				X		X
Residual Gas Analyzer	1			X***					
Screening Elbows	2		X		X				

*These gauges failed by the end of the ELS operation.

**Two UHV ion gauges were installed, one in front of and one after the screening elbow.

***This was shown on target in Figure 3, but never installed.

The Varian Residual Nitrogen Analyzer (SMART GAUGE®) is a multi-purpose gauge designed to monitor the residual nitrogen content of high-vacuum systems. The gauge also reads the system total pressure. It contains a filament and sensor that also determines the percentage of nitrogen by the glow discharge principle. The advertised sensitivity of the SMART GAUGE is a minimum detection of 10^{-9} torr (partial pressure N_2). The gauge is designed to work on the premise that a vacuum system operating normally will have 2% or less nitrogen in the residual gases. Whenever an air leak occurs, the percentage of nitrogen in the residual gases increases, resulting in an elevated scale reading on the gauge. Three SMART GAUGES were used in the ELS vacuum system.

2. Thermocouples

Thermocouples used on ELS for process control and information were all 1/8-in., ungrounded junction, Type K (Chromel-Alumel®) assemblies sheathed with seamless 304 stainless steel tubing. The insulation was high-purity MgO preformed in crushable beads. The insulation was then compacted during thermocouple fabrication.

Two different types of thermocouple attachment were used on ELS. The majority of thermocouples were clamped (surface-mounted) directly to the outside of the pipe (as shown previously in Figure 24). Where more accuracy was required, thermocouples were installed in thermowells. Thermowells were used on the cold trap, plugging temperature indicator, hot trap, and lithium tanks.

•SMART GAUGE is a registered trademark of Varian Associates, Palo Alto, CA.
•Chromel-Alumel is a registered trademark of Richmond Machine Products Corporation, Staten Island, NY.

3. Flowmeters

Flowmeters were used on ELS for flow measurement of the lithium and argon impurity addition systems. Permanent magnetic EM flowmeters of 0.5-in., 1-in. and 4-in. were used on the lithium system. The 4-in. EM flowmeter is shown in Figure 25.

The basic components of the magnetic flowmeter are the duct (lithium piping) with two signal electrodes welded to it and the permanent magnet. The relative positions of the magnet and the duct are such that the magnet centerline parallel to the pole faces passes through the electrode attachments to the duct and intersects the centerline of the duct.

The principle of operation of electromagnetic flowmeters is based on the interaction between flowing liquid metal passing through the magnetic field that produces a potential across the electrodes. The flow is determined by measuring the potential.

These flowmeters are commercially available as complete assemblies, including a pressure boundary flow duct. The magnets can also be purchased individually and the flowmeters can be assembled in-place. The latter approach was used on ELS.

A commercially available electronic mass flowmeter was used on the argon impurity addition line. The unit used was a Matheson, Model 8160-0423 with 0.25-in. end fittings. Mass flow measuring devices generate a signal that is proportional to mass flow by detecting heat transport in the gas stream. Since the specific heat (C_p) of any gas is a unique property of the gas and is essentially independent of pressure, mass flow devices are absolute measuring instruments.

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FIGURE 25. Four-Inch EM Flowmeter. Neg 7908985-3

4. Level Sensors

Three different types of lithium liquid level sensors were used on ELS, i.e., continuous, fixed, and level switch sensors. Continuous level sensors were used in both the main surge and chemistry surge tanks. On the main surge tank a continuous probe was inserted into a level well. This type of sensor operated on the induction principle and was the same design used on FFTF for sodium level detection. The sensor uses the inductive coupling between two coils to provide a continuous linear signal output over large ranges of liquid lithium levels. The sensor is installed in a dry thimble that makes contact with the lithium. The signal conditioning unit monitors the DC resistance of one of the sensor coils to provide system temperature compensation. This sensor was supplied by Westinghouse Electric Corp., Pittsburgh, PA.

On the chemistry surge tank two redundant continuous level monitoring "J-Probes" were inserted directly into the tank. The J-Probe operated on the resistive principle and was fabricated much like a grounded thermocouple. The operating principle of this sensor is based upon the differences in electrical resistivity of the stainless steel sheath ($\sim 70 \mu\Omega\text{-cm}$) of the probe. Constant current is used to produce a voltage along the sheath. The liquid lithium changes this voltage in proportion to its level on the probe. This continuous-level sensor was calibrated with a single-point eddy-current probe (manufactured by Nortec, Kennewick, WA). The two wires used were 0.016-in. diam 304 stainless steel, while the insulation was MgO. The J-Probe sheath was 0.25-in. 304 stainless steel tubing.

A single point level probe was also used on ELS for calibration of the continuous level probes. This eddy-current probe assembly is shown in Figure 26. The probe assembly had three basic parts: an eddy current test probe for manual insertion into the tank thimble, a portable electronic driver/readout unit, and an optical probe length-measuring fixture. The liquid level was located by slowly inserting the probe in the thimble. The probe would signal when the lithium level was reached. This probe was

FIGURE 26. Lithium Level Detector in Operation.

alternately used on all three ELS lithium tanks. The unit used was the same design used for FFTF sodium level detector calibration and was supplied by Nortec Corp., Kennewick, WA.

A liquid level switch was proposed for FMIT. This externally mounted proximity sensor is designed to detect the presence of liquid lithium in a metal pipe and is shown in Figure 27. Similar devices have been used extensively in sodium service, and a prototype was installed on ELS for evaluation with lithium.

Operation of the sensor starts immediately upon application of power (115 volts, 60 Hz). Two outputs allow connection of any type of monitoring devices desired that operate on switch openings or closures. When the presence of liquid lithium is detected in the pipe (when liquid fills the pipe to approximately the midpoint of the sensor face), a relay closes in the switch. This action opens both the Normally Closed (NC) contacts and closes both the Normally Open (NO) contacts. The sensor will remain in this state until the lithium level drops approximately one-half the diameter of the pipe below the midpoint of the sensor face.

5. Cameras and Lighting

A miniature black and white Closed-Circuit Television (CCTV) camera system was used for initial visual observations of the jet performance. A color CCTV camera with a 20- to 80-mm zoom lens was also used for monitoring jet performance. Video signals were stored on a video recorder. A high-speed motion picture camera that operates at speeds from 100 to 6000 frames per second was used to study the transient behavior of the lithium jet. When viewed at normal viewing speeds, the films produced with this camera result in a 3 to 200 times reduction of the apparent speed of events. This camera is a rotating-prism type. Small and medium format still cameras were used to photograph the small waves and wakes on the jet surface.

HEDL 8503-071.3

FIGURE 27. Liquid Level Switch.

Lighting for target jet photography, including CCTV and high-speed motion picture photography, was provided with a 300-W projector lamp controlled by a variable transformer. High-speed, still-life photography was lighted by a xenon strobe that provided intense bursts of light for 8- μ s duration.

6. Acoustic Monitors

Acoustic monitoring has been proposed for several applications on FMIT including cavitation detection, target diagnostics, and also detection of a loss of lithium flow triggering accelerator beam shutdown. Acoustic emission is a nondestructive testing technique that allows an operator to predict when a material, weld, or structure under stress is overstressed. Every material emits acoustic energy under stress; audible acoustic signals occur when paper is torn, glass is broken, or the wood supports of a mine shaft crack. Other materials, such as metals, also emit acoustic signals but usually well above the audio range. This also applies to liquid metals where flow noise and cavitation emission may occur. Such high-frequency emissions from metals and fluids occur well before a visible defect or effect can be seen or heard. The generated acoustic waves travel as a spherical wave packet throughout the material and are detected by a piezoelectric sensor strategically placed near the part under stress. After the detected signal is amplified and filtered, the output appears as a classical particle wave packet whose frequency is highly influenced by the sensor's resonance. Thus, where a broad frequency spectrum of information is present, broadband sensors are needed. A typical acoustic emission signal can be analyzed in many ways. Two of the most popular and revealing analyses are counts and energy.

Based on these proposed uses of acoustic monitoring on FMIT, acoustic monitoring was used for two applications on ELS. During testing of the main lithium loop, acoustic monitoring was used to monitor cavitation and additional sensors were installed on the target and main loop piping for signature analysis of the piping system as a function of flow. A picture of the

equipment used for pump cavitation studies in this work is shown in Figure 28. This includes a Physical Acoustics Corp., Model 4300 count rate analyzer, which used signals from a single sensor source to provide three parameter analyses with digital scalers and individual analog recorder outputs. The parameters are acoustic emission counts, events, and peak amplitude or energy. It also featured a variable-gain threshold detector, an integration time period, and an eight-position selectable filter for obtaining spectral frequency response bands from 0 to 2 MHz. In addition, a dual gun oscilloscope was used to visually observe the RF waveforms from two sensors, simultaneously. This roughly locates the acoustic emission source between the two sensors. A four-channel stripchart is used to record the three acoustic emission parameters plus flow rate. A hand-actuated piezoelectric spark generator provided a high-voltage pulse to the transducer for calibration. The transducer generated an acoustic pulse, which is coupled to a 0.035-in. diam, 30-ft, 300 series SS extensional mode waveguide. This waveguide is, in turn, coupled to the piping near the monitoring sensors for use in system calibration and checkout.

7. Infrared Imaging System

An infrared imaging system has been proposed as a candidate instrument to locate and focus the accelerator beam on target during operation. With this concept the beam-heated regions of the lithium jet would be detectable by infrared imaging and the IR signal could be used for aiming and focusing the beam. In addition, a combination of optical and infrared imaging has been proposed as a method of detecting excessive target erosion and/or corrosion. Localized nozzle imperfections are known to manifest themselves in small but easily imaged surface changes, such as a wake. With infrared viewing of the jet surface when the beam is on or optical viewing with the beam off, such indications of excessive wear may be seen. Based on these proposals, a commercially available AGA, Thermovision® 780 infrared imaging system was installed on the ELS simulated accelerator beam tube during

®Thermovision is a registered trademark of AGA.

FIGURE 28. Instrumentation Used for Pump Cavitation Studies. Neg 8101110-1

the last weeks of operation. This instrumentation package consisted of a single scanner infrared camera, a color monitor, and a digital tape recorder system. These are shown in Figure 29.

8. Ultrasonic Transducers

A technique to measure ultrasonic target lithium thickness was proposed for FMIT to detect the thinning or breakup of the jet under various operating conditions. Such measurements would be made with the accelerator beam off. This technique included a spherically focused element propagating a focused ultrasonic beam 1) through a liquid coupling medium to the target backwall, 2) through the backwall to the cylindrically radiused lithium stream incident surface, and 3) through the lithium to the free lithium surface where the ultrasonic beam is reflected to return to the transducer element. The basic principle of this concept is that the thickness of the lithium jet is a function of the speed at which sound travels through it. A block diagram of the system proposed for FMIT is shown in Figure 30. Based on this proposal, a prototype transducer was designed and fabricated at HEDL and installed on the ELS Mark I and Mark II targets.

9. Impurity Monitors

An on-line Plugging Temperature Indicator (PTI) and a resistivity meter have been proposed for FMIT to monitor lithium impurity trends. Based on these proposals, prototypes of each of these meters were fabricated and installed on ELS.

Plugging Temperature Indicator -- An orifice-type PTI identical to the FFTF design was selected as the reference design for FMIT. A prototype of this design is shown in Figure 31. The basic features of this design include an orifice plate, regenerative heat exchanger, air cooling system, air and lithium flowmeters, restart control valve, trace heat system, and recorder.

FIGURE 29. Infrared Imaging System.

HEDL 8202-168.1

FIGURE 30. Ultrasonic Instrumentation Block Diagram.

FIGURE 31. Plugging Temperature Indicator. Neg 7909814-4

The orifice plate has four 0.052-in. diameter holes as the plugging restrictor. The orifice plate also has a center hole, which is normally blocked by a solenoid operated valve mechanism. This center hole is used for restoring lithium flow through the orifice plate in the event that the plate becomes completely plugged with impurities. The orifice plate is located at the end of a regenerative heat exchanger in which lithium enters the meter from the top through a center tube and loses heat to the lithium flowing up the outside annulus. The lithium is cooled by flowing air along the outside of the heat exchanger. The required temperature gradient along the heat exchanger is obtained by adjusting the lithium flow rate, the air velocity, and the power input to the heaters located on the outside of the heat exchanger. Thermowells with thermocouples monitor the lithium temperature and record plugging temperatures.

Resistivity Meter -- A flow-through-type resistivity meter was selected as a potential design for FMIT. A prototype of this design is shown in Figure 32. The resistivity monitoring scheme is based on the fact that a liquid metal solution containing impurities has a higher electrical resistivity than the pure metal. Nitrogen and hydrogen impurities in lithium have been measured in concentration ranges of interest to FMIT operation.

The lithium-containing part (wetted area) of the probe is the inside wall of a section of 0.25-in. OD stainless steel tubing with a 0.010-in. wall. The 0.25-in. tube is assembled (welded) into the 0.75-in. OD tube that provides an inert annulus for passage of lead wires and thermocouples from the bottom of the sensor to a connector at the top. The 0.75-in. tube is provided with a flange and a sliding O-ring seal at the top of the tank that allow the sensor to be positioned in the tank. Four copper lead wires (12-gauge, 7-strand) and two thermocouples were brazed to the 0.25-in. tube so that resistance and temperature measurements could be made of a 5-in. long section of the sensor tube. The resistance measurements were taken with a 1700 series digital ohm-meter (manufactured by Electro-Scientific Industries, Portland, OR) capable of 1 micro-ohm resolution. A data acquisition system was established that stored data on disks and provided hard

HEDL 8503-071.2

FIGURE 32. Resistivity Meter.

copies of the output from the ohm-meter, the two resistivity meter thermocouples and the surge tank lithium flow rate.

10. Conductivity Probe

An electrical conductivity probing system was the primary device for measuring jet thickness and mapping the contour of the surface of the jet. The system measures the contour of the surface by sensing electrical contact between a movable probe and the lithium jet. Two generations of conductivity probes were tested. The first unit (Figure 33a) consisted of a linear motion feedthrough mounted on a 152-mm diameter vacuum flange mated to the target. The shaft of the feedthrough is pinned to a stainless steel rod that supports the polyamide electrical insulator holding seven pins mounted in a horizontal configuration. The probe also has an electrical feedthrough connector to provide electrical connections to each of the seven pins. Motion is provided by a stepping motor drive system. The second probe (Figure 33b) was similar except there was only one pin coupled to a three-degree-of-motion feedthrough. For the seven-pin probe, electrical contact between the probe pins and the lithium was recorded on floppy disc and visually displayed with a light and pulse height analyzer/CRT. Contact data from the single-pin probe were stored on magnetic tape.

11. Beam Position Monitor

An inductive beam position monitor was proposed for FMIT to locate the accelerator beam relative to the beam tube. This would be achieved by installing diametrically opposed pairs of sensors in both horizontal and vertical planes. The signal from each pair of sensors would indicate the beam's relative position. The beam position sensor operates on the principle that the current from the charged accelerator beam induces a voltage at right angles to beam centerline. The beam position monitor consists of an inductive pickup, alumina insulator, vacuum seal, signal conductor, and sensor housing.

FIGURE 33a. Multi-Pin Conductivity Probe for Mark I Target Testing.
Neg 8202605-2cn

FIGURE 33b. Single-Pin Conductivity Probe. Neg. 8302447-14cn

Two processes are of concern regarding alkali metal degradation of beam position monitors near the target. One is electrically conductive coating on the beam position monitor cable end-seal due to jet surface evaporation/outgassing. The other is chemical attack of the end-seal insulator. Even though these are separate effects, their origin is the same; and the end result will most likely be instrument failure in either case. Based on these concerns, a test unit was fabricated and installed on the ELS. The unit tested on the ELS is shown in Figure 34.

L. CONTROL SYSTEM

The ELS controls are an integral part of the STCL control console; however, the ELS and STCLs use separate computers. The ELS computer, fed by tape transport, has 255 channels (total) for both data and control, plus a 24,000 core memory. A printer is provided for hard copies. A block diagram of the ELS control system is shown in Figure 35. The ELS control console is shown in Figure 36. The control console has several spare alternate action switches.

1. Cold Trap Control

The operator may select any one of 20 thermocouple signals (Channel Nos. 6:24 through 6:43) to monitor the temperature profile in the cold trap. The temperature control loop consists of thermocouple TE 5:75 and a temperature relay to control the in-line heater located in the air cooling duct. This thermocouple is located at the bottom of the crystallizer. The air damper valve is manually pre-set prior to starting the air blower. The cold trap heater controls are set for manual output during normal operation.

2. Hot Trap Control

The hot trap temperature is controlled by a closed loop system of thermocouples and a temperature relay. Flow to the cold trap and/or hot trap is adjusted by motor or manual positioning of valve MOV-77 (hot trap)

HEDL 8402-230

FIGURE 34. Beam Position Monitor. Neg P18056-2

HEDL 7909-31.1

FIGURE 35. ELS Control System Block Diagram. Neg P117675-1

FIGURE 36. ELS Control Console. Neg 8101967-8

or valve MOV-11 (cold trap). A local flow readout is required for the operator at the valve control station.

3. Main Lithium Pump (EMP-1) Controls

Preheat Control -- The main lithium EM pump is preheated with pump power. In the preheat mode, the pump stator voltage must be limited to 150 volts to prevent potential pump damage. All pump temperatures are monitored by thermocouples 6:2 through 6:7. The temperature ramp rate is operator-controlled and can be adjusted by the operator manually.

NOTE: The pump is not heated until the loop is hot.

Run Control (EMP-1) -- The pump control functions include an on-off switch and variable 10-turn potentiometer (either manual or motor-driven at a pre-set ramp rate). The pump run is interlocked so that the pump cannot be started until the stator voltage has decreased to zero. The pump stator temperature and stator voltage level can be displayed. The operator is able to adjust the flow rate and set point, and to read the present flow rate recorded on a strip chart recorder. The following controls are available:

	<u>Feature</u>
• Pump	Start/Stop
• Instantaneous current trip	Reset

The following interlocks will shut down the pump:

- High stator temperature
- Fire alarm
- Low argon level (fire protection)
- Low lithium flow
- Excessive pump current

4. Chemistry Loop Pump (EMP-2) Controls

Preheat Control (EMP-2) -- The chemistry loop EM pump is preheated with the pump throat heater (HTR 5:81) and winding heater (HTR 6:15). Pump temperatures are monitored by thermocouples TE 5:81 and TE 6:15. The temperature ramp rate is set at 100°F/h. The operator can select either the manual mode (to change parameters) or the automatic mode (to increase the temperature at the selected ramp rate up to the temperature set point).

Run Control (EMP-2) -- The pump run function is interlocked so that the pump cannot be started until the stator voltage has decreased to zero. The throat temperature (TE 5:81) is monitored by the operator. The flow rate set point can be displayed. The operator must be able to adjust the flow set point. The following controls are available:

	<u>Feature</u>
• Mode selection	Auto/Manual
• Pump	Start/Stop

The following interlocks will shut down the pump:

- High throat temperature
- Fire alarm
- Low argon level (fire protection)
- Low lithium flow

M. IMPURITY ADDITION SYSTEM

Impurity additions were made by injecting gases into the lithium, rather than by dissolving solid lithium salts, because of previous poor experiences with getting solids to dissolve rapidly. In addition, the lithium salts that would have to be added are all very reactive with air and thus not available commercially in high purity. In contrast, the impurities of interest are available as high purity gases. With lithium they can be

expected to form extremely fine particles of reaction products that will dissolve much more rapidly. This method of impurity addition was demonstrated prior to the additions to the ELS.

The apparatus used to make gaseous impurity additions to the ELS is shown in Figure 37. All components in contact with lithium were made of 300 series stainless steel. The chemistry surge tank contained ~50 gallons of lithium maintained at 371°C (700°F) during gas additions. The argon cover gas volume of the chemistry surge tank was 190 liters.

Impurity gases (99.95%) were typically diluted to 1% to 3% by volume in high-purity (99.995%) argon. This dilution was necessary for three reasons:

- The exothermic reaction of some gases with lithium could cause a safety hazard.
- The delivery tube tends to plug with reaction products when pure gases are used.
- It was desired to prolong the addition time to allow measurement of absorption efficiencies with the chromatograph.

The bore of the 3.17-mm (0.125-in.) diameter delivery tube was 1.65-mm (0.065-in.). The delivery tube was positioned so that the tip was ~254-mm (8-in.) below the lithium surface. No plugging of the delivery tube by reaction products occurred as long as gas flow was maintained to keep lithium out of the bore. Earlier laboratory testing demonstrated that once lithium entered the delivery tube, plugging began in a few minutes; therefore, gas flow was always initiated prior to lowering the delivery tube into the lithium.

N. LITHIUM TRANSFER SYSTEM

A specially constructed lithium transfer system was used to transfer the lithium from drums into the ELS dump tank. The transfer system is shown schematically in Figure 38. Dual lithium drums, equipped with heaters, temperature monitors and argon pressurization equipment, were used for the

FIGURE 37. ELS Impurity Addition System.

FIGURE 38. Schematic Diagram of ELS Lithium Transfer System.

transfer. Each lithium drum was placed in a mild steel secondary container. This secondary container was inerted with argon throughout the entire heating and transfer process. The drum unloading station in EDL-101 is shown in Figure 39.

The transfer tubing was 0.5-in. 304 SS tubing with a 0.065-in. wall. Stainless steel, all-welded, bellows-sealed, manual isolation valves were used. Two 25- μ m filter assemblies (see Figure 38) were piped in parallel to allow alternate flow paths should one filter become plugged.

The filter cartridge is rated for 427°C (800°F), <1 psi (clean) pressure drop at a lithium flow rate of 10 gpm, and an allowable external-to-internal differential pressure of 200 psi maximum.

Both drums were heated simultaneously in three zones, starting with the top zone of each drum to allow the lithium to expand at the top surface. The lithium was heated to ~193.4°C (~380°F). Complete melting took ~12 hours per drum.

The pressure increase from argon purging and expansion of the heating lithium was vented to the room atmosphere through two gas-washing flasks in series. The initial flask was empty. The last flask contained a reservoir of light oil that vented the gas bubbles at a rate of less than 30 cc/min. This system allows a continual venting of pressure without reliance on a mechanical vent or manual venting of the pressure; it also precludes the inadvertent introduction of air or oil into the lithium drum.

During the heating procedure, a slow bleed of argon at a delivery pressure of 1 psig was applied to the venting system. This functioned to visually ensure the operator that the system was open for escape of gases from the heating drum and to provide an added safety factor to prevent the introduction of air into the lithium drum. As a final precaution, a pressure relief valve was provided upstream of the gas washing bottle. This relief valve was set at 5 psig.

FIGURE 39. ELS Lithium Drum Unloading Station. Neg 7910851-1

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V. SYSTEM OPERATION

A. OPERATIONS HIGHLIGHTS

The Experimental Lithium System operated safely and reliably from startup to shutdown. The system was computer-controlled and operated unattended for much of the time. The Westinghouse Hanford Company (WHC) designed and fabricated the main loop lithium pump, an annular linear induction pump which performed well, undergoing 1201 startups and shutdowns with no apparent degradation in performance. Other critical components designed and tested by WHC included the FMIT target (Mark I and Mark II designs), cold trap, hot trap, plugging temperature indicator, samplers, and on-line meters. Commercial valves and vacuum hardware representing candidate designs for the FMIT application were also tested. Chemical impurities remained low throughout ELS operation, as monitored by 100 total lithium samples. Some of the major milestones observed are outlined in Table 15.

TABLE 15
ELS MAJOR MILESTONES

• Completed Initial ATPs	July 25, 1979
• Started Preheat and Loop Cleanup	August 6, 1979
• Started Lithium Transfer	September 11, 1979
• Completed Initial Lithium Transfer	November 15, 1979
• Started Pressure Operation	March 26, 1980
• Started High Vacuum Operation	February 11, 1981
• Started Mark I Target Test	June 2, 1981
• Started Valve Test Manifold	June 2, 1981
• Completed ALIP Pump Test	August 9, 1981
• Completed Test of Nupro® Valve	November 19, 1981
• Completed Sargent* Valve Body Test	June 22, 1982

®Nupro is a registered trademark of Nupro Company, Willoughby, OH.

*Manufactured by Sargent Industries, Huntington Park, CA.

ELS MAJOR MILESTONES (Cont'd)

- Added Last Lithium June 22, 1982
- Filled Cold Trap September 10, 1982
- Completed Cold Trap Thermal/Hydraulics Test January 11, 1983
- Filled Hot Trap January 21, 1983
- Completed Hot Trap Thermal/Hydraulics Test February 28, 1983
- Completed Mark I Target Test May 6, 1983
- Started Mark II Target Test July 29, 1983
- Started Hydrogen Addition September 15, 1983
- Completed Hydrogen Removal (Cold Trap Performance Test) November 4, 1983
- Started Beam Tube Test (Lithium Evaporation) November 22, 1983
- Started Nitrogen Addition December 8, 1983
- Completed Beam Tube Test (Lithium Evaporation) December 19, 1983
- Completed Mark II Target Tests January 12, 1984
- Completed All Testing Including: January 13, 1984
 - Nitrogen Removal (Hot Trap Performance Test)
 - Hoke* Valve
 - Sargent Valve
 - Socket Weld Fittings

Of the 46 months that lapsed during ELS operation, the test facility was shut down for a total of ~15 months for ten planned major outages (target and test valve changeout and other loop modifications). These outages are shown graphically in Figure 40. In addition, the facility was shut down for another 4.7 months for outages associated with early target testing. These minor outages were for such activities as test fixture changeout and cleaning. The outage dates for shutdown and startup were based on the presence or cessation of lithium flow. The outages for the main and chemistry loops were identical except for the four outages after September 10, 1982,

*Manufactured by Hoke Inc., Cresskill, NJ.

HEDL 8402-056.8

FIGURE 40. Histogram of ELS Major Outages.

when the two loops were isolated. After this date the chemistry loop remained on-line continuously.

Based on all outages, the availability of ELS was ~60%. However, if one excludes the scheduled ELS outages, the availability of the facility was >90%. The cumulative operating hours of the ELS subsystem or test articles are presented in Table 16. The hour values given on this table are based on hour meter data, unless otherwise indicated.

TABLE 16
CUMULATIVE OPERATING HOURS

<u>Subsystem or Test Article</u>	<u>Total Hours of Operation</u>
Computer	39,000*
Preheat System	24,500*
Chemistry Loop	16,275
Main Loop	8,795
Valve Test Manifold	6,575
Vacuum System	2,000*
ALIP Pump	8,795
MSA Pump No. 1	9,457
MSA Pump No. 2	6,818
Hoke Valve (POV-134)	6,575 (includes ~10,000 operating cycles)
Nupro Valve (POV-135)	5,430 (includes ~10,000 operating cycles)
Sargent Valve Body (POV-133)	3,499
Sargent Valve (POV-133)	3,076 (includes 5019 operating cycles)
Mark I Target	1,962
Cold Trap	1,800*
Hot Trap	1,200*
Mark II Target	356

*Estimated values.

B. PRECONDITIONING

Prior to lithium transfer, the entire lithium piping system was subjected to additional in-place cleaning to drive in-situ impurities from the internal piping surfaces. The piping was alternately cycled with argon gas sweeps and evacuation, at elevated temperatures. System temperatures were allowed to stabilize at 300°F and 500°F. The argon sweep and vacuum purge cycles were performed on all piping legs at system temperature levels between 300°F and 500°F.

After system cleanup, argon impurity levels within the pressure boundary were 17 wppm hydrogen, 6 wppm oxygen, 40 wppm nitrogen, 0.4 wppm methane, and 0.8 wppm other hydrocarbons. This preconditioning of the loop prior to lithium transfer is believed to have contributed to the low lithium impurity levels reported after initial fill. It would also have helped reduce system off-gassing and aided system pumpdown during vacuum operation.

C. LITHIUM TRANSFER

Lithium for the ELS was purchased from Foote Mineral Co., Exton, PA. Five-thousand pounds were shipped from stock in standard black iron, 55-gal drums without a hydrocarbon protective liquid cover. From this inventory a total of 3924 pounds was transferred to the ELS dump tank. Detailed ELS lithium transfer data are presented in Table 17.

Before loading lithium, the argon-filled ELS was heated to 500°F (260°C) and alternately evacuated and refilled with argon to remove residual air and adsorbed water, as described in the preceeding section (see Section V.B). Lithium was transferred from the drums to the dump tank of the ELS by suction, using the apparatus described previously in Section IV.N. Maximum lithium temperature was limited to 380°F (193°C) for safety reasons and to minimize the solubility of impurities. Pressure in the drums never exceeded 2 psig.

TABLE 17
ELS LITHIUM TRANSFER DATA

<u>Drum No.</u>	<u>Station</u>	<u>Lithium Transferred (lb)</u>	<u>Transfer Time (min)</u>
1	North	170	22
2	South	155	21
3	South	181	19
4	North	155	15
5	South	204	41
6	North	185	20
7	North	178	20
8	South	182	25
9	South	173	19
10	North	209	27
11	North	187	22
12	South	187	29
13	South	172	20
14	North	172	21
15*	North	140	--
15a**	North	195	32
16	South	186	67
17	North	164	32
18	North	178	24
19	South	157	22
20	South	154	23
21***	North	175	21
22***	South	165	20
Total:		3924	

*Transfer terminated by leak from elastomer seal of carbon steel shipping drum.

**Drums 15a through 22 were of all-welded stainless steel construction.

***Drums 21 and 22 were transferred into the main surge tank.

The drums were all found to have a crust of red-black material ~0.1 in. thick on the surface of the frozen lithium. This is the characteristic color of the lithium oxide/nitride that forms when limited amounts of air contact lithium. To avoid plugging the filters, a 10-cm (4-in.) heel was left in each drum, and the lithium was not drawn down to the transfer line opening. This was apparently successful, because no problems were encountered with the 25- μ m filters, each of which had only 2.5 ft² of effective surface. By operating with one atmosphere of pressure differential, a drum could be emptied at 2 gallons per minute.

Because the need for lithium was urgent, it was necessary to accept lithium with somewhat higher levels of impurities than that normally supplied as commercial grade by the two domestic producers of lithium.^(8,9) The purchase specifications set limits of 1500 wppm sodium and 500 wppm potassium, which were not expected to have an adverse effect on ELS operation although, in the FMIT, they would yield undesirable activation products.

The vendor would not guarantee nitrogen concentrations less than 300 ppm. However, the vendor quoted the following impurity levels on a typical lithium brick analysis from this batch:

<u>Component</u>	<u>Composition (wt%)</u>
Lithium*	99.768
Sodium**	0.2200
Potassium	0.0045
Chloride	0.0041
Nitrogen	0.0031***
Trace Metals	0.0010

*Lithium composition was not obtained by a chemical measurement. It was arrived at by subtracting the impurity percent from 100%.

**Individual barrel analyses for sodium varies between 0.050 and 0.300 wt%. Sodium composition is the average value for the shipment.

***The comparable nitrogen concentrations for ANL's LPTL lithium was 50 ppm.

During the lithium transfer from drums to the ELS (a process that extended over several months), a number of samples were obtained by removing sections of the 0.5-in. transfer line that extended into the drums. In each case, the sample lithium was the last to be withdrawn from the drum before the transfer line valve was closed. Unfortunately, the lithium samples then remained liquid for perhaps an hour in the vertical tubes while the drums gradually cooled. The combination of slow cooling and vertical positioning may have had some influence on the analytical results summarized in Table 18.

TABLE 18
ANALYSIS OF LITHIUM FROM DRUMS

<u>Date</u>	<u>Drum</u>	<u>Impurities (wppm)</u>		
		<u>Nitrogen</u>	<u>Hydrogen</u>	<u>Calcium</u>
9/11/79	1	18		
9/11/79	2	7		
9/13/79	3	9	7	
9/15/79	5	12		
9/19/79	9		9	160
9/21/79	11	7		
9/21/79	12	12		275
11/12/79	17	49	43	
11/15/79	18	15		
11/15/79	19	12	27	160

The data for nitrogen is of particular interest. Considering that a nitrogen-rich crust existed on each drum of lithium, it was surprising that the nitrogen concentration was a factor of 100 less than saturation. In retrospect, we know that there was at least 500 ppm of aluminum in the lithium and that aluminum suppresses the solubility of nitrogen to the levels observed. Similarly, lumps or cakes of lithium nitride can be inhibited from dissolving in lithium by the formation of a surface film of aluminum

nitride. The calcium values obtained from the drum samples are believed to be lower than seen in later ELS samples, because sampling conditions allowed precipitation and settling of calcium oxide within the sample tube. Because nitrogen levels were lower than originally anticipated, a sample was sent to Argonne National Laboratories for confirmatory analysis. The comparative analytical results for nitrogen were HEDL: 10 ppm (avg) and ANL: 9.5 ppm (avg).

Additional information on the performance of the lithium transfer system is presented in Section VI.D.

D. NORMAL OPERATION

The ELS lithium system (main loop and chemistry loop) were operated as an entity or as two separate systems. For clarity and ease of presentation, the main loop and chemistry loop are discussed as separate systems in this section.

1. Main Loop

The main loop description is provided in Section IV. The discussion below focuses on preheat, lithium fill and drain, lithium circulation under pressure or vacuum conditions, programmable versus manual control modes of pump operation, and the empirically optimized startup and shutdown flow conditions for the lithium target.

Preheat -- The system was preheated in two modes, i.e., system drained or system filled with lithium. When the system had been drained, all heaters were energized simultaneously. When the system had been shut down and the lithium allowed to freeze in the piping system, preheat was sequential starting from known free surface areas (dump tank, expansion tank, and lithium target) to preclude pipe rupture associated with thermal expansion of the lithium. The heatup rate for the main loop was set at 100°F per hour maximum because of thermal stress considerations associated with piping and nozzle

loads. The lithium target was limited to 50°F per hour maximum heat-up rate (applied with the system drained or lithium-filled).

Lithium Fill -- Lithium transfer to the main loop from the dump tank was accomplished via pressure differential (~ 5 psi). The lithium fill operation was carried out under two different pressure conditions depending on which test program was to be performed. If the main loop was to be operated under positive pressure, the preferred fill method was to maintain the dump tank at 21 psia and the main surge tank at 16 psia. If the main loop was to be operated under vacuum conditions, the preferred fill method was to maintain the dump tank at 16 psia and the main surge tank at 10^{-3} torr.

The fill operation with both tanks under positive pressure was the easiest to perform because the argon supply had throttling capability, while the vacuum supply did not. Also, the pressure fill required a lower ΔP . Fill under pressure could be accomplished with one operator in the control room. The operator could pressurize the dump tank, vent the expansion tank, and open and close the drain valve remotely. Since the control system for the drain valve was limited to open/close, i.e., no automatic throttling capability, transfer rate control was achieved by throttling the argon flow.

Filling with the main loop under vacuum was more difficult to perform and required more operators. In addition to the operator in the control room, two operators were required to engage the manual override and throttle the drain valve in a manual mode (one operator to operate the valve located in a potentially oxygen-depleted pit and the second operator outside the pit as required to meet safety requirements under the buddy system). A fourth operator was required at the vacuum system control panel because the vacuum system was subject to pressure pulsation while the fill operation was under way. These pulses would occasionally cause the vacuum system pumps to trip, necessitating restart action by the operator.

Lithium Drain -- As noted earlier, the main lithium system is operated under vacuum or positive argon cover gas conditions. When the main loop is under positive pressure, the lithium is gravity-drained by opening both the drain valve and the pressure equalization valve (in the 4-in. argon inter-tie line between the expansion tank and the dump tank) simultaneously. A normal drain under these conditions results in a 16 psia argon cover gas pressure in the two tanks, and no additional argon makeup is required. Normal draining of the lithium when the main loop is under vacuum conditions is accomplished by first slowly pressurizing the main surge tank to 16 psia, then venting the dump tank to 16 psia. At this point, the 4-in. equalizing valve and the drain valve are opened.

Lithium Circulation -- Lithium in the main loop was circulated with an argon cover gas in the main surge tank varying from 3 psig maximum to a relatively high vacuum, 10^{-3} torr. Under a positive cover gas pressure, the loop routinely operated in an unattended mode with computer control. Previous experience with other HEDL-designed and -operated liquid metal facilities provided adequate confidence in instrumentation and the necessary safety shutdown systems for unattended operation. The loop was not operated unattended under vacuum conditions primarily because of lack of proven air in-leakage detection systems. A residual nitrogen analyzer (RNA) was used to detect air in-leakage. The RNA, which detects changes in the partial pressure of nitrogen, proved fairly reliable. The major problem with this system was the negative output signal at low partial pressures of nitrogen. The computer control system could read the negative signal; however, computer software limitations did not provide an alarm for this condition. Therefore, operation under vacuum conditions was performed with an operator stationed at the vacuum panel to isolate the vacuum system and to break the vacuum on an increasing partial pressure of nitrogen indication.

The only change in system performance while operating the loop under a positive cover gas pressure (versus high vacuum) was the associated change in the EM pump net positive suction pressure. The maximum flow under a normal cover gas pressure of 3 psig was 590 gal/min with the target installed.

No pump cavitation was observed during pressure operation. Under high vacuum conditions (10^{-3} torr in main surge tank), the maximum flow attainable was ~520 gal/min before pump cavitation occurred.

EM Pump -- The HEDL-designed and -fabricated EM pump performed flawlessly for the lifetime of the test facility. Control of the EM pump was normally provided by manual adjustment of a rheostat. However, for target testing, a programmable control system as used to provide maximum flexibility and repeatable ramp rates for startup and shutdown of the EM pump. In all cases, the loop was well behaved, and no anomalies were observed other than splashing in the target region, which is discussed below.

Target -- The programmable controller system for the EM pump enabled optimum startup and shutdown flow rates to be developed, which minimized lithium splashing in the target. Ramp rates were varied from 5 gal/min per minute to 70 gal/min per second. As expected, lithium splashing occurred in the target area at startup ramp rates greater than 15 gal/min per second. The optimum shutdown rate to preclude or minimize splashing in the target area was determined to be an instantaneous trip of the EM pump. Under the trip of the EM pump, flow decayed from 518 gal/min (nominal target design flow) to zero flow in about 4 seconds.

Another variable that affected lithium splashing in the target area was the amount of gas entrained in the lithium system. In addition to increased target splashing, entrained gas was evidenced by pressure instabilities in the vacuum system and ultrasonic detector signals. As noted in the lithium fill discussion above, the main loop was filled under either positive pressure or vacuum conditions in an attempt to determine an optimum condition to preclude gas entrainment in the lithium system. If the loop was filled under positive pressure conditions, the system was evacuated and held at a high vacuum for ~1 hour before lithium flow was initiated. Even so, some gas was still entrained in the lithium. The entrained gas was removed from the system by increasing the lithium flow to ~250 gal/min (at a nominal rate of 15 gal/min per second) where it was held for a few minutes to degas the

system before increasing the flow rate. After this degassing step, the system could be started up and shut down numerous times without subsequent gas entrainment problems. If the loop was filled under vacuum conditions, lithium flow could be initiated within one-half hour with no evidence of gas entrainment.

2. Chemistry Loop

The chemistry loop description is provided in Section IV. The discussion below addresses preheat, lithium fill and drain, lithium circulation, and lithium purification.

Preheat -- Prior to initial lithium fill, the system was preheated by energizing all heaters at one time. However, portions of the chemistry loop, primarily the cold and hot traps, were considered nondrainable; and subsequently the heaters were energized in series away from a known lithium free surface (expansion tank). This precluded any pressure boundary ruptures associated with the thermal expansion of lithium as the temperature increased. The heatup rate of the chemistry loop was set at 100°F per hour maximum because of thermal stress considerations associated with piping and nozzle loads. The purification traps were preheated at a maximum of 50°F per hour.

Lithium Fill -- Lithium fill was accomplished using differential pressure. The main surge tank was pressurized and lithium entered the chemistry loop through an inter-tie line. The chemistry loop is vented through the chemistry surge tank. The chemistry loop could be operated in common with the main loop or isolated as a separate entity, depending on the planned test mission. The chemistry loop capacity with both purification traps filled is ~120 gallons.

Lithium Drain -- The lithium drain was accomplished via the same inter-tie line used for lithium fill. As noted earlier, the purification traps were considered nondrainable because of internal construction and piping geometry.

Lithium Circulation -- Lithium circulation in the chemistry loop was performed with argon cover gas in the chemistry surge tank varying from 3 psig maximum to ~10 psia, at which point the chemistry loop pump would start to cavitate. Flow rate in the chemistry loop was nominally maintained at ~5 gal/min; however, the chemistry loop EM pump was equipped with a variac control system and could be operated from 0 to 10 gal/min depending on test needs. Loop operation under a positive cover gas pressure was routinely performed in an unattended mode with computer control. Previous experience with other HEDL-designed and -operated liquid metal facilities provided adequate confidence in instrumentation and necessary safety shutdown systems for unattended operation.

Purification -- The purification system on ELS consisted of two in-line traps, i.e., a cold trap and a hot trap. These traps were only operated for test purposes on ELS, since impurities remained low during the entire four years of ELS operation (see Section VII, Chemistry). Both traps were subjected to thermal-hydraulic and purification performance tests, and the results of these tests are reported in Section VI.E. Operationally it should be pointed out that three different control modes were evaluated on the cold trap. In summary these three modes consisted of the following.

Control Mode 1

- Economizer heater in automatic control mode.
- Crystallizer heater in manual control mode.
- Air blower speed and damper position in manual control mode.
- In-line air heater in automatic control mode.

Control Mode 2

- Economizer heater off.
- Crystallizer heater off.
- Air blower speed and damper position in manual control mode.
- In-line air heater in automatic control mode.

Control Mode 3

- All heaters off.
- Control thermocouples wired to the damper valve and set as automatic control.

These tests showed that all three control modes produced temperature control bands of $\pm 2^{\circ}\text{F}$; however, it was noted that Control Mode 3 took twice as long to respond to changes in trapping temperature as the other two control modes. For this reason Control Mode 1 was used during the hydrogen trapping studies.

The hot trap was operated with all heaters in the automatic control mode. The preheater control thermocouple during normal operation was in a thermowell in the inlet piping to the getter tank. During preheat, the preheater control thermocouple was temporarily switched to the preheater piping itself.

3. Argon/Vacuum System Operation

Argon can be introduced into the ELS by either of two operating modes. In the first of these, argon can be manually introduced through either the 1.3-cm (0.5-in.) feed-and-bleed line or the 2.5-cm (1-in.) argon supply line from the vaporizer on the liquid argon tank. In the second mode, argon can be introduced either automatically or manually through the 10-cm (4-in.) vacuum break line or manually through the 2.5-cm (1-in.) vacuum break line of the dump tank vacuum break subsystem.

The 4-in. vacuum break valve (POV-67) is interlocked with the ELS safety shutdown system and automatically opens to break the ELS vacuum on the following off-normal events:

• Fire Detection	• Low Flow
• Loss of Power/Computer	• Lithium Leak Detection
• High Temperature	

This same air-operated valve can also be manually actuated from the control room or vacuum header area. The 2.5-cm (1-in.) vacuum break valve (POV-30) is interlocked the same as POV-67.

The following summary description outlines the procedure for establishing vacuum in the ELS. First, HOV-101 and HOV-102 are shut (see Figure 3). Then the rough pump is started and allowed to warm up ~20 minutes. During this warm-up time, the main surge tank is vented to 3.5 kPa (0.5 psig) with the feed-and-bleed system. When the pressure is 3.5 kPa (0.5 psig), the feed-and-bleed valves are shut. The pressure in the header between HOV-101/102 and POV-25 is then brought to 3.5 kPa (0.5 psig).

After the 20-minute period, POV-25 is opened and the variable leak valve (HOV-104) is adjusted for a pressure of 1×10^{-3} torr at the RNA. While monitoring the percentage of N_2 on the RNA, HOV-101 is slowly opened to the full open position. When the surge tank pressure is less than 14 psi, HOV-102 is opened. During the pump down, HOV-104 is adjusted to maintain 1×10^{-3} torr at the RNA. After the surge tank pressure reaches 500 millitorr, the Roots blower is started. When the header pressure is less than 1×10^{-3} torr, HOV-104 is shut and the header RNA is turned on.

E. OFF-NORMAL OPERATION

The built-in safety alarm circuitry for ELS was described previously in Section III, which also includes a brief description of each of the three alarm conditions, i.e., Conditions I, II and III. The operator response to all three alarms is identical for both attended and unattended operation and consists of the following:

- Silence the alarm.
- Review the hard copy printout of alarm(s). (All alarms automatically print out on the hard copier.)
- Determine the cause of the originating alarm (verify whether alarm is real or not).

- Correct the problem, as required.
- Clear the alarm per normal operating procedures.
- Restart the loop (if this was Condition II or III).

A call list was maintained by the 325 Building power operator and was used to call in ELS operating personnel, if an alarm occurred during off hours.

1. Condition I Alarm

A Condition I alarm is caused when any one of the more than 200 computer channels monitoring ELS deviates from normal operating conditions. The Condition I alarm is a plus or minus deviation alarm and can be viewed as an early warning system. This alarm will normally be followed by a Condition II alarm if no corrective action is taken. When an off-normal deviation occurs, the computer automatically initiates the following:

- The CRT indicates an alarm readout.
- The high-speed printer prints out the alarm.
- An audible alarm sounds in EDL-101.
- An audible alarm sounds in the 325 Building.

2. Condition II Alarm

A Condition II alarm is caused when the signal from any one of the Condition I channels continues to deviate to a second warning level; however, this alarm can be in only one direction and is positive on all parameters except flow. In addition the following equipment failures or events can directly cause a Condition II alarm:

- Computer and/or anaplexer failure.
- Low building air supply pressure.
- Ground fault detection.
- Auxiliary temperature control failure on EMP-1 or -2.

When any of the preceeding occurs, the computer automatically initiates the following:

- Main breaker de-energizes, which de-energizes all heaters, pumps, and blowers.
- The dump tank/surge tank vacuum breaker valve POV-67 opens.
- The surge tank and dump tank feed-and-bleed valves close.
- The CRT indicates an alarm readout.
- The high-speed printer prints out the alarm.
- An audible alarm sounds in EDL-101.
- An audible alarm sounds in the 325 Building.

The Condition II alarms were tested semi-annually to verify that the proper response would occur.

3. Condition III Alarm

A Condition III alarm has only two possible causes. The first is a fire alarm and the second is a power failure. When a fire alarm occurs, the computer automatically initiates the following:

- The main breaker de-energizes, which de-energizes all heaters, pumps, and blowers.
- The main dump valve (POV-1) opens.
- The dump tank/surge tank vacuum breaker valve POV-67 opens.
- The surge tank and dump tank feed-and-bleed valves close.
- The argon flood valve POV-26 to the surge tank opens.
- The diverter valves switch from normal to emergency exhaust.
- The scrubber fan starts.
- The CRT indicates an alarm readout.
- The high-speed printer prints out the alarm.
- An audible alarm sounds in EDL-101.
- An audible alarm sounds in the 325 Building.
- An audible alarm sounds in the 300 Area Fire Station.

The system response to a loss of power is the same as the response to a fire except that the computer dumps and the following events do NOT occur:

- The diverter valves do not switch from normal to emergency exhaust.
- The scrubber fan does not start.
- No computer printout is made.
- No audible alarms sound.

The Condition III alarms were tested quarterly to verify that the proper response would occur.

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VI. SYSTEM PERFORMANCE

A. LITHIUM SYSTEM

The ELS lithium system was described previously in Section IV.A. This system was originally hydraulically prototypic of FMIT, but did not include the dump heat exchanger. The ELS also had a main loop throttle valve to facilitate pump testing. After the ELS was fabricated, detailed hydraulic analysis of the FMIT lithium system identified a potential cavitation problem in the main loop. At this time the FMIT pump head was increased from 19 to 27 feet. Subsequent performance testing of the ELS main loop pump confirmed the cavitation predictions. Details of the pump performance tests are presented in Section VI.D.1.

In addition, detailed thermal analysis of the FMIT lithium system identified a potential boiling problem in the target drain region. Based on this analysis, the FMIT drain piping was revised to include a quench tank just downstream of the target. Driven by these two changes and the need for repackaging for remote handling and maintenance, the final FMIT lithium system evolved. This design is shown in Figure 41 and is described in detail in Reference 10.

In spite of these differences between the ELS and FMIT lithium systems, the ELS proved to be an invaluable tool for aiding the final design of FMIT. Two lithium system piping changes were necessary because of hydraulic considerations observed during ELS operation. The Mark I target would not drain properly at high flow rates, and a drain modification was made to ELS. This change and the impact on the Mark I target performance are discussed in detail in Section VI.C.1. The second piping change involved the chemistry loop surge tank. This tank was undersized and flooded the argon/vacuum piping on initial fill. At the same time the design of this tank was modified to include provisions for impurity additions. The tank volume was increased from 1.6 to 100 gallons.

FIGURE 41. FMIT Lithium System. Neg 8104784-2cn

Operation of this large lithium system with either a high vacuum or inert argon cover gas interface proved to be a worthy challenge and led to a number of modifications to the argon and vacuum auxiliary systems. These changes are discussed in more detail in the following section of this report.

B. ARGON AND VACUUM AUXILIARY SYSTEMS

The final configuration of the argon and vacuum systems met all the operating requirements of the Experimental Lithium System (ELS). Both systems continued to evolve during the four years of ELS operation as new operating requirements were identified. This was due, in large part, to the fact that the technology for operating a large lithium system under vacuum was previously nonexistent. The argon system provided adequate vacuum break, pressure control, and fire suppression. The vacuum system achieved the specified vacuum levels for the main surge tank and target [10^{-1} Pa (10^{-3} torr) and 10^{-4} Pa (10^{-6} torr), respectively]. The main vacuum header vacuum pumping system met the pumpdown time requirement (<1 hour) for normal operation; while the cryopump pumpdown time was acceptable for the non-typical, multisleeved, simulated beam tube.

Vacuum operation was plagued by vacuum gauge failures and increasing vacuum and safety relief valve seat leakage. These problems have been attributed to lithium vapor/aerosol transport throughout the vacuum system.

The ELS achieved unattended operation in the pressure mode, but not in the vacuum mode. This isothermal, nonradioactive test facility was operated safely and reliably for over 16,000 hours. Of this total, ~2000 hours of vacuum operation were achieved. An earlier account of the performance of the ELS argon and vacuum systems was presented in Reference 11.

1. Argon System

The final configuration of the argon system consisted of the following five subsystems:

- Liquid Argon Supply
- Argon Delivery or Makeup
- Argon Vacuum Break
- Argon Pressure Control (Feed and Bleed)
- Argon Fire Suppression

The liquid argon supply was vendor-leased equipment and consisted of a liquid argon Dewar and vaporizer. The argon delivery or makeup subsystem routed the gaseous argon from the vaporizer to the various ELS pressure boundary functions, as required. Early attempts to break vacuum with the argon makeup system resulted in physical damage to the argon supply regulators and air in-leakage. This led to the addition of the vacuum break subsystem at the ELS.

The vacuum break subsystem provided a capability to rapidly pressurize the vacuum space should air in-leakage be detected. The equalization features of the argon vacuum break system played a major role in limiting the effects of several air in-leakages during ELS operation. This capability could be invaluable if a large leak, such as a target burn-through, were to occur in the Fusion Materials Irradiation Test (FMIT) Facility.

A series of vacuum break tests was performed on both the 1.3-cm (0.5-in.) and 10-cm (4-in.) argon piping vacuum break lines. These tests consisted of measuring the time required to break the ELS vacuum (1×10^{-1} Pa or 1×10^{-3} torr) and restore the system to a "safe" positive pressure. This pressure has been defined as a minimum of 7 kPa (1 psig).

Runs were made with the 10-cm (4-in.) equalization line at two different test conditions. The first run was made with the lithium system preheated to 260°C (500°F), but drained of lithium (an active dump tank gas storage volume of 2.3 m^3 at 13 psig). This gas storage volume was not adequate to raise the system pressure to 1 psig without being assisted with makeup argon. The second run was made with the lithium system at 260°C (500°F) and filled with lithium (an active dump tank gas storage volume of 4.6 m^3 at 7 psig). A run

FIGURE 42. ELS Vacuum Break Performance Data.

was also made on a drained system with the 1.3-cm (0.5-in.) argon makeup line. The results of these vacuum break tests through the 1.3-cm and the 10-cm (0.5-in. and 4-in.) lines are shown in Figure 42.

These data show that in an emergency, such as a pressure boundary failure, the vacuum can be broken in just a few seconds with the 10-cm (4-in.) equalization line. For normal operation, the vacuum can be broken in a few minutes with the 1.3-cm (0.5-in.) argon makeup line.

The argon vacuum break function played a vital role in the safe operation of the ELS and consequently should be included in the FMIT design to minimize the consequences of air in-leakages. However, the FMIT vacuum break argon storage capacity should be increased over that provided for the ELS, so that the vacuum can quickly be brought to a positive pressure during all operating modes without argon from the low-flow makeup subsystem. In addition, it is recommended that rapid piping temperature excursions and air in-leakage be added to the FMIT list of events that activate the vacuum break valve. The vacuum should also be broken manually if off-normal conditions so indicate.

An argon pressure control (feed-and-bleed) subsystem was installed on each of the three ELS tanks to provide vent capability and pressure control above atmospheric pressure. The feed-and-bleed lines to the dump and main surge tanks both provided excellent pressure control when the tanks were operated in common at the same pressure. When the two tanks were set at different pressures, the pressures could not be maintained with the feed-and-bleed regulators on-line. This lack of pressure control was probably due to valve seat leakage across one or both of the equalization line valves (POV-30 or POV-67). Although the chemistry surge tank feed-and-bleed function was lost, this was attributed to an operation error that resulted in a lithium surge into the gas line during vacuum operation of the chemistry loop.

The argon fire suppression subsystem delivers gaseous argon to each of the three covered liquid lithium catch pans. Tests showed that this subsystem was capable of flooding the catch pans in less than 8 minutes and maintaining makeup gas for a minimum of 20 hours. This performance would be adequate to control a major lithium leak. Other than for test purposes, the ELS argon fire suppression subsystem was not needed, since no large lithium leak occurred.

2. Vacuum System

The vacuum system consisted of two subsystems, i.e., the main vacuum header and the cryopump. The main vacuum header vacuum pumping package proved to be very durable and reliable equipment over the four years of ELS operation (~2000 hours of vacuum operation). Although frost was observed on the internals of the Roots blower and in the rough pump oil, it had no measurable impact on pump performance. However, the Roots blower developed an oil leak during the last month of operation. It should be noted that the Roots blower and rough pump on the main vacuum header was a used, 20-yr-old pumping package. The cryopump, purchased new, was a late addition to the ELS and was operated for only about seven months. The main vacuum header and cryopump vacuum pumping systems both achieved, and even exceeded, specified vacuum levels. The specified high vacuum levels of 10^{-1} Pa (10^{-3} torr) and 10^{-4} Pa (10^{-6} torr) were achieved in the main surge tank and target beam tube, respectively. With the lithium system filled to normal operating level, the main vacuum header was capable of achieving the 10^{-1} Pa level in ~10 minutes. With the target flowing and a new multi-sleeved beam tube vapor test fixture installed, the cryopump was capable of achieving the 10^{-4} Pa level in ~4 hours. The rapid pumpdown times achieved also helped maximize ELS vacuum testing time.

A typical system pumpdown with the main vacuum header is shown in Figure 43. These data show that the main vacuum header is capable of obtaining vacuum levels of 10^{-1} Pa (10^{-3} torr) in about 10 minutes with the lithium system at 260°C (500°F) and filled for normal operation [gas volume of

FIGURE 43. Main Vacuum Header Vacuum Pump Performance Measured at the Main Surge Tank (Rough Pump and Roots Blower).

1.35 m³ (47.7 ft³) and lithium surface area of 4.8 m² (52 ft²)]. The measured pumpdown time of 10 minutes shows good agreement with the calculated pumpdown time of 9.38 minutes. Test results of the cryopump installed on the beam tube are shown in Figure 44. The cryopump is capable of obtaining vacuum levels in the high 10⁻⁵ Pa (10⁻⁷ torr) range in ~4 hours at the end of the beam tube. While the levels at the free surface of the target are in the low 10⁻³ Pa (10⁻⁵ torr) range with 540°F lithium flowing at 500 gal/min.

Because the ELS vacuum system was not intended to be prototypic of the FMIT vacuum system, it is not possible to make any specific vacuum pump sizing recommendations. Since there is no radiation associated with the ELS, the pumping units were relatively close coupled to the lithium system. This will not be the case at FMIT. It may be useful, however, to use the ELS vacuum pump performance as an input into the FMIT vacuum system design.

Some general recommendations on the vacuum pumping system can be made. Close coupling of vacuum pumps and turbulent lithium surfaces is not recommended, particularly with no vapor traps to restrict lithium vapor/aerosol transport. The type of vacuum pumping systems used on the ELS are recommended for consideration in the FMIT design process. Conservative sizing of the FMIT vacuum pumping system is recommended because of design uncertainties inherent in the vacuum system sizing design equations. This is particularly true regarding the uncertainty of gas loading from a large, dynamic lithium system. VanAtta⁽¹²⁾ recommends the computed minimum pumping speed be multiplied by a system allowance factor of about 4 to give some assurance of the desired performance in the 10⁻³ torr range. Considerations should be given to increasing this factor even more for FMIT because leakage into a system with multiple argon isolation valves is not typical of vacuum applications. A system allowance factor of 20 was used on the ELS main vacuum header pumping package. Some oversizing of the vacuum pumping system is also recommended for increased design life. The life of the pumping system can also be increased by minimizing startup/shutdown cycles at FMIT. At ELS the Roots blower, and sometimes the rough pump, was turned off daily because the lithium system was not operated unattended while under vacuum.

FIGURE 44. ELS Vacuum System Performance Measured at the Target.

If a Roots blower is used on FMIT, a foreline trap is recommended. A foreline trap at this location was not used on the ELS. It appears that such a trap may have been useful in limiting the backstreaming of oil when the Roots blower seal started to fail. In addition, an on-line Residual Gas Analyzer (RGA) would be a useful tool for early detection of oil and other leaks and is recommended for FMIT.

Periodic pressure rise testing of the FMIT vacuum system is recommended. The importance of this data in differentiating between real and virtual leaks is well documented.⁽¹³⁾ By maintaining a history of these pressure rise results, it is also possible to detect vacuum valve seat leakage degradation and schedule periodic maintenance.

ELS operations and failure data strongly suggest that vapor and aerosols will have to be better controlled on FMIT. It appears that a vapor trap would be a beneficial addition to the FMIT argon and vacuum systems. Control of lithium frost appears to be particularly critical to vacuum gauge performance. Although the coupling distances between the lithium and vacuum system components will be greater at FMIT, additional vapor/aerosol control is recommended. The screening elbows used on the ELS reduced vapor/aerosol transport and extended vacuum gauge life and are also recommended for FMIT.

To minimize the effects of outgassing on the FMIT vacuum system, it is recommended that the entire lithium system be baked out at 500°F and argon purge/vacuum cycled before lithium fill. This same pre-conditioning was performed on the ELS. Outgassing can also be reduced if good cleaning procedures are used during fabrication. Cleaning specifications similar to those used on the ELS are recommended for FMIT. Stainless steel materials should be used for all vacuum and argon system pipe or tubing runs.

The type of vacuum and gas valves used on the ELS are recommended for FMIT. All valves in the vacuum system should be bellows-sealed and constructed from stainless steel. Field substitution of valve O-rings is not recommended. Substitution of Kalrez® O-rings on the beam tube valve was

*Kalrez is a registered trademark of E.I. duPont de Nemours & Co.,
Wilmington, DE.

not successful. It is possible to purchase valves with higher temperature O-ring material directly from the factory. Based on the limited experience with Kalrez O-rings at the ELS, it is recommended that Viton® O-rings be used whenever possible on the vacuum valves.

The type of flanges and seals used on the ELS are recommended for FMIT. The Conflat vacuum flanges with flat copper gaskets proved to be effective in sealing and are reusable and adaptable to vacuum system changes or maintenance. However, the copper gaskets should not be reused or used where the potential for liquid lithium exists. The soft iron or fully annealed stainless steel (HEDL-fabricated) gaskets worked in these applications, but showed some physical damage to the sealing knife-edge of the Conflat flanges. Since these special gaskets were only used for a few makeup cycles on the ELS, the reusability of the flanges with these gaskets was not determined.

The use of pipe-threaded connections, Swagelok tubing connectors, and socket weld fittings should be avoided in the FMIT vacuum system because they contribute to virtual leaks. Another factor contributing to virtual leak effects could be the presence of small lines in the vacuum system. The use of ≤ 1 -in. vacuum lines should be minimized on FMIT. Finally, the use of standard flexible vacuum hose (rubber) is not recommended for FMIT. On several occasions this type of hose came off during ELS operation.

C. TARGETS

Hydraulic testing of FMIT lithium targets included both water and lithium tests. Preliminary testing of potential target concepts was performed in water. Both straight and curved backwall concepts were tested. From this work, the original, pre-prototype target wall concept evolved, i.e., the symmetric nozzle design. A second target was built that incorporated years of experience with design, analytical predictions, water tests, and lithium tests of the original design. Full-scale prototypes of both of these targets were fabricated and tested in both water and lithium. Results of the water testing are reported in References 14 and 19. Design codes

*Viton is a registered trademark of E.I. duPont de Nemours & Co.,
Wilmington, DE.

were prepared and used to predict target performance. These predictions have been compared with experimental results and are reported in Reference 15. A summary of the results of the two prototype targets tested in lithium at the ELS follows.

1. Mark I Target

The Mark I symmetric nozzle target was described previously in Section IV.C.1. Lithium testing of the Mark I target on the ELS included confirmation of hydraulic stability, drainability, and measurement of the free-wall jet thickness and surface roughness. Details of this work were reported in Reference 16. The following is a summary of this work.

Results from the Mark I target test program support the hydraulic viability of the FMIT free-wall lithium jet concept. At steady-state prototypic operating conditions the target produced a stable lithium jet with no evidence of splashing. Some splashing was observed during flow transients, and the splashing was found to be rate-dependent. Lithium drained properly from the target assembly by gravity alone following modification to the target drain region. High-speed still-life photography revealed a jet surface with numerous small waves that grew in magnitude as they traveled through the target deuteron-beam intercept region. Measurements of the surface roughness using the electrical conductivity probe system indicated that throughout the beam intercept region surface roughness was no greater than ± 0.5 mm (well within allowances). Similar measurements showed that the jet varied by less than ± 0.3 mm from its nominal thickness of 20.2 mm (again, well within allowances).

Observations showed that lithium wetting of the target structure proceeded relatively slowly and incompletely until the target backwall was spark-deposited with a coating of iron/nickel and gold. Lithium wetted the backwall of the target quite rapidly following this coating process.

Only qualitative measurements of lithium evaporation were made with the Mark I target. These results showed that, within a few hours of operation, a significant amount of lithium frost would collect on surfaces located within 0.2 m of the target jet surface, but frost was barely detectable at a distance of 0.4 m from the jet surface.

- Jet Stability and Drainage

Closed-circuit television (CCTV) observations of the target lithium jet when it was first installed in the ELS showed that the jet was hydraulically stable and intact at flow rates under $18.9 \times 10^{-3} \text{ m}^3/\text{s}$ (300 gal/min). However, significant splashing during rapid flow startup, some splashing during most flow excursions, and inadequate drainage above $18.9 \times 10^{-3} \text{ m}^3/\text{s}$ (300 gal/min) were observed. At rates greater than $18.9 \times 10^{-3} \text{ m}^3/\text{s}$ (300 gal/min), lithium filled the drain line and splashed into the beam tube. The extent of splashing during flow excursions was rate-dependent, i.e., faster or greater magnitude changes in flow rate caused more splashing.

After several hours of operation with lithium, flow rates to $25.2 \times 10^{-3} \text{ m}^3/\text{s}$ (400 gal/min) were obtained with only minimal splashing. It is postulated that argon cover gas used during nonvacuum operations was saturated in the lithium at the cover gas pressure [10^5 Pa (18 psia)] during initial startup. Disengagement of this gas in the target jet during initial operation could cause two-phase flow and impair adequate drainage by creating an excessive pressure drop in the target drain region. The improved drainage and reduced splashing observed at higher flow rates after several hours of testing were attributed in part to a reduction in two-phase flow by argon outgassing from the lithium.

However, the design flow rate of $33.4 \times 10^{-3} \text{ m}^3/\text{s}$ (530 gal/min) was unobtainable at 10^{-2} Pa (10^{-4} torr) because of the poor drainage from the target. Experience from earlier water testing indicated that the original drain configuration did not provide optimum drainage due to the hydraulic losses in the drain region from the sudden redirection of the jet (Figure 45).

OLD DRAIN

NEW DRAIN

FIGURE 45. Drain Configuration for Mark I Target.

Jet behavior was evaluated in lithium at lower flow rates while new drain designs were developed and tested with water. The ELS and target were then modified to accept a new drain configuration. This drain modification (Figure 45) allowed the jet to fall freely for about 1.4 m before impinging gradually on the walls of an inclined 150-mm (6-in.) diameter pipe.

Testing was repeated with the new drain configuration. Splashing into the beam tube was again observed during initial startup to $12.6 \times 10^{-3} \text{ m}^3/\text{s}$ (200 gal/min), and this splashing was still rate-dependent. However, the extent of the splashing was greatly reduced. All other flow excursions and flow shutdowns produced no splashing even at maximum rate changes as limited only by the automatic electromagnetic pump controller. With the new drain configuration, the design flow rate of $33.4 \times 10^{-3} \text{ m}^3/\text{s}$ (530 gal/min) was achieved and produced a stable lithium jet with no observed splashing. Draining was excellent at the design flow rate. Flow shutdowns from $33.4 \times 10^{-3} \text{ m}^3/\text{s}$ (530 gal/min) and all intermediate rates were smooth and splash-free.

A series of radiographs of the lithium jet were taken to further evaluate its behavior. A sequence of views were taken through the side of the jet, starting from the nozzle entrance and continuing down ~ 1.0 m of the drain line. Figure 46 shows the radiograph of the beam intercept region and the upper part of the drain region of the target jet. For reference, the conductivity probes shown in the figure are located at the beam centerline position.

The radiograph indicates that the jet thickness in the streamwise direction is quite uniform throughout the beam intercept region. These radiographs also showed that the lithium jet departed the curved backwall of the target at an angle less than expected and, therefore, struck the drain wall closer to the target than predicted. The deflection of the lithium jet as it left the target backwall was determined to result from surface tension effects and relaxation of the centrifugal velocity profile in the curved jet.

FIGURE 46. Radiograph of Mark I Target Lithium Jet and Upper Drain Region.
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Even with this deflection, the revised drain improved target drainage to allow completion of the test program. This drain design does not reflect the current design philosophy for the FMIT target drain. [The FMIT drain was tested in the second generation (Mark II) lithium test target.]

- Jet Appearance

Closed-circuit television (CCTV) was used with the Rotating Window Assembly to view the lithium jet. Since the lithium jet travels at ~ 17 m/s at the design flow rate and the CCTV cameras record at 30 frames/s, the lithium travels 0.5 m in every frame of video exposure. CCTV observation, therefore, does not give stop action viewing of the jet (Figure 47). However, some general statements regarding jet behavior can be made from these observations:

- In general, the jet appeared stable and intact at all flow rates. As the flow rate increased, the jet surface became more uniform in appearance.
- Several standing wakes existed across the jet width. These appeared to originate at the nozzle exit and target sidewalls and to fan out with increased distance from the nozzle.
- As flow rates increased, the wakes appeared to diminish in depth until, at $33.4 \times 10^{-3} \text{ m}^3/\text{s}$ (530 gal/min), the surface appeared to be reasonably smooth. The wakes are believed to result from slight imperfections or waviness of the target nozzle, or from hydraulic disturbances upstream from the nozzle.

Still-life photographs of the jet were also taken. With strobed, still-life photography at 8- μs exposures, the jet surface exhibited a pattern of many small surface waves (Figure 48). For example, at ~ 3.2 mm below the nozzle exit and at a flow rate of $31.5 \times 10^{-3} \text{ m}^3/\text{s}$ (500 gal/min), surface waves with 0.4-mm wavelengths were observed. Both period and wavelength increased with increased distance from the nozzle exit until the surface was almost entirely transformed into a grainy structure at beam centerline (20 mm below the nozzle exit). The wave pattern results from the growth of limited instabilities on the jet surface which originate at the nozzle exit. These

FIGURE 47. Mark I Target Lithium Flow at 500 gal/min Using Closed Circuit Television with Overlay of FMIT Deuteron Beam Spot-on-Target.

FIGURE 48. Mark I Target Lithium Flow at 500 gal/min Using Still-Life, 8- μ s Flash.

surface instabilities grow as the lithium travels away from the nozzle, so that at ~19 mm below beam centerline, measurements indicated that jet surface roughness had more than doubled. As discussed in the next section, this roughness was within allowances and will not compromise deuteron beam heat removal capability of the jet in the FMIT.

- Jet Thickness and Surface Roughness

Two conductivity probe devices (described in Section IV.K.10) were developed to measure jet thickness and surface roughness. Measurements with the first, multi-pin probe were made at three vertical positions: 1 mm below the nozzle exit, 20 mm below the nozzle exit at the deuteron beam centerline, and 19 mm below the beam centerline. These measurements span the beam intercept region for an FMIT target.

Results of these measurements are tabulated in Figures 49, 50 and 51. Just below the nozzle exit the jet was 20.0-mm thick with a roughness of ± 0.1 mm; at beam centerline the jet was 20.2-mm thick with a roughness of ± 0.3 mm; and 19 mm below beam centerline the jet was 20.5-mm thick with a ± 0.5 -mm surface roughness. The data from the conductivity probe agreed with the appearance of the jet, as observed with high-speed still-life photography and radiography, and were within allowances for jet thickness and surface roughness. The jet profile, as determined by this measurement, showed slight roughness at the nozzle exit and increased roughness at increased distance from the nozzle exit. The jet was thinnest at the nozzle exit, growing by ~3% in thickness through the beam intercept region of the target.

These measurements provided a preliminary characterization of jet performance in lithium. Occasional bending of the probe tips, lithium attack of the electrical insulator, and shorting of some pins in the lithium environment increased uncertainty of these measurements in the region 19 mm below the beam centerline. NOTE: In addition, local disturbances on the jet surface, such as the wakes and waves, were not measured directly.

FIGURE 49. Mark I Target Characterization in Lithium: Conductivity Probe Data at 19 mm Above Beam Centerline near Nozzle Exit.

FIGURE 50. Mark I Target Characterization in Lithium: Conductivity Probe Data at Beam Centerline.

FIGURE 51. Mark I Target Characterization in Lithium: Conductivity Probe Data at 19 mm Below Beam Centerline.

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Therefore, a new single-pin probe assembly capable of scanning the entire target area in the X, Y, and Z planes with improved resolution and accuracy was developed to resolve these issues. The single pin eliminated shorting and the need for an elaborate lithium-compatible insulator; and better instrumentation and interlocks prevented bending of the probe tip during calibration.

Measurements taken on the Mark I target lithium jet with the single-pin probe assembly closely match those taken with the multi-pin probe. Because of the close agreement with the previous measurements, the results with the single-pin probe are not presented here. Scans made of the jet surface were also made that showed limited surface defects. The defects were small, but the measurements were limited in quantity because of the development nature of the probe control system. Refinements to the control system were made before initiating Mark II target testing. Results from the Mark II target were much more complete as noted later in this report.

In conclusion, the Mark I target lithium test program confirmed the hydraulic viability of a free-wall lithium jet as an appropriate target concept for the FMIT. Tests confirmed the basic hydraulic stability of the free-wall lithium jet produced by this first-generation lithium-target design. At steady-state operating conditions, little or no splashing or other gross flow anomalies were observed following modification of the drain region. Surface roughness and jet thickness measurements were within allowances. Although significant amounts of liquid metal frost were deposited very near the lithium jet, these deposits were reduced substantially a short distance away in the simulated accelerator beam tube.

2. Mark II Target

The Mark II asymmetric nozzle target was described previously in Section IV.C.2. Lithium testing of the Mark II target on the ELS included confirmation of hydraulic stability, drainability, and measurement of the free-wall jet thickness and surface roughness. Details of this work have been reported in Reference 17. The following summarizes this work.

Full-scale testing of the prototype target assembly for the Fusion Materials Irradiation Test (FMIT) Facility using molten lithium at isothermal conditions was completed. This test program confirmed performance predictions and verified water modeling techniques. Test conditions included lithium temperatures to $\sim 280^{\circ}\text{C}$ (540°F), flow rates to $0.33\text{ m}^3/\text{s}$ (530 gal/min), and pressures ranging from $1.2 \times 10^5\text{ Pa}$ (18 psia) to $\sim 1.3 \times 10^{-3}\text{ Pa}$ (10^{-5} torr). Results show that the lithium jet produced by the target is stable at all FMIT operating conditions. The contour of the jet free surface matches predictions within 1.5%. The total vapor transport of lithium and its impurities from the target into the FMIT accelerator beam tube is estimated to be a maximum of 1.0 g/day based on test results.

- Jet Stability

The stability of the FMIT lithium jet was evaluated at both steady-state and transient flow conditions. The results confirmed predictions of a stable jet at FMIT operating conditions. Stability tests were performed at a target free surface vacuum of 10^{-1} to 10^{-2} Pa (10^{-3} to 10^{-4} torr) and at a positive pressure of $1.2 \times 10^5\text{ Pa}$ (18 psia). Lithium temperature was 260°C (500°F). Results were comparable for operation at vacuum and pressure. For steady flow conditions the lithium jet was stable at all flow rates from $3 \times 10^{-3}\text{ m}^3/\text{s}$ (50 gal/min) to $0.033\text{ m}^3/\text{s}$ (530 gal/min). No lithium was observed to be ejected from the surface of the jet, nor were any other steady-state stability anomalies identified with the video, still-life or high-speed motion pictures.

A typical photograph of the jet surface at the FMIT operating flow rate of $0.033\text{ m}^3/\text{s}$ is shown in Figure 52. Other than the wake near the center of the jet, the surface appears quite uniform over the region of interaction with the beam, particularly considering the high reflectivity of liquid lithium. The wake was also observed in water tests and results from a small defect at the nozzle exit. Though not anticipated, this defect provided the opportunity to quantify the effects of machining imperfections on nozzle performance. Measurements of the defect and its resultant wake are discussed later.

FIGURE 52. Mark II Target Lithium Jet Surface. Neg 8402910-17

Transient flow tests were also performed to determine if the target became grossly unstable during either a flow increase or decrease. Of primary interest was whether or not significant splashing occurred, or if the bulk lithium flow was redirected toward the beam tube. Flow rate changes (both increase and decrease) from $6 \times 10^{-5} \text{ m}^3/\text{s/s}$ (1 gal/min/s) to $4 \times 10^{-3} \text{ m}^3/\text{s/s}$ (70 gal/min/s) were performed from 0 to $0.033 \text{ m}^3/\text{s}$ and back to 0 again. A loss of flow transient was also performed by rapidly removing power to the pump. During the slower transients, the target was well-behaved. Little or no splashing was observed during flow increases until the rate was raised somewhat above $9 \times 10^{-4} \text{ m}^3/\text{s/s}$ (15 gal/min/s). This poses no problem for FMIT since flow increases can be accurately controlled to any desired rate. No significant splashing or anomalous behavior was observed at any flow decrease rates, including during the loss-of-pump-power test.

The stainless steel structure of the Mark II target was wetted by the lithium more rapidly and completely within a few hours of lithium exposure than was the original target after several hundred hours. No explanation of this difference has been developed. Because of this wetting, a thin film of lithium moved up the back side of the nozzle, into the light ports and into a section of the beam tube. Though not a serious effect, divertors may be needed along the walls near the entrance to the beam tube to prevent surface-tension-driven movement of lithium into the accelerator beam tube in FMIT.

- Jet Contour

Lithium jet thickness and the depth of surface phenomena were measured at discrete locations and by scanning across the surface of the jet with the automated single-pin conductivity probe measurement system. These results showed good agreement with predictions, requirements and water test results with the same target. Measurements were taken at a flow rate of $0.031 \text{ m}^3/\text{s}$ and a target pressure of 10^{-1} to 10^{-2} Pa (10^{-3} to 10^{-4} torr). Measurements were also performed with the target pressurized to 10^5 Pa (15 psia) for a comparison with data taken with water. (All water tests of this target were performed at atmospheric pressure.)

Measurements of jet thickness and surface phenomena were made at 17 discrete locations over the region of the jet that intercepts the deuteron beam. Results of the discrete measurements are presented in Figure 53 as a function of distance downward from the nozzle.

As predicted, the jet rapidly thins after exiting the nozzle. The thinning is caused by the transition from the velocity profile produced by the nozzle to the centrifugal velocity profile induced by the curved wall. At 0.5 cm below the nozzle the jet has thinned from the average nozzle exit dimension of 2.06 cm to a nominal depth of 1.96 cm. When it reaches the beam centerline, its nominal thickness has reduced to about 1.91 cm. Below beam centerline the jet continues to thin but at a slower rate than near the nozzle exit. The discrete point measurements agreed well with the predictions, being within 1.5% (0.03 cm) at all locations. The jet is slightly

FIGURE 53. Mark II Target Lithium Jet Thickness and Roughness Measurements: Vertical Contour.

thicker than predicted. Essentially all of this minor discrepancy can be attributed to the as-built dimension of the nozzle exit, which is ~ 0.02 cm larger than designed.

As Figure 53 shows, nominal thickness of the jet is well within the limits of allowable variations. The bases for these limits are discussed in Reference 18. Note that the limits (± 0.05 cm) are smaller in the 1.0-cm vertical window centered on the beam centerline. This is because the bi-Gaussian beam from the accelerator deposits $\sim 60\%$ of the deuterons in a 1.0-cm vertical x 3.0-cm horizontal window. As a result, $\sim 60\%$ of the neutrons are generated in this region, and a similar percentage of the beam energy is absorbed. Outside of the 1.0-cm vertical window the thickness variation limit is increased to 0.1 cm.

The magnitude of surface disturbances, or roughness, is also shown for the discrete measurements in Figure 53. Surface roughness variations must be limited to an amplitude of 0.1 cm to prevent rapid intermittent penetration of the beam to the target wall. Therefore, in the region of highest beam intensity, the jet (including surface roughness) must be no thinner or thicker than 1.75 or 2.05 cm, respectively. As the figure shows, surface roughness at all locations is less than ± 0.04 cm, and minimum and maximum thicknesses including roughness are well within limits.

Discrete thickness measurements provide very accurate data for the locations examined but can miss surface phenomena away from the specific locations. Therefore, the probe assembly was also used to scan horizontally across the jet surface. Scans were performed at three separate elevations, near the nozzle exit, at the beam midplane and near the bottom of the beam heated region. The results of the scan of greatest interest, at beam midplane, are shown in Figure 54. Even though local variations in thickness occur at several points across the width of the jet, minimum and maximum thicknesses at all locations are well within the allowable limits. Both of the other horizontal scans showed similar results, though the nature of the surface disturbances changed with distance from the nozzle. The jet was found to be within the thickness and roughness limits at all three elevations.

The wake near the center of the jet seen in Figure 52 is clearly evident in Figure 54. Even though the wake appears quite prominent in the photograph, the depth of the wake was measured to be only 0.02 cm less than the nominal jet thickness at beam centerline. Minimum jet thickness in the wake is well above the 1.75-cm limit. The wake was caused by a small defect in the exit region of the nozzle. The defect was too small to be measured with the target assembled, but it was estimated to be ~ 0.2 cm across x 0.01 cm deep.

Another prominent surface effect measured on the jet and shown in Figure 54 is a drop in thickness at both vertical sidewalls of the target.

FIGURE 54. Mark II Target Lithium Jet Thickness and Roughness Measurements: Horizontal Contour.

The corner of the nozzle where the front wall joins the sidewalls induces local instabilities in the jet. Though the drop in thickness near the walls is substantial, the thickness remains well within allowances. Furthermore, as shown on Figure 54, the beam does not extend horizontally to the locations where the greatest drop in thickness occurs.

Measurements of the target jet taken at a positive pressure with water indicate that jet thickness and surface roughness are nearly identical with results taken with lithium at a vacuum. As discussed in Reference 19 and shown in Figure 53, the correlation of lithium and water test results is good.

In conclusion, the FMIT Mark II prototype target performed as predicted in tests with lithium. The target produces a jet that is stable at steady-state FMIT operating conditions (excluding the deuteron beam) and remains

stable at all expected transient flow conditions. Nominal jet thickness matched predictions within a few percent and was within allowable limits. Surface roughness was less than the limit of ± 0.1 cm over the entire beam intercept region. Transport of the vapors of lithium and its impurities from the target is estimated to be less than 1 g/day in FMIT (see Section IX). These results show that the Mark II target satisfies its design and operating conditions and provide necessary input to the final design of the FMIT target and facility.

In comparing the performance of the Mark I and Mark II targets, it is clear that both produced a lithium jet that was stable and well behaved at steady-state operating conditions. Both produced acceptably low levels of surface roughness on the lithium jet surface. Both also produced lithium jets that were predictable in thickness and contour. Nozzle differences caused the Mark I jet to thicken slightly as it moved down from the nozzle, while the Mark II jet thinned somewhat. However, because of its improved drain design, the Mark II target produced less splashing during flow transients. With the improved drain design on a Mark I type target, either design could be used to meet the hydraulic design criteria for FMIT.

D. EM PUMPS

1. Main Loop Pump

The Annular Linear Induction Pump (ALIP) for the main loop was described previously in Section IV.E.1. Testing of this pump included a dry pull test and a complete performance test with lithium. Reference 20 provides an earlier account of this testing.

In summary, the results of the Annular Linear Induction Pump (ALIP 600-30) test demonstrate that the measured performance provides good correlation with predicted performance. The developed head at the design flow rate of $0.038 \text{ m}^3/\text{s}$ (600 gal/min) was 221 kPa (32 lb/in²). The cavitation inception Net Positive Suction Head (NPSH) at $0.038 \text{ m}^3/\text{s}$ (600 gal/min) was 39.3 kPa (5.7 lb/in²) absolute.

Pump coastdown tests were performed on the ALIP 600-30 pump design. When power was interrupted, pump flow typically dropped from $0.041 \text{ m}^3/\text{s}$ (646 gal/min) to zero in ~6 seconds.

Pump internal temperatures were closely monitored during all phases of pump testing. The air-cooled ALIP 500-30 pump design showed no heatup problems. Even with the EL3 piping system throttled to 300 gal/min, the pump coils ran only $\sim 38^\circ\text{C}$ ($\sim 100^\circ\text{F}$) higher than the bulk lithium temperature.

Two different control systems were tested with the ALIP 600-30 pump. Both solid-state and variac controllers were evaluated. No problems were encountered with either controller; however, the variac control system demonstrated greater rate and ramp control, and was capable of supplying 540 volts. This additional voltage, above the 480-volt solid-state controller capability, produced a 244 kPa (6 lb/in^2) pump head increase at the design flow rate of $0.038 \text{ m}^3/\text{s}$ (600 gal/min).

Specifically, pump performance tests were run at 200, 300, 400, 480, 500, and 540 volts with the bulk lithium temperature at $\sim 260^\circ\text{C}$ ($\sim 500^\circ\text{F}$). The 500- and 540-volt conditions were only achieved with the variac controller. Tests were repeated at surge tank pressure levels ranging from 122 kPa to $\sim 2.7 \times 10^{-1} \text{ Pa}$.

For pump head measurements, surge tank pressure and bulk lithium temperature were both held constant. Then, for each test voltage, the test was performed in two phases. First, with the main throttle valve (MOV-2) open, voltage was slowly increased to test level, or until cavitation occurred. If no cavitation was observed at the test voltage, the full flow data were recorded. Then MOV-2 was throttled in stages to achieve the desired $0.00317 \text{ m}^3/\text{s}$ (50 gal/min) increments. At each flow increment, additional pump data were recorded.

Plots of pump head versus flow from runs of major interest are presented in Figures 55 and 56. These data show good agreement with the predicted

FIGURE 55. Pump Performance at 122 kPa in Surge Tank with Solid-State Controls.

FIGURE 56. Pump Performance at 2.7×10^1 Pa in Surge Tank with Solid-State Controls.

head values. Note that both figures show data from two different runs at 480 V. The variations seen in these data are believed to primarily result from measurement inaccuracies of the instrumentation. For convenience, the predicted pump head curves for the 200- and 480-volt conditions have also been added to the measured performance data. In summary, these data indicate that the measured pump head provides good correlation with predicted pump performance at, and below, the $0.038 \text{ m}^3/\text{s}$ (600 gal/min) design point.

Switching from solid-state controls to variac controls did not result in any significant changes in pump performance. However, by increasing the supply voltage to 540 volts with the variac controller, a 244 kPa increase in pump head was observed at the pump design flow rate of $0.038 \text{ m}^3/\text{s}$.

Cavitation threshold tests on the ALIP EM pump were conducted on ELS with the loop operated at constant flows, pump voltage and lithium temperature, while the surge tank pressure was slowly lowered until cavitation developed. Cavitation measurements were made at 260°C and at several flow rates of interest with both the Silicon Controlled Rectifier (SCR) solid-state and variac pump controls. The results of these runs are presented in Table 19. These data are illustrated in Figure 57 and show a slight reduction in cavitation pressure with the variac controls.

With these measured surge tank pressures, the cavitation inception NPSH for the pump, at $0.038 \text{ m}^3/\text{s}$, can be calculated from the following relationship:

$$P_1 = P_2 + P_3 - P_4 \quad (1)$$

where:

- P_1 = Pump inlet pressure at cavitation, kPa (absolute) = NPSH
- P_2 = Surge tank pressure at 600 gal/min = 19.3 kPa (absolute)
- P_3 = Static lithium head pressure at pump = 26.2 kPa (absolute)
- P_4 = Piping loss at 600 gal/min = 5.9 kPa (absolute)

TABLE 19
PUMP CAVITATION INCEPTION DATA

Controls	Flow (gal/min)	Voltage (V)	Surge Tank Absolute Pressure (lb/in ²)
Solid-State	757	470	6
	664	470	4
	563	478	2
	532	473	1.5
	515	472	0
Variac	782	480	6
	675	480	4
	575	480	2
	670	470	4
	520	470	0

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FIGURE 57. Pump Cavitation Inception Data.

Therefore, at the $0.038 \text{ m}^3/\text{s}$ flow condition, the NPSH for the pump equals 39.3 kPa (absolute). At $0.033 \text{ m}^3/\text{s}$, the NPSH for this pump equals 30.3 kPa (absolute). Based on these measured cavitation inception performance data, it can be concluded that the pump would not cavitate at $<0.038 \text{ m}^3/\text{s}$ when operated in FMIT [50.3 kPa (absolute) pump suction pressure available] under hard vacuum conditions. This calculated cavitation inception NPSH (39.3 kPa) shows good agreement with the measured pump inlet pressure (37.9 kPa) during the cavitation measurement.

From Eq. (93) in Reference 21, the NPSH at cavitation inception for the pump would be predicted as:

$$P_T - P_V + P_e = 1.8 \frac{\rho V^2}{2} \quad (2)$$

where:

P_T = Total pressure at pump entrance

P_V = Vapor pressure of lithium at 260°C

P_e = Pressure caused by electromagnetic end conditions of EM pump

ρ = Density of lithium at $260^\circ\text{C} = 32.1 \text{ lb/ft}^3$

V = Velocity in pump annulus at $0.038 \text{ m}^3/\text{s} = 33.36 \text{ ft/s}$

also:

$$P_T - P_V = \text{NPSH} \quad (3)$$

where:

P_V = Negligible ($<< 1 \text{ lb/in}^2$)

$P_e = 1 \text{ lb/in}^2$ (Reference 21)

$\rho = 32.1 \text{ lb/ft}^3$

$V = 33.36 \text{ ft/s}$

Substituting these values and solving for $P_T - P_V$ results in a calculated NPSH at $0.038 \text{ m}^3/\text{s}$ of 7.93 lb/in^2 (absolute). Although this predicted NPSH value [7.93 lb/in^2 (absolute)] is conservatively higher than the measured value at $0.038 \text{ m}^3/\text{s}$ [5.7 lb/in^2 (absolute)], it provides a "state of technology" basis for EM pump design. It should be noted that this general equation for calculating NPSH at cavitation inception does not take into account specific pump geometries and related form losses.

Cavitation threshold was not greatly affected by the type of pump control tested. It should also be noted that the NPSH measurements made at the cavitation threshold may be conservative because of the possible presence of entrained gas (argon) during the cavitation measurements. Argon was used as the cover gas to change the pressure in the surge tank. Entrained gas is known to enhance cavitation.

Pump coastdown tests were performed on the ALIP pump to assist in FMIT safety analyses. Pump flow dropped from $0.041 \text{ m}^3/\text{s}$ to zero in $\sim 6 \text{ s}$, when power was interrupted. The piping system then functioned like a manometer, with flow direction changes for ~ 2 minutes before reaching equilibrium. The coastdown data are presented graphically in Figure 58. Runs were made at two different recorder chart speeds. A chart speed of 100 mm/s was used to record data on Figure 58.

Tests were performed to measure internal temperature buildup with the pump throttled to conditions similar to those predicted during operation with the FMIT target. One test was run with the pump at 480 volts and the loop throttled to $0.019 \text{ m}^3/\text{s}$. A second test was run with the pump at 480 volts and the loop throttled to $0.025 \text{ m}^3/\text{s}$. Figure 59 shows the temperature profile for the pump center coil when operated at $0.019 \text{ m}^3/\text{s}$ (480 volt) and $0.025 \text{ m}^3/\text{s}$ (480 volt) test conditions. Figure 59 also shows the bulk lithium temperature during these two tests.

The coil thermocouple plotted on Figure 59 is near the longitudinal centerline of the coil region. Data are also available for the two adjacent

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FIGURE 58. Pump Flowrate Coastdown at 480 Volts.

FIGURE 59. Pump Coil Temperatures at 480 Volts.

coil thermocouples and the lamination thermocouple. The coil temperature profile of these three thermocouples was uniform. For the $0.019 \text{ m}^3/\text{s}$ and $0.025 \text{ m}^3/\text{s}$ runs, the lamination temperature peaked at 188°C and 193°C , respectively, well below the design temperature of 538°C .

All of the coil region thermocouples were physically spot welded to the lamination material near the pump duct and were not mounted directly on the coils. The bulk lithium temperature measurement was made on the 10.2-cm (4-in.) pipe just downstream of flow meter MFM-1. The inlet and outlet duct temperatures at the beginning and end of each of these two runs were also recorded. These pump duct temperatures were fairly constant at 260°C .

In conclusion, results from the main loop pump test demonstrate that the measured performance provides good correlation with predicted performance. Test results also confirm that the static head of lithium currently planned for FMIT is adequate.

2. Chemistry Loop Pump

The two-stage a-c electromagnetic conduction pump used on the ELS chemistry loop was described previously in Section IV.E.2. This pump was destructively examined after 9500 hours of lithium service at 270°C . The pump had operated without incident before examination. The examination was motivated by an earlier pump failure at another laboratory. The other pump was operated at higher temperature (450°C) with less pure lithium for ~9500 hours when a duct rupture occurred. No evidence of service-related damage was observed in the ELS pump. More details on the pump examination are discussed in the corrosion section (Section X.C) of this report.

E. PURIFICATION HARDWARE

1. Cold Trap

A cold trap has been proposed as the means for controlling hydrogen, oxygen and carbon in the FMIT lithium system. A full-scale prototype of air-

cooled, in-line trap was fabricated in-house and subjected to thermal and purification testing at ELS.

Thermal performance tests at ELS demonstrated that the prototype cold trap was adequate to meet the FMIT trapping requirements of 0 to 3 gal/min lithium flow at an inlet temperature range of 425°F (218°C) to 518°F (270°C). However, the tube and shell economizer was found to be oversized and should be redesigned before FMIT application. Tests showed that an economizer coil with half the number of turns would have resulted in better temperature profiles across the crystallizer. Oversizing of the economizer could result in plugging in the 1-in. economizer tube when operating at small ΔT 's between the trap inlet temperature and the trapping temperature. The trace heat system, insulation and air cooling system were all adequate.

The prototype cold trap was also tested for hydrogen removal at lithium flow rates of 0.5 and 2.0 gal/min. The hydrogen impurity level was reduced from 110 wppm to ~70 wppm by cold trapping at 360°F, with trapping efficiencies ranging between 88% and 1%. A total of 27 grams of hydrogen (215 grams of LiH) were added to the chemistry loop inventory. Approximately 4% of the useful life of the cold trap is estimated to have been spent during this study. As expected, no increase in cold trap pressure drop was observed during this test. Estimates of the hydrogen removal rates at 0.5 and 2.0 gal/min indicate that the trapping rates are equal to or greater than the expected hydrogen isotope formation rate in FMIT. Consequently, the cold trap should maintain the hydrogen isotope concentration in the FMIT Facility below 80 wppm. Hydrogen concentrations ≤ 80 wppm should pose no operational concern at the FMIT operating temperatures (425° to 518°F).

Based on a predicted need for hydrogen removal from the FMIT lithium system, a total of four purification tests were performed with the 106-gallon ELS chemistry loop lithium inventory. A simplified schematic of the ELS chemistry loop is shown in Figure 60. The hot trap was valved out and frozen during cold trap testing. Two separate hydrogen additions were

FIGURE 60. Simplified Schematic of ELS Chemistry Loop During Lithium Purification Study.

made during this series of tests. Details of the impurity additions are presented in Section VIII.

Removal of hydrogen from lithium by cold trapping is dependent on the solubility of hydrogen in lithium. The solubility of hydrogen in lithium has been investigated by several workers.⁽²²⁻²⁴⁾ A solubility curve for hydrogen is shown in Figure 61.⁽²⁴⁾ Also shown in the figure are the solubilities for nitrogen, oxygen, and carbon for reference. The lowest value shown for hydrogen is 63 wppm. The curve suggests that 63 wppm is the lowest hydrogen concentration obtainable by cold trapping. This value occurs around 392°F and presumably remains constant to the lithium freezing point. All of these workers have made this same observation. They determined the hydrogen either by isotope dilution, resistivity measurements or by determining the partial pressure. This study is also in agreement with their earlier work. However, the hydrogen in this study was determined by a chemical method developed by R. F. Keough.

FIGURE 61. Solubility of Nonmetallic Impurities in Lithium as a Function of Temperature.(24)

The first two purification tests were performed after the first hydrogen addition. The results of these two tests are shown in Table 20. Both of these tests were made with a lithium flow rate of 0.5 gal/min through the cold trap. The data from the first purification test are shown graphically in Figure 62. The test was terminated after 19 hours of trapping at 405°F (207°C) and 68 hours of trapping at 370°F (188°C) with a resulting hydrogen

TABLE 20

HYDROGEN COLD TRAPPING RESULTS AT 518°F LITHIUM INLET TEMPERATURE
AND 0.5 gal/min LITHIUM FLOW FOR TESTS 1 AND 2

Sample No.	Date	Time	Trapping Temperature (°F)	Lithium Flow (gpm)	Air Flow (cfm)	Blower Speed (%)	Damper Position (% Closed)	Time at Trapping Temperature (h)	Hydrogen Concentration (wppm)
45	09-22-83	1430	490**	3.0	0	0	100	After Mixing	100
46	09-26-83	1510	405	0.5	8	25	85	0.17	99
47	09-27-83	0945	405	0.5	8	25	85	19	100
48	09-27-83	1518	370	0.5	35	25	75	2	86
49	09-28-83	0915	370	0.5	35	25	75	21	81
50	09-30-83	0825	370	0.5	35	25	75	68	76
51	10-04-83	1510	500**	0.5	0	0	100	After Reheat	89
53	10-05-83	1500	370	0.5	35	25	75	0	87
52*	10-05-83	1534	370	0.5	35	25	75	0.5	83
54	10-06-83	1030	370	0.5	35	25	75	19.5	78
55	10-07-83	1000	370	0.5	35	25	75	43	75
56	10-10-83	1142	370	0.5	35	25	75	116	70
57*	10-10-83	1252	370	0.5	35	25	75	117	73

*Flow-through tube samples; all others are thief samples.

**Isothermal conditions in chemistry loop.

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FIGURE 62. Cold Trap Results for Hydrogen with 370 °F Trapping Temperature and 0.5 gal/min Lithium Flow at 518°F Inlet Temperature for Tests 1 and 2.

concentration of 76 wppm. Earlier predictions for this trap design suggested that the hydrogen concentration should have been reduced to ~65 wppm in less time. These estimates were based on sodium cold trap efficiency data. The trapping efficiency during Test 1 has been estimated to range from 84% to 2%. Trapping efficiencies are calculated from Eq. (4). As shown on Figure 62, the trapping rate (hence efficiency) typically starts high and decreases rapidly with decreasing concentration.

Based on these results, the trap was then reheated (trap brought to 500°F isothermal condition) to drive the hydrogen in the cold trap back into solution and raise the hydrogen concentration in the lithium. The second trapping test was then initiated. For this test, the trap was maintained at the lower cold trapping temperature [370°F (188°C)] for 117 hours. At the end of this test, the hydrogen concentration was approaching 70 wppm. The

data from the second purification test are also shown graphically in Figure 62 and show good agreement with the results from the first test. The trapping efficiency for Test 2 ranged from 100% to 5.2%.

Based on the reduced hydrogen level (89 wppm) in the lithium after the first reheat of the cold trap, a second hydrogen addition was performed. After the second addition, the hydrogen level reached ~110 wppm. At this time, cold trapping Test 3 was initiated. The cold trapping temperature was reduced from 370°F (180°C) (Tests 1 and 2) to 360°F (175°C). All other test parameters remained constant. The data from this test are also shown graphically in Figure 63. The results of this test are shown in Table 21. The trapping efficiency during Test 3 ranged from 87% to 4%.

The trap was reheated again to drive the hydrogen from the trap and increase the concentration in the lithium. This time the isothermal reheat temperature was increased to 680°F (380°C). The resulting hydrogen concentration was ~110 wppm and the fourth trapping test was initiated. For Test 4, the lithium flow rate was increased to 2 gal/min. All other test parameters were the same as Test 3. The results of this test are shown in Table 22. The data from this test are also shown graphically in Figure 64. The trapping efficiency during Test 4 ranged from 20% to 1%.

The hydrogen concentration in the lithium did not decrease when the crystallizer temperature was set at 405°F (207°C) to 410°F (210°C) for 112 hours, even though there was a -28 wppm H_2 driving force (ΔC) for precipitation as the lithium passed through the cold trap. This is in agreement with PTI observations. Precipitation in the PTI orifice plate did not occur until the lithium was $\leq 385^\circ F$ (196°C). From these observations, it was concluded that supersaturation or undercooling of ~50°F is required before lithium hydride will precipitate on bare stainless steel. This information provides a guide for operation of a lithium cold trap and also gives some assurance that precipitation of lithium hydride will not occur in the economizer section of the cold trap until the lithium temperature is 50°F (27°C) below the hydrogen saturation temperature. (The preceding statements may not be true for H_2 concentrations >110 wppm.)

TABLE 21

HYDROGEN COLD TRAPPING RESULTS AT 518°F LITHIUM INLET TEMPERATURE
AND 0.5 gal/min LITHIUM FLOW FOR TEST 3

Sample No.	Date	Time	Trapping Temperature (°F)	Lithium Flow (gpm)	Air Flow (cfm)	Blower Speed (%)	Damper Position (% Closed)	Time at Trapping Temperature (h)	Hydrogen Concentration (wppm)
60	10-19-83	0646	500	0.5	0	0	100	After Mixing	108
			(Isothermal)						
61	10-19-83	1237	410	0.5	15	25	80	0	111
62	10-19-83	1730	410	0.5	15	25	80	5	89 (112)
63	10-20-83	1520	410	0.5	15	25	80	27	108
64	10-24-83	0620	410	0.5	81	25	60	112	104*
65	10-24-83	0950	360	0.5	70	25	65	1	95
66	10-24-83	1150	360	0.5	70	25	65	3	86
67	10-24-83	1350	360	0.5	70	25	65	5	76
68	10-25-83	1448	360	0.5	70	25	65	30	72
69	10-28-83	0625	360	0.5	70	25	65	94	69

*Slight trapping temperature excursion occurred.

TABLE 22

HYDROGEN COLD TRAPPING RESULTS AT 518°F LITHIUM INLET TEMPERATURE
AND 2.0 gal/min LITHIUM FLOW FOR TEST 4

Sample No.	Date	Time	Trapping Temperature (°F)	Lithium Flow (gpm)	Air Flow (cfm)	Blower Speed (%)	Damper Position (% Closed)	Time at Trapping Temperature (h)	Hydrogen Concentration (wppm)
71	11-01-83	0835	518	1.0	0	0	100	After Reheat	108
			Isothermal						
72	11-01-83	1520	410	2.0	81	25	60	3	Not Analyzed
73	11-01-83	1722	410	2.0	81	25	60	5	112
74	11-04-83	1710	410	2.0	81	25	60	29	110
76*	11-03-83	1100	360	2.0	123	25	41	2.5	90
75	11-03-83	1335	360	2.0	123	25	41	5	74
77	11-04-83	1430	360	2.0	130	25	35	30	70

*Flow-through tube sample; all others are thief samples.

FIGURE 63. Cold Trap Results for Hydrogen with 360°F Trapping Temperature and 0.5 gal/min Lithium Flow at 518°F Inlet Temperature for Test 3.

FIGURE 64. Cold Trap Results for Hydrogen with 360°F Trapping Temperature and 2.0 gal/min Lithium Flow at 518°F Inlet Temperature for Test 4.

The cold trap efficiency for hydrogen removal was estimated using the following relationship:

$$\frac{dc}{dt} = -\epsilon \frac{F}{V} (C_i - C_o) \quad (4)$$

where:

$\frac{dc}{dt}$ = Change in concentration/time

ϵ = Efficiency

F = Trap flow rate (gal/min)

V = System volume (106 gallons)

C_i = Concentration in the lithium as it enters the cold trap

C_o = Concentration in the lithium as it exits the cold trap
(63 wppm)

The rate of decrease in hydrogen concentration observed for the 0.5 gal/min and the 2.0 gal/min flow rates gives efficiencies of 0.71 and 0.22, respectively.

Based on a wide range of uncertainty for the estimated FMIT impurity burden and the cold trapping efficiency found during this test program, it is recommended that the crystallizer volume and residence time of the FMIT cold trap design be increased. The largest uncertainty in estimating the FMIT impurity burden was from carbon entering the lithium system during a heat exchanger coolant oil leak. The range of potential oil leakage from the lithium-to-organic heat exchanger used for the FMIT impurity burden estimates was 1 to 20 quarts. Examination of the impurity burden from a potential 20-quart oil leak clearly shows that providing a cold trap large enough to remove this burden is impractical. However, doubling the current cold trap crystallizer volume would appear to be a reasonable compromise. Doubling the volume would also double the residence time for the same lithium flow rates. It would also provide for the cleanup of 1 quart of oil over a 20-year plant life, as well as remove all other impurities. Any larger oil leaks would require cold trap replacement.

It is also recommended that oxygen and carbon additions be made to the ELS chemistry loop to determine trapping efficiencies for these impurities before procuring the FMIT cold trap. Data on cold trapping these impurities in lithium is not available in the literature and would be beneficial for the FMIT lithium cold trap design. The addition of each of these impurities under the controlled conditions afforded by the ELS chemistry loop would also be useful in gaining additional understanding of the PTI operation.

One aspect of cold trapping that was not investigated and is needed for lithium systems, is the accumulation of experience that allows the user to predict the useful life of a cold trap. This requires adding impurities to a cold trap until the pressure drop across the trap increases to the design value. Experience in sodium systems has shown that a practical pressure drop is ~20 psid. Sodium experience has also shown that the 20 psid is expected when ~10 vol% of the total crystallizer capacity is filled with impurities. The FMIT cold trap crystallizer volume is based on sodium experience that may not be applicable to lithium systems.

2. Hot Trap

A hot trap has been proposed as the means to control nitrogen impurity in the FMIT lithium system. A full-scale prototype of the in-line, titanium getter hot trap was fabricated in-house and subjected to thermal and purification testing at ELS.

Thermal performance tests at ELS demonstrated that the prototype hot trap was adequate to meet the current FMIT trapping requirements of 0 to 3 gal/min lithium flow at an inlet lithium temperature range of 425°F (218°C) to 518°F (270°C) and at trapping temperatures in the range of 700°F (371°C) to 1025°F (552°C). The preheater was sized adequately to maintain 1025°F (552°C) at the design flow rate of 3 gal/min. The economizer was also sized adequately to maintain the trap ΔT well below the 50°F (28°C) maximum allowable. The trace heat system and insulation were both adequate.

The in-line, titanium getter hot trap was tested at lithium flow rates of 0.5 and 2.0 gal/min. After the first test at a getter temperature of 932°F (500°C), the hot trap no longer reduced the nitrogen impurity level. The last test, at a getter temperature of 1025°F (550°C), showed renewed impurity removal potential. These results clearly indicate that the 932°F (500°C) trapping temperature is not practical for a titanium getter hot trap. Testing at the higher trapping temperature was very limited because of the termination of the ELS test program.

Hot traps remove impurities from liquid metals by providing a large surface area of a hot metal (getter) that forms stable reaction products with the impurities. Hot traps are usually operated above the normal system operating temperature. Elevating the temperature increases the reaction rate, the diffusion rate, and the solubility of the impurity in the getter material, thereby increasing the effectiveness of the getter. Other facets of system operation must be considered when increasing the getter temperature. Corrosion and mass transport of the getter containment vessel and the associated regenerative heat exchanger increase with temperature. Consequently, it is desirable to operate the hot trap at the minimum temperature that will still remove nitrogen at an acceptable rate. The temperature selected for the initial ELS testing was 932°F (500°C).

Based on the predicted need for nitrogen removal from the FMIT lithium system, a total of four purification tests were performed on the 106-gallon ELS chemistry loop lithium inventory. The hot trap tests were conducted with the cold trap isolated and the lithium in it frozen. (Refer to Figure 60 for chemistry loop schematic.) After the first nitrogen addition the hot trap temperature was increased to 932°F (500°C) and sampling was started to follow the nitrogen concentration. Table 23 summarizes the results from the trapping run. The time column of the table gives the elapsed hours at test conditions.

At the conclusion of Test 1, the hot trap temperature was decreased to 500°F (260°C) and the second nitrogen addition made. After the addition,

TABLE 23
HOT TRAP NITROGEN TEST 1 RESULTS

<u>Trap Conditions</u>	<u>Sample No.</u>	<u>Time (h)</u>	<u>N₂ Concentration (wppm)</u>
2 gpm/932°F	84	0	230
	85	2	180
	86	6	155
	87	24	103
	88	72	115 (118)*
	89	168	35 (33)*

*Re-analysis of the same sample tube.

the hot trap was increased to 932°F (500°C) and Test 2 started. Table 24 summarizes the results from Test 2. When the results showed that nitrogen removal was not occurring, it was decided to change operating conditions to improve the removal rate. First the residence time in the trap was increased by decreasing the trap flow rate to 0.5 gal/min. Table 25 summarizes the results for Test 3. Since the ELS testing was scheduled to terminate within a few days and Test 3 had not produced encouraging results, it was decided to increase the trap temperature to see if this had an effect on nitrogen removal. Table 26 gives the results of two samples before terminating the ELS testing. The lack of any nitrogen reduction after the first 3.5 hours at 1025°F has been attributed to a time interval necessary to remove a getter blocking coating on the titanium and is discussed in more detail later in this section.

Results from the hot trap testing show that the titanium became ineffective as a getter material at 932°F (500°C) after only one test run. Additional high temperature testing is required. Trapping efficiencies for Test 1 are shown in Table 27. The trapping efficiencies were estimated by

TABLE 24
HOT TRAP NITROGEN TEST 2 RESULTS

<u>Trap Conditions</u>	<u>Sample No.</u>	<u>Time (h)</u>	<u>N₂ Concentration (wppm)</u>
2 gpm/932°F	90	0	457
	92	2	443
	93	6	464
	94	19	454

TABLE 25
HOT TRAP NITROGEN TEST 3 RESULTS

<u>Trap Conditions</u>	<u>Sample No.</u>	<u>Time (h)</u>	<u>N₂ Concentration (wppm)</u>
0.5 gpm/932°F	95	2	412 (413)*
	96	6	422
	97	24	440

*Re-analysis of the same sample tube.

TABLE 26
HOT TRAP NITROGEN TEST 4 RESULTS

<u>Trap Conditions</u>	<u>Sample No.</u>	<u>Time (h)</u>	<u>N₂ Concentration (wppm)</u>
0.5 gpm/1025°F	98	3.5	439
	99	7	340

TABLE 27
NITROGEN REMOVAL EFFICIENCY FOR TEST 1

<u>N₂ Concentration in Lithium (wppm)</u>	<u>Average Efficiency (%)</u>
230 - 180	11
180 - 155	3
155 - 103	2
103 - 34	0.6

dividing the amount of nitrogen removed, during a particular test interval, by the total quantity of nitrogen that flowed through the hot trap during that test interval. Results from Test 2, where the nitrogen concentration did not decrease, show that the decrease in trapping efficiency during Test 1 was mostly caused by a progressive failure of the titanium foil to function as a getter rather than a function of the decreasing concentration of the unreacted nitrogen. Hot trap capacity at 932°F (500°C) was much lower than expected, since it had been predicted that the 112 lb of titanium foil in the ELS trap (based on the performance of the titanium in the ELF experiment)⁽⁵⁾ should remove 726 grams (1.6 lb) of nitrogen. Consequently, the 39 grams (0.086 lb) of nitrogen picked up during Test 1 should not have saturated the trap. However, the ELF titanium temperature was 1000°F (538°C) and, in ELS Test 1, the titanium temperature was 932°F (500°C).

In order to obtain an explanation for why the ELS hot trap capacity was lower than expected, some of the work from earlier experimenters was reviewed. The reaction of nitrogen and titanium has been investigated by several experimenters.⁽²⁵⁻²⁶⁾ However, most of the work was performed in the temperature range of 700°C to 1400°C and requires extrapolation of their data to arrive at information applicable to ELS and FMIT operating temperatures. Wasilewski⁽²⁶⁾ prepared a mathematical relationship to calculate both the diffusion of nitrogen in alpha titanium (the stable phase of titanium at temperatures <1621°F (<883°C) and nitrogen in titanium nitride (TiN) from a least-squares fit of experimental data. They are as follows:

1) Diffusion Nitrogen in Alpha Titanium

$$D = 1.2 \times 10^{-2} \exp \left(-\frac{(45,250 \pm 2250)}{RT} \right) \quad (5)$$

2) Diffusion Nitrogen in Titanium Nitride (TiN)

$$D = 5.4 \times 10^{-3} \exp \left(-\frac{(52,000 \pm 3500)}{RT} \right) \quad (6)$$

where:

D = Diffusion coefficient (cm^2/s)

R = Universal gas constant (1.987 cal/mole)

T = Absolute temperature ($^{\circ}\text{C} + 273$)

Substituting the ELS hot trap temperatures (932°F and 1025°F) into the above expressions, gives the following diffusion coefficients:

	932°F	1025°F
$D_{\text{N}\alpha\text{Ti}}$	$1.9 \times 10^{-15} \text{ cm}^2/\text{s}$	$1.1 \times 10^{-14} \text{ cm}^2/\text{s}$
D_{NTiN}	$1.1 \times 10^{-17} \text{ cm}^2/\text{s}$	$8.4 \times 10^{-17} \text{ cm}^2/\text{s}$

These diffusion coefficients indicate that the transport of nitrogen in both titanium metal and titanium nitride is relatively slow. The coefficients also show that, if titanium nitride forms on the surface of the foil, the diffusion rate should decrease significantly.

Wasilewaki⁽²⁶⁾ derived a relationship between surface thickness (reaction layer) and the diffusion coefficient. The relationship for a foil that has a proportionally large surface area to thickness is:

$$d = 2.5 \sqrt{Dt} \quad (7)$$

where:

d = Penetration of diffused solute (N_2 in this case), (cm)

D = Diffusion coefficient (cm^2/s)

t = Time (s)

Substituting the conditions for hot trap Test 1 into the above expression, we obtain:

$$d = 2.5 \sqrt{1.9 \times 10^{-15} \text{ cm}^2/\text{s} \times 6.05 \times 10^5 \text{ s}}$$

$$d = 8.5 \times 10^{-5} \text{ cm}$$

The estimate predicts that the nitrogen penetrated a very short distance into the foil.

If we assume that the nitrogen removed all reacted to form titanium nitride (TiN), we can estimate the theoretical amount and volume.

nitrogen weight = 39 grams

TiN weight:

TiN volume:

$$V = \frac{172 \text{ grams TiN}}{5.22 \text{ grams/cm}^3} \text{ (density of TiN)}$$

$$V = 32.9 \text{ cm}^3$$

If we assume further that the TiN was equally distributed on the surface of the foil, the thickness can be estimated as follows:

$$\begin{aligned}\text{area} &= (932 \text{ ft}^2) (2 \text{ sides}) (927 \text{ cm}^2/\text{ft}^2) \\ &= 1.7 \times 10^6 \text{ cm}^2\end{aligned}$$

$$\begin{aligned}\therefore \text{TiN thickness} &= \frac{32.9 \text{ cm}^3}{1.7 \times 10^6 \text{ cm}^2} \\ &= 1.9 \times 10^{-5} \text{ cm}\end{aligned}$$

Both estimates predict the foil-nitrogen reaction in Test 1 was on, or near, the surface only. At the start of the test, there was a large surface area free to react with the nitrogen in the lithium. As the test progressed, nitrogen removal became limited by the diffusion rates and/or the solubility of nitrogen in the titanium getter.

The solubility of nitrogen in titanium was not discussed by the investigators in the literature reviewed for this report. Bagnall⁽⁵⁾ attempted to determine the impurity concentration profile in the titanium foil after the ELF test; however, because of the limitations of the instrumentation, the foil was analyzed to a depth of only $\sim 5 \mu\text{m}$. The nitrogen profile was similar from the surface to this depth. He reported the relative abundance of O_2 , H_2 and N_2 , not the percent by weight concentration.

Other reactions and/or film formation on the surface of the titanium foil may have contributed to the decrease in the removal rate. We believe that precipitates of calcium oxide were present in the loop.⁽²⁷⁾ During hot trap testing, the soluble calcium increased. This could have been from the hot titanium reducing the calcium oxide to calcium metal and forming titanium oxide on the surface of the foil. The precipitates of both aluminum nitride and lithium silicon nitride may have affected the reactivity of the titanium foil. There were no observed increases in soluble aluminum or silicon during the tests, consequently reactions (if they did occur) would have had to occur in the solid state. H. U. Borgstedt⁽²⁸⁾ reported the presence of a surface film and or a reaction layer on zirconium and titanium

foil used for a lithium hot trapping study. Both nickel and manganese transferred from the stainless steel container to the foils, thereby decreasing the activity of the getter. The foils also had a surface concentration ranging up to 50% in calcium. Scanning electron microscopy showed the surface of the foils were covered with fine grained crystals (cubic in structure) that contained the calcium.

In Test 4, when the hot trap temperature was increased to 1025°F (552°C), 19.8 grams of nitrogen were removed in 7 hours. Unfortunately, the testing had to be terminated to meet project goals; consequently, the outcome of the 1025°F (552°C) test is uncertain.

In conclusion, thermohydraulic testing of the hot trap showed the design to be adequate for FMIT use. However, the hot trap purification tests were inconclusive and show that significant development work is needed before selecting a getter material, establishing the operating conditions for a FMIT trapping system and predicting the trap life for the FMIT lithium system. This work should include more high temperature testing on the ELS and eventual destructive examination of the hot trap to evaluate surface contamination of the getter.

A screening study similar to the work conducted by J. M. McKee⁽²⁹⁾ for oxygen removal from sodium should be performed for nitrogen removal from lithium. Titanium, zirconium, yttrium, and alloys of these elements should be evaluated. McKee found that an alloy of Zr-13% Ti was the best getter material for removing oxygen from sodium. The combination getter material (Zr-Ti), used in the ELF hot trap, should be reconsidered. If additional testing is not performed before selecting a getter material for the FMIT hot trap, a combination of Zr and Ti is recommended for the FMIT design with a 1000°F (538°C) trapping temperature. Finally, based on over four years of effective nitrogen control at ELS with soluble getters (i.e., aluminum and silicon), consideration should be given to the use of this approach to

nitrogen control at FMIT (see Sections VII and VIII for more discussions on soluble gettering observed at ELS).

F. IMPURITY SAMPLING HARDWARE

1. Flow-Through Tube Sampler

The Flow Through Tube Sampler (FTTS) used on the ELS was previously described in Section IV.G.1. As discussed, both filtered and unfiltered sample tubes were used. A total of 78 samples were taken with this type of sampler during ELS operation. The ELS lithium chemistry is discussed in Section VII. Overall these sample tubes worked well; however, lithium flow blockage occurred on several of these samples. The flow blockage was due to three different problems.

Nitride contamination was reported to cause plugging at the connection point of the chemistry loop mechanical connectors. This occurred despite the use of inert bagging procedures during sample tube installation and removal. Care must be taken during changeout of a sample tube so that nitride plugging doesn't occur at the exposed ends of the tube. The sampler must be provided with an inert glovebox or an inert gas blanket when the sample tube is changed. The inert bagging procedures used at ELS did not effectively eliminate this problem.

A second cause of flow blockage was cold plugging caused by inadequate preheating of the sample tube. The original furnace cover that provided both the heaters and insulation was found to be inadequate and was removed. Sample tube preheating was subsequently achieved with tape heaters. Careful reheating and re-insulating of each sample tube proved to be adequate for preheating a sample tube. This activity, which may be acceptable for ELS, appears to be tedious as well as time-consuming for remote sampling at FMIT.

Combining the heaters, insulation and support in one unit that folds back to gain access to the sample tube is a superior design; however, the

heater wattage must be adequate, the thermocouples properly placed and the integral unit rigid enough to support itself as it is raised and lowered. Redesign of the sampler cover for FMIT application seems a necessity.

The third cause of loss of flow was plugging of the original 15- μm (2-in² surface area) filter. The particulate concentration in the ELS lithium was higher than originally anticipated due to the reactions between oxygen and calcium and between nitrogen and aluminum and silicon. These reactions are discussed in more detail in the chemistry section (Section VII). This high particulate concentration caused premature plugging of the filter during the one-hour sampling period. In some cases the filter plugged in just a few minutes. Based on this experience a second, larger (7-in² surface area) 10- μm filter was used and found to be adequate.

It is recommended that the FTTS be used for taking lithium samples at FMIT. Both filtered and unfiltered samples should be taken. The larger (7-in² surface area) 10- μm filter was adequate and is recommended for FMIT. The upper heater-insulation-cover combination for the FTTS (see Figure 20 in Section IV.G.1) should be redesigned to provide a more rugged structure. Additional heater capacity and extra insulation should be included in the design so that the cold spots encountered at ELS can be eliminated. A heater and insulation should be added to the sampler body to minimize the heat loss out the bottom of the sampler cabinet.

2. Thief Sampler

The thief sampler used on ELS was previously described in Section IV.G.2. The thief sampler worked satisfactorily on the ELS. Twenty-two samples were taken with this type of sampler during the cold and hot trap studies. Table 28 shows a comparison of duplicate samples taken with the FTTS and with the thief sampler during the cold trap evaluation for hydrogen removal. The first two samples and the last two samples were taken simultaneously.

TABLE 28
RESULTS OF SAMPLING DEVICE COMPARISON

<u>Sample No.</u>	<u>FTTS</u>	<u>Thief Tube</u>	<u>H₂ (wppm)</u>
ELS-52	X		83
ELS-53		X	87
ELS-56		X	70
ELS-57	X		73

The results obtained show no appreciable difference between the two samplers and are within the precision of the analytical method. The ELS lithium chemistry is discussed in Section VII.

In conclusion, a differential pressure of 4 to 5 psig is required to fill the sample tube; consequently, the thief tube sampler would not be applicable for systems operated under vacuum. This device is not planned for use on FMIT.

3. Gas Sampler

The gas sampler used on ELS was previously described in Section IV.G.3. The gas sampling concept worked satisfactorily on the ELS. Sixteen samples of argon cover gas were taken from various locations in the ELS during fill and operation. The cover gas chemistry is discussed in Section VII.

Care must be taken during gas sampling to avoid air in-leakage into either the sample cylinder or the ELS. This can be achieved by thorough helium leak checking and by not allowing the system to vent all the way to atmospheric pressure while sampling.

G. VALVES

1. Lithium Valves

The lithium valves used on ELS were described previously in Section IV. All system and test valves worked well. One lithium valve failure was reported during ELS operation. The 1-in. Hoke test valve stuck open after ~2000 hours and 5000 operating cycles and showed increased seat leakage. This valve was removed from the loop after 3500 hours, cleaned, and inspected to determine the cause of the failure. A buildup of lithium impurities in the upper region of the valve bellows appeared to have caused the failure. It was postulated that non-uniform trace heating of the valve bonnet allowed it to act as a diffusion cold trap and collect impurities. The valve was re-installed on ELS with a revised trace heat arrangement. The valve was tested for an additional 3075 hours and did not fail to operate.

Bellows and seat leakage tests were performed on three different 1-in. lithium test valves (Nupro, Sargent and Hoke). Table 29 shows the results of these leakage measurements. The leakage measurements were made with gaseous helium and a wet test meter. The measurements were made at ambient temperature after the valves had been disassembled, cleaned and reassembled. Some of the apparent increase in seat leakage observed from the Hoke valve may have been the result of the disassembly/reassembly procedure. There was no observable damage to the valve seat.

One common type of valve operator failure occurred during ELS operation. Most of the PRE-CON motor operators used on the 1-in. and 0.5-in. Nupro valves failed. Vibration inherent in this design caused the connecting shaft backing nut to loosen and separate or the valve position potentiometer to loosen and give erroneous feedback. After repeated attempts to correct these vibration problems, these valves were operated by hand. This design is not recommended for FMIT automatic throttle valve operators.

TABLE 29
LITHIUM VALVE LEAK TEST RESULTS

<u>Manufacturer</u>	<u>Valve Type</u>	<u>Nominal Size (in.)</u>	<u>Temp (°C)</u>	<u>Total Operating Cycles</u>	<u>Total Service (h)</u>	<u>Bellows Leakage*</u>	<u>Seat Leakage at 20 psi (std cm³/sec-He)</u>
Hoke	Bellows Sealed Modified Plug	1	N/A	0	0	None	1×10^{-2}
			270	5,000	3,500	None	4.5×10^{-1}
			270	10,000	5,500	None	2.1×10^{-1}
Sargent	Bellows Sealed Y-Pattern Glove	1	N/A	0	0	None	2.5×10^{-1}
			270	5,000	2,000	None	1×10^{-1}
Nupro	Bellows Sealed Plug-Poppet	1	N/A	0	0	None	1.5×10^{-3}
			270	0	3,500	None	5×10^{-3}
			270	5,000	3,500	None	1×10^{-5}
			270	10,000	5,800	None	4×10^{-3}

*No detectable leak with helium leak detector sensitivity of 2×10^{-10} atm-cc/s.

2. Gas and Vacuum Valves

No formal seat leakage or flow tests were performed on any of the numerous argon and vacuum valves used on the ELS (see Appendix A for a complete list of valves). However, day-to-day operation of the ELS indicated seat leakage deterioration in some of the valves. This deterioration was particularly noticeable in the target area on the simulated beam tube vacuum isolation valve, on the target light source, and on the vacuum sensor isolation valves. All of these valves were subjected to some lithium splashing and frost, which resulted in the valves either becoming inoperable or exhibiting seat leakage.

Seat leakage was most noticeable on the 15.0-cm (6-in.) target beam tube isolation valve. This valve held a vacuum prior to the first beam tube vapor test, but would not hold a vacuum after that test. The seal material on this valve was a field-installed substitute Kalrez O-ring because of the 500°F operating temperature requirement of this valve on the beam tube. This seal performance might also be attributed to seal replacement problems. However, this same, but much less dramatic, loss of vacuum sealing ability was also observed in other portions of the vacuum system. The majority of the elastomeric O-rings in the other vacuum valves were manufactured from Viton. One of these valve failures was attributed to an over-temperature application, while the second was believed to result from frost. Seat leakage problems were also observed in the safety relief valve on the main surge tank after this valve had vented some argon gas.

It appears that equalization line valves (POV-30 and/or POV-67) seat leakage resulted in the inability of the dump and main surge tank feed-and-bleed systems to control the dump and main surge tanks at pressures of 3 and 1 psig, respectively. With the feed-and-bleed systems activated, pressures

in these two tanks tended to equalize after being pressurized to these levels. Lack of pressure control was probably due to seat leakage across one or both of these valves. It is recommended that both of these valves be removed and seat-leak-tested prior to resumption of ELS operation.

These experiences with valves, as well as frost effects on the vacuum sensors and pumps, suggest that a vapor trap would be beneficial in the FMIT argon and vacuum system design, particularly where high-quality vacuum sealing is required.

The elastomer diaphragm pressure regulating valves used on the ELS were found to be inadequate for breaking vacuum. The first time the vacuum was broken with this type of regulating valve, the elastomer diaphragms were sucked into the valve and gross air in-leakage occurred. When the argon supply line was brought on line, the entire supply line up to the pressure regulating valve was pulled to a negative pressure. After this failure, alternate methods for vacuum break were devised (see Section VI.B).

H. STATIC MECHANICAL SEALS

1. Lithium Seals

The static mechanical lithium seals used on the ELS were described previously in Section IV.I. All of the lithium seals used on the ELS worked well. No lithium was observed beyond the flanges of any of the designs tested. However, on two of the seal designs, lithium had weeped beyond the final sealing edge.

The 4-in. Rocky Mountain Nuclear connector on the Mark II target leaked beyond both the inner and outer seals of this dual seal joint. The leakage was slight beyond the outer metal O-ring seal and was not visible before separating the joint. This connector was in service for 356 hours. The operating temperature during this time was from ambient to 750°C (1352°F), with most of the hours at 260°C (500°F). The helium leak rates for this joint before and after testing were:

	<u>Before Testing</u>	<u>After Testing</u>
Inner Seal	3.6×10^{-8} atm cc/s	$<1.1 \times 10^{-8}$ atm cc/s
Outer Seal	3.6×10^{-7} atm cc/s	2.5×10^{-5} atm cc/s

However, all leak data were measured when the joint was cold, and they may not be representative of actual leakage during operation. The outer seal of the joint was a silver-plated hollow Inconel O-ring. The silver appeared to be attacked by the lithium and/or lithium/air reaction products. The inner seal was made from 17-4 PH stainless steel. Based on this experience, a soft iron plate is recommended for the outer seal, and a A-286 stainless steel is recommended for the inner seal. Additional bench testing of these seals is recommended.

Two of the 1-in. Grayloc connectors on the valve test manifold leaked beyond the sealing line of the seals. The weepage was very slight. One of these connectors weeped on two different occasions, with two different seals. In all three cases the seals that weeped were made from AISI 630 material. AISI 660 seals were also used in these same connectors, as well as on other similar connectors with no weepage observed. Based on these limited data, it is recommended that the AISI 660 seals be used for future ELS operation.

In conclusion, it would appear that thermal expansion compatibility between the seal and connector materials is essential for high-temperature service. It would also appear that small lithium leaks (like small sodium leaks) have a tendency to self-seal. It also appears that lithium will leak from a smaller leak path than sodium. From the limited ELS data it appears that the minimum acceptable helium leak requirement should be 1×10^{-7} atm cc/s.

2. Argon/Vacuum Seals

Several different types of static mechanical seals were evaluated in the argon and vacuum systems (see Section IV.I, Table 11 for description). Static mechanical seal testing on the ELS consisted of initial helium leak testing to a minimum acceptance level of 1×10^{-7} std cc/s. In addition, vacuum integrity was demonstrated with the on-line RNA set to monitor nitrogen partial pressure in the vacuum system and with periodic helium mass spectrometer leak tests.

All the static mechanical argon and vacuum seals tested were found to be compatible with the ELS liquid metal vapor/aerosol environment during the four years of ELS operation. However, the elastomer and copper gaskets were not intended for liquid lithium service. During testing of the FMIT target, lithium (driven by wetting of the stainless steel and surface tension) came in contact with a copper gasket in the vacuum system causing gasket deterioration. A vacuum leak was observed on the RNA, and the seal was replaced with a fully annealed 316 stainless steel gasket. At this same time, all copper gaskets in close proximity to the target were replaced with annealed stainless steel or soft iron gaskets (as shown in Table 11). Both of these HEDL-made gaskets provided good seals but required higher loading than the copper gaskets. These harder gaskets were more damaging to the sealing knife edges of the conflat flanges. The knife-edge damage was visible without magnification, but quantitative measurements of the damage were not made.

I. TRACE HEAT AND INSULATION

The ELS trace heat system and insulation were previously described in Section IV.J. While the trace heat hardware and insulation used on the ELS performed very well, numerous cold spot problems occurred during ELS operation. The problems occurred in spite of the fact that a thorough trace heat system pre-operational dry preheat performance test was performed. Piping temperatures were thoroughly checked using contact pyrometry to find localized cold spots. The dry preheat test included heating the entire ELS

lithium system to a maximum temperature of 260°C (500°F). The temporary drum transfer piping was preheated to a maximum temperature of 232°C (450°F). This scan indicated that the ELS trace heat system piping temperatures varied by +140°F/-220°F from the nominal 260°C (500°F) setpoint. Damaged insulation and faulty installation were also observed during this scan.

No failures of any of the permanent heater elements used on the ELS occurred during the entire operating period. However, one heater termination burn-through did occur. The heater termination failure was caused by the termination being covered with insulation and that caused the copper wire to become brittle and break.

Based on heat trace operating experience from ELS, it is recommended that the FMIT trace heat design consider the following:

- Apply tight specifications and inspections for minimum heater/pipe gap on FMIT fabrication if the contact heater attachment concept is used. Gaps as small as 2 in. between active heat elements caused flow blockage during startups on ELS.
- Add additional heater capacity and/or control to known heat-sink locations associated with electromagnetic (EM) flowmeter cages, EM pump shells, liquid metal valve stems, and pipe hangers.
- Verify trace heat designs experimentally prior to FMIT lithium fill. Use contact pyrometry scans of the piping system before lithium fill for this purpose.
- Do not bury heater and thermocouple terminations in the insulation. Glass-tape all terminations.

J. INSTRUMENTATION

1. Pressure Transducers

The pressure transducers used on ELS were described previously in Section IV.K.1. In general both (individual and differential) types of liquid metal pressure transducers performed well. The bourdon tube of the inlet sensor on the main loop pump was inadvertently overpressurized and permanently distorted. The exact cause of this overpressurization was never

identified; however, this failure may have resulted from improper trace heating. Lithium pressure drop (ΔP) values are accurate within an uncertainty of ± 0.25 psi. Half of this uncertainty is attributed to the monitor/computer, not to the ΔP pressure sensor.

All the argon and vacuum pressure sensors shown on Table 13 performed well except the high and ultra-high vacuum sensors. The particular sensors that had trouble surviving the high frost/aerosol ELS environment included the capacitance manometer, millitorr, cold cathode, and ultra-high vacuum (UHV) gauges.

The capacitance manometer installed on the MARK II target failed after ~ 90 hours and was not repaired or replaced. The cause of failure was not determined, but it is most likely that the diaphragm was damaged by the pressure pulse associated with the emergency vacuum break. Several emergency vacuum breaks occurred during the testing of this gauge. It is possible, however, that this gauge may have been affected by lithium frost/aerosols. At the time the erroneous negative signal was reported, the diaphragm was still responding to changes in pressure.

Although there were a number of Millitorr gauge failures, these gauges showed some potential where lithium frost could be controlled. Without protective in-line screens, these gauges failed in the first few hours. Figures 65a and 65b show this gauge before and after frost exposure. The gauge shown in Figure 65b was used on the main vacuum header for ~ 800 hours of vacuum operation. After screening elbows were installed on the main surge tank, this type of gauge survived 6 months of service. The screening elbow increased the life of the gauge to ~ 90 hours on the target.

The cold cathode gauge on the main vacuum header indicated a higher than actual vacuum level after exposure to lithium frost. This was caused by a buildup of frost on the cathode (see Figures 66a and 66b for photographs of this gauge before and after frost exposure). The gauge shown in Figure 66b was used on the main vacuum header for ~ 800 hours of vacuum

a. Before Service. Neg 8303558-13cn

b. After ~ 800 Hours of Vacuum Service. Neg 8303558-2cn

FIGURE 65. Millitorr Gauge Before and After Service.

a. Before Service. Neg 8303558-15cn

b. After 4800 Hour of Vacuum Service. Neg 8303558-9cn

FIGURE 66 Cold Cathode Gauge Before and After Service.

operation. Possible preventative measures to shield the gauge could be a protective screen or a vapor trap.

The cold cathode gauge in the RNA pumping system at first appeared to be unaffected by the frost. No problems occurred with this gauge during three years of service. However, this gauge was protected from frost by a small variable-orifice leak valve. It was inspected after 2.5 years of operation, and no visible frost was observed.

The UHV gauge was the only ultra-high vacuum gauge used on the ELS, and it proved to be very susceptible to early failure in the target and beam tube locations. Advantages of this type of gauge are its ultra-high vacuum capability and double setpoint interlock control. Disadvantages of this fine-wire filament gauge are its sensitivity to lithium frost, vibration, pressure pulses, and physical damage. This gauge also has a complex operating sequence, high sensitivity to gas type and low (1 atm) pressure rating.

Physical examination of this gauge suggests that some gauge failures may have resulted from the pressure pulse associated with the vacuum break operation. These thin-filament gauges also appear to be highly prone to frost and vibration damage. Once again, the protective screens probably contributed to the extended life of these gauges. Figures 67a and 67b show the before and after service condition of the gauge used on the main vacuum header after 800 hours of vacuum service.

The residual nitrogen analyzers were used on the MARK II target, main vacuum header, and RNA pumping system. This dual-function gauge measured total pressure and nitrogen partial pressure. The nitrogen measuring function was used to detect air in-leakage, and the results are reported in Section VI.B. Although no failures were reported, these gauges became sluggish and required frequent cleaning. The gauge on the target started and responded to pressure changes more slowly after only 2 months of operation and had to be cleaned. The gauge on the RNA pumping system required the least frequent cleaning (about every 6 months).

a. Before Service. Neg 8303558-3cn

b. After ~800 Hour of Vacuum Service.
Neg 8308466-1cn

FIGURE 67. Ultra-High Vacuum Gauge Before and After Service.

It should be noted that the vacuum gauges that were mounted on the target during testing in ELS were typically located within a few feet of the lithium jet. Because of the radiation environment in the FMIT test cell, the closest vacuum sensor to the target will be located roughly 20 feet from the target.

2. Thermocouples

The thermocouples used on ELS was described previously in Section IV.K.2. No thermocouples failed on ELS. However, trouble was experienced with loose connections at the thermocouple termination screws, possibly caused by vibration or poor workmanship during installation. Both thermocouple attachment methods were satisfactory (i.e., banded directly to the piping skin and inserted into the thermowell). The banded thermocouples are accurate within an uncertainty of about $\pm 10^{\circ}\text{F}$ ($\pm 6^{\circ}\text{C}$), while the thermowell values are accurate within an uncertainty of about $\pm 5^{\circ}\text{F}$ ($\pm 3^{\circ}\text{C}$).

3. Flowmeters

The ELS flowmeters were described previously in Section IV.k.3. No flowmeters failed on ELS. The only problems encountered on the liquid metal EM flowmeters were cold spots caused by poor installation of the heaters or lack of adequate insulation. The gas flowmeter worked well; however, it should be noted that, when overranged, it gave a false reading. The liquid metal flowmeter values are accurate within an uncertainty of $\pm 10\%$ of reading. The gas flowmeter values are accurate within an uncertainty of $\pm 1\%$ of full scale.

4. Level Sensors

The level sensors used on ELS were described previously in Section IV.K.4. All three level probes used on ELS performed well. Several lithium level readout anomalies were reported during four years of ELS operation; however, these problems were attributed to dirty switch contacts on

the panel mounted meters. The accuracy of the continuous readout induction level probe was $\pm 1/8$ in. or 0.5% of reading (whichever is greater), while the accuracy of the continuous readout J-Probe was $\pm 1/4$ in. or 2% of reading (whichever is greater).

5. Cameras and Lighting

The cameras and lighting used on ELS were described previously in Section IV.K.5. All camera and lighting systems worked well. The one major obstacle to good viewing and photography of the lithium jet was frosting of both the lighting and viewing port sapphire windows. Periodic ELS shutdown was required for window cleaning. The rotating window assembly (multiple windows) for the viewing port greatly helped alleviate this problem.

6. Acoustic Monitors

The acoustic monitors used on ELS were described previously in Section IV.K.6. Acoustic emission monitoring equipment was used at the outlet of the main loop lithium pump and at the target zone for noise or signature analysis. All instrumentation, transducers, coupling techniques and the extensional mode waveguide calibrator performed satisfactorily. Lithium acoustic coupling between the liquid and the stainless steel pressure boundary does not appear to be a problem at the frequencies and acoustic energy magnitudes associated with acoustic emission monitoring techniques.

The onset of incipient pump cavitation was detected by acoustic emission monitoring at 8 to 15 gal/min lower flow rate than by other correlatable methods. Both repetitive and nonrepetitive events were observed. Correlation between acoustic events and the following parameters were noted:

- Pump cavitation
- General lithium loop cavitation
- Pressure
- Flow
- Throttle valve position

- Gas entrainment
- Type of pump excitation (Variac or SCR)
- Power line frequency
- Pump efficiency

In general, cavitation was observed near 508 to 512 gal/min flow with pump impulse synchronous events occurring about 518 to 522 gal/min. Event duty factor for this condition was low (>30%). The cavitation duty factor increased with flow rate above detection threshold. Variations between cavitation and flow occurred with the above parameters.

Flow noise was also monitored for preliminary target characterization at two points in the target zone. There were indications that randomly timed events were occurring in the vicinity of the nozzle throat with the frequency spectrum and energies of cavitation levels being noted. Turbulence noise was also observed in the vicinity of the 90° pipe bend just before the entrance to the flow straightener upstream from the nozzle.

Acoustic monitoring has been proposed as a means of detecting target drain thermal striping.⁽³⁰⁾ Thermal striping refers to temperature fluctuations on a solid surface caused by the mixing of the fluid streams of different temperatures. Temperature fluctuations in the fluid adjacent to a solid surface cause cyclic thermal strain in the solid. If the strain exceeds the fatigue limit of the material, the solid will develop surface cracks. Continued exposure to this thermal cycling may lead to component failure. The potential for thermal striping in FMIT exists because the lithium jet will be nonuniformly heated as it continuously absorbs 3.5 MW from the deuteron beam. A peak temperature, which is expected to be 540°C hotter than the surrounding lithium, will be produced ~4 mm from the surface of the drain wall. This large, local temperature difference and turbulent mixing within the lithium jet create the potential for the surface of the target drain to experience large, rapid temperature fluctuations.

Because the region of concern is fairly distant from the target region, commercially available acoustic monitors may be placed on the drain pipe and last for the life of the target in spite of the radiation. This plan needs to be investigated further. Very sensitive mechanical shock detection, which lends itself readily to the protection of system interfacing and is based on acceptable speed-of-sound data, will be possible. A block diagram of the conceptual system is shown in Figure 68.

7. Infrared Imaging

The infrared (IR) imaging system tested on ELS was described previously in Section IV.K.7. Three IR viewing experiments were performed at ELS. The first was to discover the state-of-the-art of commercial IR imaging hardware, and more importantly, to see what the isothermal jet looked like in the IR region under various flow conditions. The AGA Model 780 system was used. From the photographs in Figure 69 at different flow rates, the changing surface conditions are readily seen. Because emissivity can vary dramatically with surface conditions, and because the radiation source was not suspected to be other than that emitted by the jet, the result was not encouraging from a beam profilometry standpoint. It was later concluded that the reflected IR jet images from surrounding hot steel (higher emissivity and greater surface area, therefore greater IR source strength) were distorting the jet surface image.

A second test was performed with the jet viewed from a distance of 5 m through a trace-heated beam tube mockup. The arrangement employed an Inframetrics 550 system, a small 2.5-cm sapphire window, and lenses of less than optimum design. A good quality jet image was seen, not "washed out," by a large background source conducive to multiple internal reflections.

The third test was designed to try to prove that a detectable component of the jet IR signal was from self-emission. The way in which this was performed was to record the thermal image of the jet and its surroundings, having added several extra thermocouples for temperature calibration, at a

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FIGURE 68. Target Drain Thermal Striping Acoustic Monitoring System Block Diagram. Neg W405028-7

100 gpm

200 gpm

300 gpm

400 gpm

500 gpm

FIGURE 69. Infrared Images of the Lithium Jet at Different Flowrates.
Neg 8501104-1

temperature of $\sim 500^{\circ}\text{F}$. Then the loop was dumped and the bulk lithium in the surge tank was heated to $\sim 600^{\circ}\text{F}$ while the target superstructure (nozzle, sidewalls, etc.) was kept at 500°F . Once flow was started, it was believed that it would take from 0.5 to 1 minute for the surroundings to heat up to the lithium temperature. In the interval, a measurement of an apparently higher jet temperature would indicate a self-emission component. In performing the experiment, the surroundings heated up in about one-tenth the time anticipated. The data from this test were not encouraging nor fully understood. Several complications included the 7-mm sapphire window separating the IR camera from the jet at 20% per mm attenuation and the surrounding, mirror-like superstructure with its lithium coating and presumably less IR background. Additional concepts being considered for FMIT test-end instrumentation are discussed in Reference 30.

One positive outcome of these tests was the ability of the IR system to provide an image of the target jet without optical (visible) means. An IR system may be useful to view the target jet surface during the time the beam is on and optical viewing is not possible.

8. Ultrasonic Transducers

The ultrasonic transducers tested on ELS were described previously in Section IV.K.8. Ultrasonic pulse-echo techniques were successfully used to characterize the target jet during water tests. Therefore, the same method was attempted to characterize jet performance in lithium. Although the stainless steel pressure boundary of the target area appeared to be wetted by lithium, wetting was not adequate to provide acoustic coupling between the lithium and the stainless steel. No measurement results were achieved.

9. Impurity Monitors

The impurity monitors used on ELS were described previously in Section IV.K.9. From the startup and operation of the ELS until hydrogen was added several times to the chemistry loop, no definite plugging of the PTI

orifice plate was observed during plugging runs other than the complete loss of flow when the orifice plate was cooled below the freezing point of lithium. Some flow perturbations were observed whenever the main loop and chemistry loop piping were connected. These perturbations were caused by gas bubbles collecting in the PTI and being flushed out spontaneously. This flow anomaly is characterized by a sawtooth pattern on the flow recording.

The first plugging run that displayed definite plugging (PTI Run 83-3) (see Figure 70) was made after hydrogen was added to the chemistry loop. (Chemical analyses of the lithium showed 108 ppm H_2 in solution.) During the cooldown, a slow plugging break began at 459°F, and a faster break occurred at 385°F. When the orifice plate was reheated, a rapid unplugging occurred at 432°F; and a higher temperature, slower unplugging break was seen at ~520°F. Averaging the corresponding flow anomalies gives two plugging temperatures (408°F and 489°F) -- indicative of two different compounds having two different precipitation/dissolution rates. The plug at 408°F was probably caused by lithium hydride, while the plug at 489°F was probably caused by lithium oxide. Plugging runs made at EBR-II routinely give this pattern for sodium samples, though for different impurities.

Other plugging runs of interest occurred after the cold trap and the chemistry loop were heated to 680°F over a weekend to re-dissolve the hydrogen collected from a previous trapping run. PTI Run 83-11 (see Figure 71) was made with the cold trap and chemistry loop at 680°F. During the cooldown cycle, a rapid flow decrease (beginning at ~575°F) threatened to completely plug the PTI circuit. The blower was turned off immediately, and the pump power was increased to establish high flow in the PTI piping; consequently, no unplugging temperature was recorded.

The cold trap crystallizer temperature was decreased to 518°F. After about 24 hours, PTI Run 83-12 (see Figure 72) was made. During the cooldown, a slow plugging break started at 452°F. After cooling to ~420°F, the operator turned off the blower and allowed the PTI to reheat. Unplugging began

1. BARE ORIFICE FLOW
2. BARE ORIFICE TEMPERATURE
3. BLOWER ON
4. START OF FIRST PLUG
5. START OF SECOND PLUG

6. BLOWER OFF
7. START OF FIRST UNPLUG
8. START OF SECOND UNPLUG
9. BARE ORIFICE FLOW AND TEMPERATURE

FIGURE 70. PTI Run 83-3.

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FIGURE 71. PTI Run 83-11.

HEDL 8503-071.9

1. BARE ORIFICE FLOW
2. BARE ORIFICE TEMPERATURE
3. BLOWER ON
4. START OF PLUG

5. BLOWER OFF
6. START OF UNPLUG
7. BARE ORIFICE FLOW AND TEMPERATURE

HEDL 8503-071.11

FIGURE 72. PTI Run 83-12.

at 552°F. The average of the plugging and unplugging temperatures is 502°F. The 502°F plugging temperature is in fair agreement with the cold trap temperature (518°F). Chemical analyses showed that there were 110 ppm H₂ and 188 ppm O₂ (sample taken at 680°F) in the lithium. No hydrogen plug was observed, since the operator only cooled the PTI to 420°F. Had the PTI been cooled to ~385°F, a hydrogen plug would have started to form. The plugging and unplugging temperature observed was probably caused by lithium oxide.

A number of other plugging runs were made. The outcome was inconclusive, or no plugging was observed. The above runs are included to illustrate the potential of the PTI.

The outcome of a plugging run was observed to be significantly influenced by the PTI throttle valve. The ELS PTI is the most sensitive when the PTI throttle valve is nearly full open and the pump (EMP-2) power is used to adjust the desired flow in the PTI circuit. C. C. McPheeters and J. C. Biery⁽³¹⁾ studied this effect in detail and concluded that, with no throttle upstream, the percent plug and the percent decrease in liquid metal flow correspond one-to-one; however, if the valve is throttled so that the flow is reduced by 90% below the open valve flow rate, a very large percentage of plug (70% to 80%) must be formed before an appreciable (5% to 10%) decrease in flow occurs.

ELS testing has shown that supersaturation or under-cooling of ~50°F is required before lithium hydride will precipitate on bare stainless steel. This is important information for operation of PTIs and cold traps. Before this study, ideas about precipitation of lithium impurities were influenced by sodium experience. In sodium, ~25°F supersaturation result in precipitation of oxygen or hydrogen on bare stainless steel.

For FMIT lithium system operation, if the PTI orifice plate temperature is maintained at ~5°F above the freezing point of lithium (362°F), then a plug starts to form in the bare orifice plate when and if the hydrogen in the lithium increases to ~80 wppm or a 415°F saturation temperature.

(NOTE: This is the FMIT impurity limit for hydrogen isotopes.) After lithium hydride has precipitated in the orifice plate and that partial plug is used for further PTI analyses, the sensitivity of the PTI increases. (For FFTF sodium systems, the sensitivity changes from 25°F for a bare orifice to +5°F with a partial plug.) This is the main reason for using the PTI in the cyclic mode where a partial plug is maintained on the orifice plate. However, before a partial plug is obtained, we must use the sensitivity obtainable with a bare orifice.

ELS PTI experience, even though minimal, has shown that the PTI has potential application for use on the FMIT lithium system. It should be included as an on-line device for FMIT operation. Remember that the PTI is particularly sensitive to valving used in series to decrease the pressure drop across the orifice plate. The ELS experience has shown that the PTI will not detect hydrogen until it has increased to ~80 wppm.

The present ELS PTI damper is manually controlled. Attempts at controlling the damper from the ELS control room console resulted in wide over-corrections. The following PTI control methods are recommended: 1) blower manual off/on, 2) blower auto control for high and low lithium flow trips, and 3) orifice plate temperature control for auto blower (off/on switching). PTI testing on the ELS should be resumed before the FMIT PTI is procured. The PTI response to hydrogen should be further defined. Oxygen and carbon should be added to the chemistry loop lithium, and both the PTI and cold trap should be evaluated for the detection and removal of these impurities.

When the ELS resistivity meter was tested, it responded to lithium temperature changes but not to hydrogen concentration changes. The hydrogen concentration varied between ~65 to 110 wppm during this test program. A post-test evaluation was undertaken to determine why the probe had not performed as expected. When the probe was cut apart, it was found that the four wires and the braze joints where the wires were attached to the sensor tube were intact and that the insulation on the wires was in good condition. It was also determined that the wires were attached to the proper connectors,

so that the meter should have performed correctly. Resistance measurements taken before and during the examination showed that the resistance of the probe changed from 5.5 mΩ before it was cut apart to 17.2 mΩ after removing the outer 0.75-in. tubing. The 17.2 mΩ reading is in good agreement with a model that was built to determine the resistance of 5 in. of the tubing used to fabricate the sensor. It also agrees with readings taken during fabrication of the ELS probe. (Note that readings were taken before the sensor was welded into the 0.75-in. tubing.)

It was concluded that, since the 0.75-in. tubing and the 0.25-in. tubing were welded together near the bottom end of the probe (lithium inlet) and were then welded together again ~8 in. from the lower weld (lithium outlet), a parallel resistance path is formed that includes both pieces of tubing. Calculations show that this combination would decrease the resistance from 17 mΩ for the 0.25-in. tube alone to ~3 mΩ for the tubing combination. When this combination is inserted in lithium, the added parallel resistance from the lithium entering the 0.25-in. tube (which is the resistance to be measured) is overwhelmed by the parallel resistance of the 0.75-in. tube, which drops to near zero when in contact with lithium. Consequently, the small changes in lithium resistivity caused by increasing or decreasing the impurity concentration in the range of interest would go undetected.

It is recommended that a resistivity meter be developed for monitoring the FMIT lithium. The concept has been proven by workers at ANL⁽³²⁾ and at the University of Nottingham.^(33,34) The meter design should use small-diameter piping and be supplied with dynamic (forced convection) lithium flow. The meter should be tested on the ELS before being used on the FMIT lithium system. Figure 73 is a sketch of a meter similar to the one developed at Nottingham.

1. 0.125-in. diam TUBING, 0.010-in. WALL (STAINLESS STEEL)
2. 2.0-in. diam., 14 GAUGE PLATE (STAINLESS STEEL) WELDED OR BRAZED TO ITEM 1
3. THERMOCOUPLE, WELDED TO ITEM 1

4. FOUR LEAD WIRES WELDED OR BRAZED TO ITEM 2
5. FURNACE BOX (HEATER, INSULATION, THERMOCOUPLE AND COVER)
6. FAN

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FIGURE 73. Schematic of Resistivity Meter.

10. Conductivity Probe

The conductivity probe tested on ELS was described previously in Section IV.K.10. The three-degree-of-motion, single-pin concept evolved from an earlier linear-motion (in/out), seven-pin probe concept. Both units worked well, but the three-degree-of-motion unit was easier to calibrate and provided much more detail in jet contour mapping. The single-point probe also induced less lithium spray. Both probes measured the contour of the surface by sensing electrical contact between a movable probe and the lithium jet. By comparing the results with probing to the target wall, the local thickness of the lithium was determined with an accuracy of ~ 0.01 cm. The magnitude of surface disturbances on the jet due to waves and wakes was also determined using this system. The accuracy of the measurements of surface disturbances was approximately the same (0.01 cm) as for thickness measurements. The magnetic tape data acquisition system proved to be more versatile for data reduction than the floppy disc system. Visual lights and a pulse height analyzer with CRT display were useful for probe operation.

11. Beam Position Monitor

The beam position monitor tested on ELS was described previously in Section IV.K.11. The ELS test unit was close-coupled to the lithium target. This location afforded the worst-case lithium vapor environment. An electrically conductive coating formed over the beam position monitor cable end-seal during the first few hours of operation causing failure. In addition, a vacuum leak was observed at the beam position monitor housing/insulator interface. The latter problem was attributed to poor quality control during fabrication. The early bridging of the insulator will necessitate heating the end-seal surfaces for FMIT application to prevent vapor buildup.

K. CONTROL SYSTEM

The ELS is a computer-controlled system capable of unattended operation. The control system was described previously in Section IV.L. The control system worked satisfactorily and contributed to the large number of operating hours logged on ELS. This control system enabled unattended around-the-clock operation of the loop.

The PDP-8e computer (supplied by Research Inc., Minneapolis, MI) performed well. The number of computer failures was small. The loss of air conditioning in the control room (EDL-108) probably contributed to these failures. The computer Central Processing Unit (CPU) had to be replaced on two occasions. On both of these occasions the air conditioning had failed just prior to the CPU failures.

The high-level hot box temperature control card failed once causing the temperature reference points to shift. A capacitor blew on this control card after about 12 months of operation. The original floppy disc drive started destroying discs after about 9 months of operation and was replaced with a magnetic tape drive.

The Teleray 3300 control terminal failed once near the end of the test program. A failed memory chip was found. The cathode ray tube (CRT) screen was cleaned at the same time. The original Okidata OP110 printer was not reliable and kept jamming paper. After about 9 months this printer was replaced with a new Centronics 101 printer. Four solid-state relay failures and one unidriver control card failure occurred in the four years of operation.

In addition to this relatively small number of control system failures and subsequent system shutdowns, a larger number of system shutdowns were caused by loose connections in the control circuit. This was particularly true near the end of ELS operation. Because of budget limitations, only limited preventative maintenance was performed on the control system. Prior

to any re-start of ELS, a complete end-to-end check of all circuits should be performed.

Although the ELS control system performed well, it should be noted that it was difficult and time-consuming to make software changes on this dated computer system.

L. LITHIUM TRANSFER SYSTEM

The lithium transfer system is shown in Figure 38 (described previously in Section IV.N). A summary of the lithium transfer operation is given in Section V.C. The transfer system generally worked well and is recommended for FMIT with the following revisions.

A number of anomalies occurred during the ELS lithium transfer. The standard carbon steel shipping drums received from the vendor were not adequate for lithium transfer. Also, individual drum transfers were interrupted a number of times by plugging of the transfer line caused by cold spots and nitride contamination.

Post-transfer examination of the bulk lithium drums revealed that visible leakage had occurred from most of the 15 carbon steel drums used. However, the leakage was small and well controlled under an argon blanket until a major leak occurred from the fifteenth drum. In summary, the carbon steel drums are sealed with a low-melting-point ($\sim 400^\circ$) elastomer. Although this same container had been acceptable for transfer of bulk sodium, it did not prove acceptable for the higher-melting-point lithium. The last eight drums used in the ELS transfer were of stainless steel, all-welded design. No leakage was observed from these containers.

Establishing flow proved difficult on most of the drums transferred. In most cases, flow was interrupted shortly after initiation. This was attributed to cold plugs in the transfer system. Flow was usually re-established by selectively increasing heat, as indicated by temperature

scan data. A nitride plug eventually formed at the inlet of the transfer line. This nitride plug occurred after numerous drum change-outs and was attributed to air contamination. This plug formed in the 0.5-in. union used to change dip leg tubes. Analyses of the plug material gave 25.5 wt% nitrogen and 63.1 wt% lithium.

Based on the ELS lithium transfer experience the following recommendations are offered:

- Bulk Lithium Containers

Elastomer-sealed bulk lithium containers should not be used for the direct transfer of molten lithium. While these containers may be adequate for storing lithium bricks immersed in oil, all experience at HEDL indicates that they are not reliable containers at temperatures above the melting point of lithium (356°F). The all-welded, stainless steel drums used to conclude the ELS transfer operation proved to be reliable for direct vacuum transfer of molten lithium at 380°F.

- Transfer System Design

A dip leg should be used on FMIT transfer to siphon the bulk lithium container(s). The dip leg should be positioned a couple of inches above the bottom of the container(s). This design feature precludes transfer of high impurity "crud" normally found riding on the liquid lithium metal surface; it would also reduce transfer of large particulates that may have settled in the liquid metal.

The FMIT transfer system should be designed with 1-in. pipe. Lithium vendor experience indicates that the repeated cold plug problems at ELS could have been minimized with a larger-diameter transfer line. The ELS transfer line was 0.5-in. x 0.065 in. wall stainless steel tubing.

The FMIT transfer system should include two 25- μ m filters piped in parallel. The ELS filter design performed satisfactorily, although no quantitative data are available. The parallel arrangement, properly valved, affords alternative flow paths should one path be blocked. No filter plugging was observed at ELS.

Individual trace heaters and control should be provided at all known heat sinks or changes in cross section on the FMIT transfer system. At ELS, line heaters bridged valves and filters, which resulted in poor temperature control and cold spots.

Argon feed and bleed capabilities, similar to the ELS transfer system shown previously on Figure 38, should be used on the FMIT transfer system. This design prevents overpressurization of the lithium container as well as back-diffusion of air into the system during venting. This design feature proved to be satisfactory during ELS transfer.

- Lithium Transfer Conditions

The FMIT lithium transfer temperature should be minimized to limit the amount of impurities brought into solution and subsequently transferred. The low (nominally 380°F) transfer temperature at ELS is believed to be one of the factors contributing to low nitrogen concentrations in the transferred lithium.

A heel should be left in the bulk lithium container after transfer. The 30- to 40-lb heel left in each 55-gal drum at ELS is believed to be another factor contributing to the low nitrogen concentrations observed. A thin ($\sim$ 0.63 in.) layer of "crud" was observed over the lithium in each transferred drum. With the dip leg transfer, this layer of high impurity material was left in the drum.

VII. CHEMISTRY

A. LITHIUM

Operation of the ELS began March 26, 1980 and continued until January 13, 1984. In that time, there were ten major outages and numerous minor or partial shutdowns to perform maintenance or modifications and to add or remove test components. Each of these disturbances provided an opportunity for impurities (primarily air and adsorbed water) to enter the system. Operation of the system for 2000 hours under vacuum was also conducive to air contamination. A total of 25 samples of lithium were taken in the 26 months of actual operation through June 1983. During this time, no attempt was made to purify the lithium. Both hot and cold traps were available, but removable impurities remained at such low levels that use of the traps was not warranted.

Operation of the ELS was changed radically in the last few months of operation. Impurities were intentionally added to and removed from the chemistry loop, and the entire system was operated briefly at 700°F (371°C). The chemistry of that period will be separately discussed in Section VIII.

All 25 of the samples were taken in 0.5-in. diam stainless steel tubing by the flow-through technique [with the samplers operated at system temperature, normally 500°F (260°C)]. A few samples were taken with 10- μ m in-line filters in the sample tubes. The results of these analyses are summarized in Table 30. Concentrations of the most important impurities are plotted with a histogram of loop operation in Figure 74.

Major points to be found in these data are:

- 1) The sodium content of the as-received lithium was 600 to 700 wppm above the purchase specification of 1500 wppm. Disregarding the first two sodium analyses (which are believed to be in error), there does not appear to be a significant decrease in the sodium concentration, despite extended

TABLE 30

ELS IMPURITIES WITH MAIN AND CHEMISTRY LOOPS COMBINED
(wppm from Flow-Through Samplers)

Date	Impurities Analyzed																	
	N	H	C	O	Al	Ca	Cd	Cl	Cr	Cu	Fe	Ni	Mg	Mn	K	Na	Si	Zr
3/25/80	15	60	2	20 ^c		223							142			2680		
4/07/80	14	60	2	<100 ^d		280			40	2	8	40	56	5	23	2600		
7/11/80	56	50	8	<100 ^d		350			10	30	80		120	3	15	2000	400	
7/23/80	75	53	17			280			110		420	22	44		12	2080	280	25
8/05/80	18	49	5		500	210	0.5	20	17	5	39	4	115	5	7	2350	230	21
8/22/80	18	55	11		390	500	0.4		12	8	45	5	50	7	4	2080	375	12
9/24/80 ^a	12	40	6		500	345	0.5		35	3	100	12	56	23	4	2280	380	22
11/03/80	20	55	9	15 ^c	580	280			33	5	77	19	28		4	2090	315	23
12/03/80 ^a	60	67	6		540	210			7	5	10	6	28	20	5	2090	375	
1/09/81 ^a	13				550	145			6	6	12	3	40	6		2080	310	
1/20/81 ^a	315 ^b		9	40 ^c	500	100			5		11	5	55	8		2030	325	40
1/29/81	15					150			8				66	3	3	2320		
3/05/81	22	51	4.5		650	83		39	10		54	34	61			2700	450	
4/17/81	44	63	2		570	89			8		55	29	55			2290	510	
6/03/81	33				620	40			12	12	120	40	15			2730	470	
7/02/81	17	62			630	46			11		40	5	75	17		2300	460	26
10/16/81	43	63	1.9		560	70				6	15	1	65			2280	460	
1/11/82	39	83	2		450	120			3	5	11	1	62				440	
3/16/82	60	57	1		496	47			12	5	20	4	61	7			420	
6/17/82	11	58	1.6	84 ^c	450	68			3	7	29	4					480	
9/28/82	12	48	1.2	133 ^c	262	28			10		13	2	51	8			400	
10/28/82	11	41	0.8	24 ^c	352	41			21	13	33	1	59				323	
1/18/83 ^a	22	46	0.2		245	17			21	9	14	2	52		4.5	2220	400	
1/24/83 ^a	9	42	3.8		235	50			25		60	3			4.5	2270	400	
2/28/83 ^a	13	38	3.0		196	45			34	14	73	5	47	53	4.5	2250	280	
1/13/84 ^{a,e}	60	55	0.5	47 ^c	110	33			34	20	29	4	11		1	2090	330	

^aFiltered.^bAverage of 4 analyses, suspect sample tube contamination.^cORNL analysis.^dPrivate company analysis.^eAfter impurity additions/removal tests.

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FIGURE 74. Histogram of ELS Operation and Plot of Selected Impurities.

operation under vacuum. Sodium is more volatile than lithium and does tend to be enriched in vapor deposits produced during vacuum operation. However, the deposits observed in the ELS are not nearly as enriched in sodium as Raoult's law predicts. Deviations from Raoult's law are common for other metals in lithium.⁽³⁵⁾ In addition, since the system is operated essentially isothermally, few places in the head space are significantly cooler than the bulk lithium temperature. Even in these places, the temperature will probably be high enough to cause sodium to preferentially remain in the gas phase, rather than be deposited with lithium vapor. The main loss of sodium should have been to the vacuum pumps and associated vacuum lines, but examination of pump oil showed only fractional grams of alkali metals.

2) Potassium, at 10 wppm, is much lower than the 500-wppm limit specified in the purchase order. Potassium is about 30 times more volatile than sodium at 500°F and, therefore, more prone to evaporate from lithium. This is reflected in a potassium concentration decrease by a factor of ~3 during the period of normal ELS operation. From the final potassium analysis, it appears that the concentration decreased even further during the last months, probably during the period of high-temperature vacuum operation.

3) Nitrogen remained reasonably constant at ~10 to 75 wppm, even though air was known to have frequently entered the system. The failure of the nitrogen to increase is explained by the reaction of nitrogen with aluminum present as an impurity in the lithium.⁽²⁷⁾ When nitrogen gas dissolves in lithium, it forms lithium nitride by the reaction

The dissolved lithium nitride then reacted preferentially with aluminum, an impurity initially present at 550 wppm in the ELS, to form the more stable and insoluble aluminum nitride.

The particles of aluminum nitride are six times as dense as lithium and tend to settle in the less turbulent portions of the system, thus effectively keeping both dissolved and suspended particulate nitrogen at a low level.

Analyzing lithium for nitrogen was not an effective means of detecting air contamination in the ELS because of the aluminum nitride precipitation and settling. However, since the concentration of dissolved aluminum decreases in proportion to the amount of nitrogen precipitated, aluminum analyses could be used to indirectly monitor air contamination. The aluminum concentration of the lithium decreased 300 wppm during the normal operation of the ELS. The stoichiometry of the reaction indicates that 155 wppm of nitrogen had been removed as AlN, which is equivalent to the nitrogen in 17 ft³ (470 μ) of air at system temperature. Lithium deposits in gas lines and in cooler areas above the lithium pool may also have absorbed additional air before they could reach the bulk lithium and precipitate aluminum.

4) Silicon remained at ~400 wppm throughout the normal ELS operation. Silicon, like aluminum, can control nitrogen in liquid lithium by precipitating a nitride. With silicon, the product is the ternary nitride Li₅SiN₃⁽³⁶⁾ produced by the reaction

Aluminum nitride is more stable than the lithium-silicon nitride; therefore, it forms preferentially, so the silicon concentration would not be expected to start decreasing until the aluminum had been largely reacted.

5) In liquid lithium, calcium also reacts with a major impurity: i.e., oxygen.⁽²⁷⁾ The insoluble product is apparently calcium oxide, which is substantially more stable than lithium oxide.

The concentration of calcium in the ELS lithium at startup was about 300 wppm, which is 100 wppm higher than the average of the three calcium analyses obtained from the lithium transfer samples. The transfer samples are believed to have lost part of their calcium by reaction with particulate lithium oxide during the prolonged period before the samples froze. Settling in the vertical tube would remove the precipitated calcium oxide from the sample.

The calcium in the ELS lithium decreased from 300 to 30 wppm during normal operation (Figure 75). Two major sources of oxygen were available to cause this change: 1) oxygen in the form of oxides and adsorbed water on interior surfaces of the system and added components, and 2) air inleakage. The 270-wppm calcium change corresponds to precipitation of 108 wppm of oxygen. That is equivalent to the oxygen in 47 ft³ (1330 L) of air. An estimate of the contribution of surface oxygen, both oxide and water, can be made by considering the difference between the 17 ft³ of air required to provide nitrogen for the aluminum precipitation noted earlier with the equivalent to 47 ft³ of air required to provide oxygen for the observed calcium precipitation. It can be concluded that

$$\frac{(47 - 17) 100}{47} = 63.8\%$$

or 69 wppm of the 108 wppm of oxygen required to precipitate 270 wppm of calcium came from sources other than air leakage. From Figure 75, it can be seen that most of the calcium loss occurs early in the operation of the system and is presumably due to oxide and adsorbed water reaction, since aluminum remains relatively constant during the early operation, indicating little or no nitrogen (air) leakage. It was not until early 1982 that aluminum began to show a significant decrease. Intensive high-vacuum testing of the target occurred at about this time. In addition, a major modification to a large drain line may have been responsible for some air contamination.

A number of direct measurements of oxygen in lithium by activation analysis were attempted, but the high blanks and erratic results did not allow any conclusions to be made. However, it is possible to estimate the oxygen concentration (under some circumstances) from the calcium concentration. It is reasonable to assume that the common ion effect applies to the solubility of calcium oxide in lithium. This can be expressed as

$$[Ca] [O] = K \quad (8)$$

where brackets denote the concentration of the ion in solution, and K is the conditional solubility product constant. The value of K has not previously been determined; but it can be estimated, since the solubility of calcium levels off at about 30 wppm when the lithium apparently has become saturated with oxygen (40 wppm) toward the end of the normal ELS operation. Substituting these values in the previous equation gives:

$$(30)(40) = K = 1200 \text{ (at } 500^{\circ}\text{F or } 260^{\circ}\text{C)}$$

Dissolved oxygen concentrations can then be estimated indirectly by measuring dissolved calcium concentrations.

$$\text{wppm oxygen} = \frac{1200}{\text{wppm calcium}}$$

This relationship is plotted in Figure 75. It can be seen that, when the loop was first started and the calcium was 300 wppm, the dissolved oxygen should have been 4 wppm. This plot indicates how the solubility of calcium should decrease until the oxygen reaches saturation. Adding more oxygen would cause lithium oxide to precipitate, rather than increase the dissolved oxygen concentration and, therefore, would not decrease the calcium concentration below 30 wppm.

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FIGURE 75. Predicted Solubility Relationship Between Calcium and Oxygen in Lithium at 500°F.

6) Insoluble impurities suspended in the ELS lithium were collected on filters in flow-through samplers and measured on several occasions. The results of these analyses are summarized in Table 31. Calcium, aluminum, and nitrogen are the principal impurities found. Oxygen was not measured. Typically less than the equivalent of 4 ppm total of the major impurities were filtered out. It is evident that the precipitated impurities had settled rather efficiently in the ELS, probably in the relatively quiescent areas of the surge and dump tanks. The low density and viscosity of lithium favors settling, but perhaps more important is the presence of areas of low turbulence. Frequent shutdowns may also aid the settling and caking processes.

TABLE 31
ANALYSIS OF ELS FILTER DEBRIS

<u>Date</u>	<u>Volume of Li Filtered (gal)</u>	<u>Results</u>	
		<u>Impurity</u>	<u>Wt (mg)</u>
9/24/80	~6	Ca	75
		Al	10
		Mg	0.6
		Fe	0.5
			<u>86.1</u>
12/03/80	10.5	Ca	16
		N	3.2
			<u>19.2</u>
1/09/81	3.6	Ca	13
		N	21
		Al	12
		Mg	1.9
		Fe	7.7
		Ti	<u><0.2</u>
			55.6
1/20/81	1.8	Ca	17
		N	40
		Al	28
		Mg	2.5
		Fe	1.5
		Ti	<u><0.2</u>
			89.0

7) In general, the scatter in analytical results from different but (presumably similar) ELS lithium samples is much greater than would be expected based on replicates and synthetic samples. Contributing factors include frequent use of unfiltered samples, sample tubes that have not been properly cleaned, lack of an inert atmosphere glovebox for taking samples, and unrecognized perturbations of the system. All but the last factor can and should be corrected in future operations.

B. ARGON COVER GAS

Sixteen samples of argon cover gas were taken from various locations in the ELS during its fill and operation. The resulting analyses are summarized in Table 32. The 1979 samples were taken during the fill period. Only the two 1980 samples were obtained while the loop was operating. Cover gas samples taken from an operating liquid lithium system would be expected to be low in the reactive gases (oxygen, nitrogen, and hydrogen), and that is what was seen in those two samples. Most hydrocarbons are less reactive and may persist in the gas for some time. The sources of hydrocarbon gases are probably oils and organic materials on component internals.

During the hydrogen additions (see Section VIII), a laboratory-type chromatograph was connected directly to the ELS for measurement of hydrogen. This device operated automatically, taking samples every 10 minutes. This sort of instrumentation would have been useful during the normal pressure operation of the loop. However, It could not be used during vacuum operation.

No analysis of the vacuum was available during the evacuated operation of the ELS, although a residual gas analyzer (RGA) was available for this purpose. The RGA was faulty and did not work properly, but this technique has promise for detecting gaseous impurities during critical vacuum operation.

TABLE 32
ELS COVER GAS ANALYSES

Date	Location	Gas (volume ppm)			Hydrocarbons ^a
		O ₂	N ₂	H ₂	
9/10/79 ^b	Dump tank	6	40	19	0.9
9/13/79	Dump tank	<4	7	2.4	7.0
9/20/79	Dump tank	c	c	0.8	1.5
9/24/79	Dump tank	<4	<8	5	0.4
9/26/79	Dump tank	3	8	0.3	0.6
9/28/79	Dump tank	<3	<5	<0.1	1.6
11/13/79 ^d	Dump tank manifold	<5	<7	<0.3	c
11/13/79 ^d	Dump tank	<5	<7	0.3	c
11/29/79 ^d	Dump tank	<3	<5	<0.3	<0.7
8/05/79	Surge tank manifold	27	57	2.5	65.
8/05/79	Main surge tank	17	36	0.9	15.
8/08/79	Main surge tank	11	20	<0.5	5.1
8/22/79	Main surge tank	9	11	<0.5	76.
9/26/80	Main surge tank	<3	<5	<0.5	50.
11/17/80	Main surge tank	<3	<5	<0.5	2.9
3/11/82	Main surge tank	<4	<6	0.6	c

^aHydrocarbons are measured by a flame ionization detector and reported as methane equivalent ppm.

^bNo lithium in the system.

^cNot analyzed.

^dGas pumped into sample cylinder at 20 to 30 psig compared to normal flow at 2 to 3 psig from system.

VIII. IMPURITY ADDITIONS

The last phase in the operation of the ELS was the evaluation of the lithium purification systems. The ELS has both a 33-gal (125-l) hot trap packed with corrugated titanium foil and a 33-gal (125-l) cold trap packed with stainless steel York mesh. Both traps were filled with lithium, but neither had been used for earlier purification, although both had been operated briefly during thermohydraulic performance studies. For this evaluation, the 100-gal chemistry loop was isolated from the main loop. This resulted in a system (Figure 60) with exceedingly high purification capability, but well suited for experimentation.

After three years of ELS operation, it became obvious that purification testing of the ELS traps would require impurity additions to the loop, due to the low impurity levels in ELS. The impurity levels remained at low levels, as indicated in Table 33.

TABLE 33
IMPURITIES IN ELS LITHIUM

<u>Impurity</u>	<u>Range (wppm)</u>	<u>Typical (wppm)</u>
H	38 - 83	50
N	9 - 75	15
O	15 - 133	25
C	0.2 - 17	2
Si	230 - 510	350
Ca	500 - 17	*
Al	650 - 110	*

*Concentration decreased steadily from initial maximum value during loop operation.

A series of laboratory pot tests were initiated to demonstrate the impurity addition concept for hydrogen, nitrogen, oxygen and carbon. The results of this work are reported in Reference 27.

Only a limited time was available for the ELS lithium purification study, so the decision was made to evaluate only hydrogen and nitrogen purification. Hydrogen and deuterium are expected to be the major impurities in the FMIT as the result of accelerator beam-lithium interaction. Nitrogen is generally regarded as the most corrosive impurity in lithium and would occur in the FMIT as the result of nitrogen or air leaks into the evacuated system, as well as from maintenance operations. Hydrogen has a solubility of 63 wppm at 392°F (200°C), while nitrogen has a solubility of 1400 wppm at that temperature. Thus, hydrogen should be effectively cold trapped while nitrogen requires hot trapping. Carbon and oxygen, two other impurities of interest, both have solubilities lower than hydrogen and would presumably be cold trapped even more readily.

A. HYDROGEN

At the start of the hydrogen addition, the level of dissolved hydrogen in the lithium was about 65 wppm. The hydrogen addition was made in two stages with the apparatus described previously in Section IV.M (see Figure 37). Specifically, hydrogen was added to the chemistry loop lithium by bubbling a mixture of 98.5% argon plus 1.5% hydrogen through the lithium. The flow rate during this addition was varied between 0.5 and 2.1 liters with a nominal rate of ~0.8 liters per minute. The surge tank automatic vent system (set to control at ~5 psig) was used to discharge the excess argon. Gas chromatographic analysis of the surge tank cover gas showed that more than 99.7% of the hydrogen reacted with the lithium. The first addition consisted of bubbling 5709 liters of the gas mixture through the lithium.

During the hydrogen addition, the chemistry loop operating conditions were: 1) bulk lithium temperature 371°C (700°F), 2) lithium flow rate 4 to 6 gpm, and 3) cold trap in hot standby (0.0 gpm at 260°C). The chemistry

loop was isolated from the main ELS lithium piping, limiting the lithium inventory to the volume contained in the chemistry loop. Refer to Figure 60 for a schematic of the chemistry loop during the hydrogen additions. Note that the hot trap was isolated and the lithium in it frozen during the cold trapping study. Table 34 lists the chemistry loop components and lithium inventory.

TABLE 34
CHEMISTRY LOOP LITHIUM INVENTORY

<u>Component</u>	<u>Lithium (gal)</u>	<u>Lithium (g)</u>
Surge Tank	68 (11.5 in. deep)	128,690
Cold Trap	35	66,237
Hot Trap	0*	0*
Loop Piping	<u>2.7</u>	<u>5,110</u>
TOTAL	105.7	200,037

*The hot trap was isolated and frozen for the cold trap study.

The hydrogen additions are summarized in Table 35. Hydrogen was also returned to the loop by reheating the cold crystallizer, thereby enabling additional cold trap testing. The hydrogen recovery data from reheating the crystallizer are shown in Table 36.

TABLE 35
SUMMARY OF HYDROGEN ADDITIONS

<u>Addition</u>	<u>Argon/Hydrogen Mixture (L)</u>	<u>Average Flowrate (L/m)</u>	<u>Hydrogen Added (g)</u>
1	5709	0.80	7.6
2	4803	0.81	6.4

TABLE 36
HYDROGEN RECOVERY DATA (FROM COLD TRAP REHEATING)

<u>Sample No.</u>	<u>Date</u>	<u>Time</u>	<u>Isothermal Cold Trap Temperature (°F)</u>	<u>Lithium Flow (gpm)</u>	<u>Reheat Time (h)</u>	<u>Prior H₂ Level (wppm)</u>	<u>New H₂ Level (wppm)</u>	<u>ΔH₂ Lost (wppm)</u>
51	10/4/83	1510	500	3.0	98	100	89	11
58	10/12/83	1112	500	0.5	46	89	76	13
59*	10/12/83	1150	500	0.5	46.6	89	Not Analyzed	Not Analyzed
70	10/31/83	0933	680	1.8	75	108	102	6
71	11/1/83	0835	518	1.0	23	108	108	0

*Flow-through tube sample; all others are thief samples.

Results from the hydrogen additions show that hydrogen can be added to lithium quantitatively. However, reheating the crystallizer and equilibrations with the system did not return all the hydrogen to the system. Note, from Table 36 that the hydrogen recovery the first time the crystallizer was reheated was 11 wppm or 2.2 g low. The second time, the hydrogen was 13 wppm or 2.6 g low. If the losses had been a function of the re-equilibration temperature, then the missing hydrogen would have re-appeared during the relatively long equilibration at 680°F. The sum of the losses (4.8 g) from reheating the cold trap the first two times plus the inventory of hydrogen found after the third reheat (average of samples 70, 71 and 72) gives a total hydrogen inventory of 132 wppm or 26.7 g, which is in good agreement with the theoretical amount (27 g) added. These observations suggest an interaction between hydrogen and some other impurity (possibly oxygen) that was also present in the cold trap. The interaction could have been satisfied stoichiometrically with 4.8 g of hydrogen or perhaps the higher temperature shifted the equilibrium so that no additional loss of hydrogen occurred when the trap was reheated the third time. H. Katsuta⁽³⁷⁾ reported a disparity between the solubility of hydrogen, measured by the equilibrium pressure of hydrogen above the lithium, when the hydrogen was controlled with a cold trap. He suggested an interaction between oxygen and/or nitrogen. Katsuta⁽³⁸⁾ also reported a similar observation studying the Na-O-H system when a cold trap was used to establish the solubility of oxygen and hydrogen in sodium.

B. NITROGEN

Dissolved nitrogen in the chemistry loop lithium was ~20 wppm before starting the nitrogen additions. Nitrogen in the ELS lithium remained low (<40 wppm) during operation without purification because of the dissolved aluminum that was present as an impurity in the lithium when it was purchased. The aluminum reacts with dissolved nitrogen to form a relatively insoluble aluminum nitride (ALN). Laboratory studies⁽²⁷⁾ that were conducted on ELS lithium showed that in addition to the aluminum-nitrogen reaction, there was also another reaction between dissolved silicon and dissolved

nitrogen to form a relatively insoluble ternary nitride ($\text{Li}_5\text{-SiN}_3$). Precipitation of this compound begins when the dissolved aluminum is nearly depleted. The ELS lithium purchased contained ~ 500 wppm Al and ~ 400 wppm Si. Consequently, before the dissolved nitrogen in the chemistry loop lithium could be increased to ~ 400 wppm, the desired level for conducting the hot trap tests, the aluminum and silicon had to be removed by bubbling an argon-nitrogen mixture into the lithium. A laboratory study⁽²⁷⁾ was conducted to determine bubble flow rate and a temperature for the addition. It was determined that nitrogen was absorbed by lithium much more efficiently than hydrogen, so a higher concentration in the impurity addition mixture (97% argon + 3% nitrogen) was used, as well as a lower addition temperature ($\sim 500^\circ\text{F}$). Refer to Figure 60 for a schematic of the chemistry loop during the nitrogen additions. Note that the cold trap was isolated and the lithium in it frozen during the testing with nitrogen. Another significant change in operation, different than for the cold trapping study, is the inclusion of the two 25- μm filters (2.25-ft² surface area), one in a parallel flow path near the Flow-Through Tube Sampler (FTTS) and the other in the outlet of the hot trap. The hot trap was maintained at 500°F during the nitrogen additions, and flow in the hot trap circuit was established intermittently so that the hot trap filter collected some of the precipitate formed and also kept the inventory of lithium in the hot trap circuit (~ 35 gal) mixed with the remainder of the chemistry loop lithium. The same impurity addition apparatus used for the hydrogen addition was used for nitrogen (see Figure 37). Nitrogen additions were made intermittently. The gas addition tube plugged after adding 1839 liters and had to be removed for cleaning. At other times the gas addition was stopped so a thief sample could be taken. Other times the addition was terminated because of (miscellaneous) conflicting operational activities. Table 37 summarizes the nitrogen gas additions.

A total of 342-g nitrogen were added to the chemistry loop lithium. R. F. Keough calculated that 1.8 lb (820 g) of precipitate was formed. Enough precipitate was collected on the two 25- μm filters to cause a significant flow decrease. Figure 76 shows the effect of adding nitrogen on the

TABLE 37
SUMMARY OF NITROGEN ADDITIONS

<u>Addition No.</u>	<u>Argon/Nitrogen Mixture (g)</u>	<u>Average Flow Rate (g/m)</u>	<u>Nitrogen Added (g)</u>
1a	1839	9.9	69
1b	424	7.1	16
1c	707	2.6	26.5
1d	1556	2.6	58.3
1e	637	2.5	23.9
1f	1061	3.1	39.8
(Chemical analysis found 230 wppm N ₂ . First hot trapping run was started.)			
2	2887	3.0	108.3
(Chemical analysis found 450 wppm N ₂ . Second hot trapping run was started.)			

aluminum and silicon concentration and graphically illustrates how the dissolved nitrogen increased after the aluminum and silicon were depleted. After the aluminum and silicon were essentially removed (10 and 30 wppm, respectively), the nitrogen increased significantly less than the theoretical amount added, i.e., during Addition 2 (see Table 37) 108-g nitrogen were added to the chemistry loop lithium inventory, which should have resulted in a theoretical increase of 536 wppm. Chemical analyses gave 450 wppm. R. F. Keough suggested that the decrease in observed nitrogen may have come from gettering by the chromium in the surface of the stainless steel, which could have been particularly reactive after several thousand hours in contact with low-nitrogen lithium.

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FIGURE 76. Effect of Adding N_2 on Dissolved Impurities in the ELS at 500°F. (27)

IX. VAPOR/AEROSOL TRANSPORT

A. EARLY FROST OBSERVATIONS

Frost was discovered in the vacuum system piping during the first piping modification after ~8 hours of vacuum operation (shown in Figure 77). A thin film of white frost was found throughout the vacuum system piping internals. Efforts were immediately begun to characterize the frost. Samples of the frost from the vacuum piping ~10 ft above the main surge tank were chemically analyzed, and a viewport was installed on the main vacuum neader. The chemical analysis showed that the major components of the frost were lithium (8 mg), sodium (3 mg), and potassium (0.9 mg).

The rate of frost formation in the 10-cm (4-in.) vacuum piping over the main surge tank is estimated from Sample 1 data to be $0.17 \text{ mg/cm}^2/\text{day}$ during pressure operation of the system. This estimate is based on a total deposit of 11.9 mg uniformly distributed on a 215-cm^2 surface area over an 8-hour period. At the time Sample 1 was taken, the ELS had ~4000 hours of pressure operation and ~8 hours of vacuum operation. However, this surface was isolated from the lithium system during all pressure operation. Sample 2 was taken ~6 months later. At this time, the ELS had accumulated ~6000 hours of pressure operation and ~100 hours of vacuum operation. Sample 2 was removed from a 2-3/4-in. blind flange located ~2 ft above the main surge tank. Table 38 shows a comparison among the frost samples (Samples 1 and 2) and the lithium pool compositions. Sample 2 was never isolated from the lithium system. No isolation was possible. These data are presented merely to substantiate the existence of frost in the ELS vacuum piping. It should also be noted that the lithium pool composition shown represents the initial concentrations of these elements. When the first frost sample was taken (12/30/80), the potassium level had already reduced to the detection limit of 5 wppm.

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FIGURE 77 Typical Frost Deposit on Vacuum System Piping. Neg 8014619-1

TABLE 38
COMPARISON OF FROST AND LITHIUM POOL COMPOSITIONS

Element	Composition (%)		
	Frost Sample 1*	Frost Sample 2**	Lithium Pool
Li	67	81	99.7
Na	25	3	0.22
K	8	16	0.0023

*Non-loop side of vacuum isolation valve.

**Loop side of vacuum isolation valve.

Samples of other deposits from the vacuum piping were also collected and analyzed when the system had to be opened for maintenance and modification. In all cases, these four deposits (shown in Table 39) did not result from direct lithium splashing. Deposits resulting from splashing were observed around the target and chemistry surge tank, but are not included in this discussion. The four samples shown in Table 39 are presented to demonstrate the presence of lithium aerosols in portions of the ELS vacuum piping. Clearly the compositions of these deposits are approaching the pool composition, particularly the 2-in. equalization line deposits (Samples 1 and 2). The target return to the main surge tank has an 18-in. free fall and was expected to be an excellent source of splash-induced lithium aerosols. The composition of the splash-induced aerosols should closely approximate the lithium pool composition.

The deposit formed on the inside diameter of the large flange on the 2-in. equalization line (Sample 2) demonstrates the vapor/aerosol trapping potential of cooling surfaces. This 4.5-in. OD flange essentially acted as a cooling fin on this piping run.

Quantitative vapor/aerosol transport rate measurements were also made over the chemistry surge tank during pressure operation. These measurements were made by drawing a known volume of gas through a 0.5-in. tubing run and $\frac{1}{8}$ -in. sintered steel filter and measuring the residue. The chemistry surge

TABLE 39
COMPOSITION OF OTHER LIQUID METAL DEPOSITS FROM ARGON/VACUUM PIPING

Sample No.	Date	Location	Description of Deposit	Composition (%)		
				Li	Na	K
1	3-17-82	Filter on 2-in. Target/ Surge Tank Equalization Line	Granules and Lumps on Surge Tank Side of Filter	98.82	0.34	0.84
2	5-20-83	Flange Midway Along 2-in. Target/ Surge Tank Equalization Line	Solid Annular Ring on Flange ID	99.9	0.001	0.0001
3	5-20-83	4-in. Elbow on Roots Blower Suction Line	Powder and Granules on Elbow ID	96.0	1.0	3
4	5-20-83	1.5-in. Vacuum Gauge Line on Main Surge Tank	Powder and Granules	96.7	0.7	2.6

tank was at 518°F and 6.5 psig during this test. A total of 1068 liters of argon gas was passed through the filter at an average flow rate of 1 μ /min. The results of this test are shown on Table 40. The data show fair agreement with the composition of Frost Sample 1 on Table 38 and suggest an aerosol-free environment in the chemistry surge tank. The average concentration of liquid metal vapor in the chemistry surge tank argon cover gas is estimated to be 0.17 μ g/ μ during pressure operation. These results cannot be directly correlated to the expected quantity of vapor over the lithium during vacuum operation, the normal FMIT operating mode.

TABLE 40
CHEMISTRY SURGE TANK VAPOR/AEROSOL COMPOSITION DATA

Element	Composition (%)	
	Vapor/Aerosol	Lithium Pool
Li	77	99.7
Na	17	0.22
K	6	0.0005

B. SIMULATED ACCELERATOR BEAM TUBE VAPOR/AEROSOL TRANSPORT TESTS

Vapor/aerosol transport tests were also conducted in the Experimental Lithium System (ELS) simulated accelerator beam tube to determine the quantity of liquid metal vapor deposits that will be present in the FMIT beam tube as a result of evaporation from the liquid lithium target. A 16.5-ft (5-m) long simulated accelerator beam tube was attached to the face of the Mark II target. This simulated accelerator beam tube was previously described in Section IV.D. The quantity of deposits is important to diagnostic equipment design and to vacuum system design in FMIT. Liquid metal vapors could adversely affect such diagnostics as beam position monitors and optical detection devices. It is also of interest to vacuum system designers to know how much material is expected to be collected in the vacuum pumps and instrumentation.

The following is a summary of the results of the vapor/aerosol tests. The measured deposition rates are summarized in Table 41. The 540°F test at vacuum was designed to match predicted performance at FMIT operating conditions while the 750°F test at vacuum was intended to measure the effect of temperature variations and a potential lithium boiling situation. The 540°F test at pressure was run to correlate relative transport rates between vacuum and pressure operation. Plots of the measured deposition distribution are shown as a function of distance from the target in Figures 78 through 80. Sodium was the most significant contributor to the deposit during vacuum operation, while lithium was the greatest during pressure operation.

In the vacuum environments the deposits drop significantly with distance from the target, particularly with the cooler beam tube. This is clearly shown in Figures 78 and 79. The 750°F (399°C) test results in Figure 79 exhibit the sharpest drop in beam tube temperatures and the sharpest drop in deposition rate along the beam tube of the three tests. The sticking coefficient is clearly not one along the beam tube as assumed in earlier predictions. If the sticking coefficient were one, then the sodium and potassium would have deposited at the beginning of the beam tube just as the lithium did. The decrease in lithium deposits at vacuum suggests a sticking probability of close to one for lithium. Sodium deposition appeared to be delayed at vacuum until the vapor reached the point along the beam tube where the beam tube temperature dropped below the saturation temperature for this liquid metal. Potassium's vapor behavior was different from that of lithium and sodium.

The sodium and lithium tend to deposit along the tube beginning at the point where the beam tube temperature equals the dew point of the substance. This is shown in Figure 81. The approximate ELS beam tube pressure distribution for the 540°F (280°C) vacuum test is plotted in this figure. The saturation temperatures for K, Na, and Li for these pressures are plotted down to the melting point of these substances. The beam tube temperatures for the tests are also plotted. The dew point is the point at which the

HEDL 8407-231.3

FIGURE 78. Measured Vapor Deposition on ELS Beam Tube - Vacuum Test with Lithium at 540°F (282°C).

HEDL 8407-231.2

FIGURE 79. Measured Vapor Deposition on ELS Beam Tube - Vacuum Test with Lithium at 750°F (399°C).

HEDL 8407-231.1

FIGURE 80. Measured Vapor/Aerosol Deposition on ELS Beam Tube - Pressure Test with Lithium at 540°F (282°C).

HEDL 8407 231 4

FIGURE 81. Beam Tube Pressure and Temperature and Liquid Metal Saturation Temperature for the 540°F (282°C) Vacuum Test.

TABLE 41

SUMMARY OF DEPOSITION MEASUREMENTS IN SIMULATED
ACCELERATOR BEAM TUBE

<u>Test Conditions</u>	<u>Lithium (g/day)</u>	<u>Sodium (g/day)</u>	<u>Potassium (g/day)</u>
540°F (282°C) - Vacuum	0.241	0.895	1.23×10^{-4}
540°F (282°C) - Pressure	0.0496	4.33×10^{-3}	1.25×10^{-4}
750°F (399°C) - Vacuum	1.84	57.2	7.9×10^{-3}

saturation temperature equals the beam tube temperature. Thus, for each of the tests the position in the beam tube where the liquid metals are expected to deposit are indicated. The lithium and sodium deposit roughly at their dew points. Potassium deposited earlier than expected, probably because it alloys with the sodium as it makes its way down the beam tube. NaK exhibits lower vapor pressure than either Na or K and thus is expected to deposit faster. Also, there is some probability for sticking even when the temperature is above the dew point temperature.

At pressure, the deposits are nearly constant along the beam tube. This is consistent with the following argument. At vacuum (10^{-6} to 10^{-4} torr), the fluid is in the molecular to transition flow regime. The mean free path in the beam tube in this regime is ~ 1 m. Therefore, an atom which has evaporated from the target surface will very likely strike the beam tube wall near the target before it interacts with other vapor molecules. The atom will adhere to the wall depending on the amount of kinetic energy lost in the collision. At pressurized conditions, however, when the mean free path is 10^{-4} cm, the particles can be convected by the gas toward the cooler surfaces of the beam tube, away from the target.

The amount of deposits measured during the pressure test were less than those measured at vacuum for the same lithium temperature. Since the high-speed lithium jet works effectively as a vacuum pump itself, the pressure at

or near the surface of the jet probably was lower than in the beam tube, limiting the amount of convection to the beam tube.

The approximate deposit thickness rates of increase for each test are plotted in Figures 82 through 84. The thicknesses were obtained by dividing the deposition rate by the approximate liquid metal density (0.5 g/cc Li, 0.8 g/cc K, 0.9 g/cc Na). The total deposition thicknesses drop from 1 cm/yr near the beginning of the beam tube to 10^{-4} cm/yr beyond 4.5 m from the target. These thicknesses are important when considering the impact of deposition on diagnostic components such as beam viewing ports and beam position monitors.

Expected deposition rates for FMIT based on ELS test information are shown in Figure 85. Note that the sodium rates are reduced substantially from those measured in ELS because of the significant reduction (factor of 10) in sodium concentration in the FMIT lithium as compared with the ELS lithium. The deposition rate at the FMIT vacuum pump port located 4.3 m from the target is expected to be 1.22×10^{-6} g/cm² day. The approximate rate of deposition thickness increase is 1.0 cm/year at the beam position monitors (BPM) and halo feelers located 8 to 26 cm from the target, 0.01 cm/yr at the BPMs and halo feelers located 1 m from the target, 0.01 cm/yr at the in-cell beam viewing system located 1.3 m from the target and less than 1 μ m/yr at the IR optical imaging device located at the last bending magnet 8.7 m from the target.

These results indicate that FMIT instrumentation located in the beam tube near the target must be designed to accommodate a significant amount of liquid metal vapor. But liquid metal vapors should not be a significant problem to the vacuum components or accelerator in FMIT.

HEDL 8407-231.23

FIGURE 82. Measured Thickness of Vapor Deposit on ELS Beam Tube - Vacuum Test with Lithium at 540°F (282°C).

HEDL 8407-231.14

FIGURE 83. Measured Thickness of Vapor Deposit on ELS Beam Tube - Vacuum Test with Lithium at 750°F (399°C).

HEDL 8407-231.19

FIGURE 84. Measured Thickness of Vapor Deposit on ELS Beam Tube - Pressure Test with Lithium at 540°F (282°C).

HEDL 8402-056.3

FIGURE 85. Predicted Liquid Metal Vapor Deposition in FMIT Beam Tube Based on ELS Test Data.

X. MATERIALS CORROSION

A multi-laboratory approach was used in the lithium corrosion/erosion studies to obtain test data on selected reference materials for the detailed design of FMIT lithium system piping and components. Technical direction for the program was provided by the FMIT Project at HEDL. Major testing at HEDL was conducted utilizing two experimental lithium loops: the Experimental Lithium System (ELS) and the Beryllium-7 Experimental Lithium Loop (7BELL). ELS is a full-scale, isothermal lithium system that simulates FMIT design hydraulic conditions and requirements (with the exception of a deuterium beam), while 7BELL is a small, ΔT experimental lithium loop. These loops provided actual lithium system operating data in the evaluation of materials compatibility and transport. Other organizations contributing to this overall effort included Westinghouse Research and Development Center (W-R&D) and Colorado School of Mines (CSM), Department of Metallurgical Engineering. Reference 39 compiles the separate studies from all three contributing laboratories and organizations involved.

This section presents a summary of the corrosion-related work associated only with ELS. This work included destructive examination of several welds from the 10-cm main loop piping, several valve designs, and a flattened, thin-walled EM pump throat.

A. PIPE AND WELDMENTS

After 6500 hours of operation in the ELS (at 270°C), the dummy lithium target piping spoolpiece was removed for installation of the Mark I target and for examination of spoolpiece welds. The welds were made on the 304 SS base material with 308 filler material. This examination was made to ascertain the safe long-term operation of FMIT lithium system piping and components and to support the design and procurement activities of FMIT lithium system components.

A total of four welds were made to join the two 10.2-cm (4-in.) 90° elbows to the straight section of the spoolpiece. The position of welds 1 through 4 is schematically shown in Figure 86. The sides of the welds are marked to correctly identify the exact position of each weld with reference to the lithium flow path. All four welds were cut and removed from the spool piece to serve as specimens for metallographic examination. Care was taken during the cutting operation to ensure the inclusion of the heat-affected zone (HAZ) in the specimen. The composition of the 304 SS pipe used in the fabrication of the spoolpiece is given in Table 42.

Photomicrographs were obtained from the weld specimens in the as-polished and the etched conditions. Intergranular lithium attack of 304 weldments in the HAZ was the main concern. The photomicrographs in the as-polished condition were obtained at a magnification of 250X. As evident from Figures 87 and 88, there is no apparent lithium attack of the 304 SS weldments after 6500 hours of isothermal operation. Since the photomicrographs of all four welds in the as-polished condition revealed no attack, a photomicrograph of only Weld 1 is reproduced here. The surface appearance of the OD and ID side of the pipe is almost identical, indicating very little attack by lithium. Little or no attack was expected from the low, isothermal temperature conditions present in ELS.

The weldments were then etched with glyceresia to reveal the detailed metallurgical structure (Figures 89 and 90). The etching (Figure 89a)

TABLE 42
COMPOSITION* OF DUMMY TARGET SPOOLPIECE PIPING (Heat No. M-0881)

<u>Material</u>	<u>Fe</u>	<u>Cr</u>	<u>Ni</u>	<u>Si</u>	<u>Mn</u>	<u>C</u>	<u>S</u>	<u>P</u>
304 SS	Bal	18.63	9.83	0.49	1.73	0.061	0.015	0.024

*Composition in wt%.

FIGURE 86. Configuration of Welds in the ELS Dummy Target Spoolpiece. Neg 8200521-1

(a) WELD AREA 120 μm AS-POLISHED

(b) AWAY FROM WELD 120 μm AS-POLISHED

HEDL 8201-141.6

FIGURE 87. Photomicrographs of ID Side of Weld 1 from Lithium-Exposed (6500 hours at 270°C) ELS Dummy Target Spoolpiece. Neg 8200521-6

(a) WELD AREA 120 μm AS-POLISHED

(b) AWAY FROM WELD 120 μm AS-POLISHED

HEDL 8201-141.7

FIGURE 88. Photomicrographs of OD Side of Weld 1 from ELS Dummy Target Spoolpiece. Neg 8200521-7

FIGURE 89. Photomicrographs of ID Side of Weld 2 (Region 2-3) from Lithium-Exposed (6500 Hours at 270°C) ELS Dummy Target Spoolpiece. Neg 8200521-9

HEDL 8503-071.12

FIGURE 90. Photomicrographs of Weld 1 (the Other Side of Weld from 1-2) from Lithium-Exposed (6500 Hours at 270°C) ELS Dummy Target Spoolpiece. Neg 8200521-10

revealed a banded structure that is a normal result of pipe fabrication procedures. Grain coarsening in the proximity of the weld is not readily apparent here, although a certain amount of grain growth seems to be present near Weld 1 (Figure 90b). The structure near Weld 2 (Figure 89) shows no grain growth because the temperature of the region examined is fairly uniform. These results were directly influenced by the weld sequence and close proximity of Welds 2 and 3.

As evident from the figures, the glyceric acid etchant darkened the grain boundaries and the twin boundaries. The preferential darkening of these boundaries is due to the etching of the carbide precipitates in the sensitized HAZ. Another important observation is that the sensitization in the HAZ of the 304 SS weldments in the ELS target spoolpiece appeared to be minimized. This again is because the heat-affected zone, especially near Welds 1 and 4 of the ELS dummy target spoolpiece, probably did not have enough time to be sensitized in the sensitizing temperature range due to the material acting as a large heat sink.

Scanning Electron Microscopy (SEM) was also performed on the weldments from the ELS dummy target spoolpiece to ascertain the relative concentration levels of major elements of the steel present on the exposed surface. The SEM data are given in Figures 91 through 93. Energy Dispersive Analysis for X-rays (EDAX) was performed on the lithium-exposed (6500 hours) weldment pieces as well as some of the as-received 304 SS pipe from the same heat as the spoolpiece. EDAX was performed for six elements present on the steel surface (Fe, Cr, Ni, Si, Mn, and Al). The relative x-ray intensities were normalized with respect to the intensity of iron, which is the major element of steel. It is apparent from the figures that the as-received grain structure is still fairly well preserved even after 6500 hours of lithium exposure, as expected for 270°C service. This is also substantiated by the negligible compositional change from the as-received surface to the lithium-exposed surface, as revealed by the relative x-ray intensity data. Within experimental error, there is negligible loss of Cr, Ni, Al, and Si from the surface of the steel. Such a result is expected for three reasons:

(a)

100 μm

**RELATIVE X-RAY INTENSITIES FROM AREA SCAN:
Fe-1.0, Cr-0.436, Ni-0.08, Al-0.005, Si-0.008**

(b)

10 μm

HEDL 8201-141.11

FIGURE 91. SEM Photographs of ID Side of As-Received 304 SS Pipe (Heat M-0881). Neg 8200521-11

(a) 100 μm

RELATIVE X-RAY INTENSITIES FROM AREA SCAN:
Fe-1.0, Cr-0.434, Ni-0.077, Al-0.007, Si-0.009

(b) 10 μm

RELATIVE X-RAY INTENSITIES FROM PARTICLE:
Fe-1.0, Cr-0.484, Ni-1.322, Mn-1.394, Al-0.119, Si-0.036

HEDL 8201-141.12

FIGURE 92. SEM Photographs of ID Side of Lithium-Exposed (6500 Hours at 270°C) ELS Dummy Target Spoolpiece Region Near Weld 1.
 Neg 8200521-12

(a)

100 μm

RELATIVE X-RAY INTENSITIES FROM AREA SCAN:
Fe-1.0, Cr-0.43, Ni-0.083, Al-0.006, Si-0.007

(b)

10 μm

RELATIVE X-RAY INTENSITIES FROM PARTICLE:
Fe-1.0, Cr-0.11, Ni-0.065, Al-0.005, Si-0.003

HEDL 8201-141.13

FIGURE 93. SEM Photographs of ID Side of Lithium-Exposed (6500 Hours at 270°C) ELS Dummy Target Spoolpiece Region Near Weld 4.
 Neg 8200521-13

- 1) The lithium exposure temperature (270°C) and the nitrogen level (~30 wppm) in lithium were very low. At such a low temperature, the lithium corrosion rate of 304 SS is expected to be quite low since the corrosion rate is an exponential function of temperature.
- 2) The nitrogen level of ~30 ppm is substantially lower than the levels used by other authors⁽⁴⁰⁻⁴³⁾ that contributed to high corrosion rates.
- 3) The ELS was operated in an isothermal mode rather than in a ΔT mode. In the ΔT mode one part of the loop is operated at a higher temperature than the other. The ΔT mode will result in material being transported by lithium from the high-temperature side to the low-temperature side.

In the isothermal mode, the dissolution into lithium will take place initially. In the absence of a good sink where the dissolved material can precipitate from solution, the lithium will become saturated and the dissolution rate will slow down.

In actual practice, the FMIT will run in a ΔT mode, and the dissolution rate (hence the corrosion rate) will be higher. However, even with a ΔT , the corrosion rate of 304 SS at 270°C is expected to be only a fraction of a micron per year--based upon data obtained from the 7BELL test run in a ΔT mode. Such low corrosion rates will lead to extremely low levels of Fe, Cr, and Ni in the lithium, since these elements are expected to be deposited in the cold leg. The low metallic content will mean small amounts of activated species when lithium is bombarded by deuterons and neutrons in the target region of FMIT.

The SEM data on the ELS dummy target spoolpiece weldments also indicated the presence of particles on the lithium-exposed surfaces. Some of these particles were enriched with Mn, Ni, Al, Si, and Cr (Figure 92); others are depleted in Cr (Figure 93b). Particles depleted in Cr were also found by W-R&D Center workers in their rotating-disc studies (see Reference 39), which were also run at 270°C in an isothermal, low-nitrogen condition.

Butt-welded 304 SS coupons welded with 308 SS filler material tested in 7BELL did not reveal any apparent intergranular attack (IGA) in the heat-affected zone after 3718 hours at 270°C (520°F). The corrosion rate for these 304 SS coupons was measured to be $\sim 0.2 \mu\text{m}/\text{yr}$. There was no significant difference in the corrosion rate between 304 and 304L SS. Butt and tubular 304 SS weldments with 308 SS filler material displayed corrosion rates approximately two times greater than 304 SS parent metal, although this rate is still insignificant in terms of gross corrosion weight loss.

After 6500 hours of isothermal ELS operation at 270°C (520°F), the weldments in the ELS dummy target spoolpiece also did not show any evidence of intergranular attack (IGA). In addition, operation of the FMIT hot trap will involve temperatures in the 500°C range; and although previous studies have indicated higher corrosion rates (up to 0.001 in./yr) at these temperatures, the current FMIT corrosion allowance requirement of 0.020 in. for a 20-year life is considered adequate to ensure a structurally sound lithium system design. The SEM data of the ELS weldments indicated negligible changes in the surface concentrations of the alloying elements in the isothermal mode. The corrosion rate in a ΔT mode at FMIT temperatures, while greater, is insignificant; and, as such, we can conclude that there will be no IGA of either 304 SS parent metal or the weldments for extended periods of FMIT operation.

Based on the present data, 304, 304L, and 308 weld metal have been recommended for fabrication of FMIT lithium piping and components for long-term operation at 270°C (520°F). This recommendation is based on the assumption that the nitrogen level in FMIT lithium is maintained below 400 ppm (the current lithium system specification requirement). This is a reasonable requirement based on the ELS experience, where a nitrogen impurity level of <50 wppm was maintained during 9,000 hours of operation.

B. VALVES

Material corrosion studies were performed on four different 1-in. valves of ELS. These valves included two 1-in. Sargent Y-pattern globe valves. The first Sargent valve tested was a body only (with a valve seat brazed in place) and was subjected to 3500 hours of flowing lithium at 270°C. The second Sargent valve tested was a complete operating valve assembly and was subjected to 2000 hours of flowing lithium at the same temperature. The third valve evaluated was a 1-in. Nupro plug-poppet type subjected to 5800 hours of flowing lithium at 270°C. The fourth valve evaluated was a 1-in. Hoke-modified plug-type valve subjected to 5500 hours of flowing lithium at 270°C. A summary of the results of these studies follows.

Sargent Valve Body with Brazed Seat

The valve seat brazement of the first Sargent Valve (body only) was destructively examined. Optical metallography of the 1-in. Sargent valve seat brazement was taken in four locations, 90° apart on the seat circumference. An illustration of a typical valve design with the micrograph from Figure 94 (bottom half) in the inset, is included as Figure 95 to provide clarification of the brazement location and the configuration. The photomicrographs, taken in the as-polished condition, are shown in Figures 94 through 98. The figures are oriented such that the BNi4 brazement is sandwiched by the Stellite® 6B (valve seat) on the left and the 316 SS (valve body) on the right. Micrographs of just the top and bottom of each specimen are shown since these are the only lithium-contact regions.

The BNi4 brazement in the as-polished condition appears to be reasonably free of precipitates. However, Specimens 1 (Fig 96) and 2 (Figure 94) do contain second-phase precipitates near the bottom. The precipitation is more extensive in Specimen 2 (Figure 94) along the centerline. The second-phase precipitation, presumed to be nickel boride, is apparently a

*Stellite is a registered trademark of Cabot Corp. Inc., Columbus, OH.

TOP

120 μ m

BOTTOM

120 μ m

FIGURE 94. Photomicrographs of Valve Seat Specimen 2 in the As-Polished Condition.

FIGURE 95. Examination of BNi4 Brazement from 1-in. Valve Body after Lithium Exposure at 270°C for 3500 Hours in ELS. Neg 8206132-1

TOP

120 μ m

BOTTOM

120 μ m

FIGURE 96. Photomicrographs of Valve Seat Specimen 1 in the As-Polished Condition.

TOP

120 μm

BOTTOM

120 μm

FIGURE 97. Photomicrographs of Valve Seat Specimen 3 in the As-Polished Condition.

FIGURE 98. Photomicrographs of Valve Seat Specimen 4 in the As-Polished Condition.

function of the brazement gap width and brazing process. The second-phase formation is influenced by a wider gap in that the nickel-rich liquid cools slowly in the center of the gap, providing sufficient time for the precipitation to occur.

As evident from Figures 94 and 96, lithium attack of the braze alloy is apparent near the centerline and along the boundaries of the second-phase precipitation. The precipitation of nickel boride increases the silicon concentration of the nickel-rich liquid that solidifies next, and thus the α -nickel matrix around the second-phase precipitates is richer in silicon than the general silicon level in the α -nickle phase. Silicon is soluble in nickel up to 8 wt% at the brazing temperatures around 1100°C. The lithium then preferentially attacks these silicon-rich, alpha-nickel regions promoting centerline attack. The depth of the attack is $\sim 60\text{ }\mu\text{m}$ as shown in Figure 95. The extent of lithium attack disclosed in this brazement, as compared with the relatively insignificant results obtained from the 7BELL test coupons discussed previously, is directly related to the presence of second-phase precipitation. Consequently, if elimination of the second-phase precipitation could be guaranteed in a qualification of the brazing process, acceptability of the braze alloy in the valve application for lithium service would be more easily justified.

The investigation of BNi4 braze alloy, as a bonding material in the attachment of valve seats potentially selected for FMIT, provided somewhat conflicting results. Minor lithium attack was observed in one of four total test coupons from the 7BELL testing after 3718-hours exposure to 270°C lithium. These coupons consisted of BNi4 braze alloy attaching Stellite 6B (valve seat material) to 304 SS (valve body material). The lithium attack, presumed to be caused by the presence of alpha-nickel phase in the braze near the lithium contacting region, was considered insignificant and non-detrimental to valve operation or design life. A separate test specimen consisting of BNi4 braze alloy attaching Stellite 6B to 316 SS completed ~ 3500 hours of 270°C lithium testing in the ELS. Post-test examination of this test article disclosed evidence of lithium attack to a depth of $60\text{ }\mu\text{m}$

in the brazement in one of four locations examined. However, this attack was influenced by the presence of a second-phase precipitation (presumed to be nickel boride) in the braze alloy. Lithium corrosion attack of the degree measured is not expected to occur in a uniform and homogeneous brazement, controlled to assist the braze formation and prevent the second-phase precipitation. Further investigation of the BNi4 braze alloy in lithium service was performed in ELS on the Sargent valve assembly to qualify this material for the FMIT valve (20-yr) application. (See discussion of Sargent valve assembly.)

Nupro Valve Assembly

Destructive examination was also performed on a 1-in. Nupro, 316 SS valve after ~5800 hours of exposure to 270°C lithium and 10,000 cycles of operation. The valve assembly consisted basically of 316 SS components with a Stellite 6B valve plug insert. The valve is a welded construction and contains no brazed assemblies. Optical metallography and SEM data were obtained for the major valve components contacted by the liquid lithium. A composite illustration of the primary areas of interest is included as Figure 99. The valve cutaway shown in the center of this figure is for illustration only, since a hand-operated configuration is depicted whereas the test article was pneumatically operated. Micrographs were taken in the as-polished and etched conditions for comparative results in observing the general material structures.

There was no evidence of lithium attack on the AISI 316 components (bellows, stem, stem adapter, valve body and valve seat) or the Stellite 6B plug insert, consistent with corrosion rate data on similar alloys. Additionally, there was no observable intergranular attack or deterioration of material structures in the heat-affected zone of the critical weld areas. The valve seat was also examined for possible lithium-erosion effects from lithium impinging at velocities up to ~2.0 m/s, and the valve body was examined for mechanical abrasive damage by the up and down movement of the lower stem assembly during valve cycling. There appeared to be no lithium-erosion

HEDL 8204-066.4

FIGURE 99. Destructive Examination of ELS Valve After Lithium Service at 270°C for ~5800 Hours and 10,000 Operating Cycles. Neg 8202827-1cn

damage. In fact, the machining grooves on the seat surface were still visible. Slight abrasion was evident in the valve seat contact and valve stem adapter-to-body guide areas. However, these wear marks were determined to be normal valve wear and had no effect on valve operating performance as substantiated by the helium leak test data. In this regard, the comparative leak test results of the pre-test and post-test conditions were essentially unchanged at a seat leak rate of 1.5×10^{-3} std cc/s He at 10 psig, confirming valve sealing integrity and acceptability.

In conclusion, the structural stability and integrity of this 1-in. valve assembly was maintained after being subjected to the described test conditions. On this basis, the subject valve design is recommended as a candidate for FMIT lithium system application.

Sargent Valve Assembly

A complete Sargent valve assembly was also tested at ELS. This valve was exposed to 270°C lithium for ~2000 hours and subjected to 5000 operating cycles. The valve was then cleaned and examined. Four sections (at 90° intervals) of the stellite valve seat were made and the following observations were noted on the inlet (0°) section. In summary, the "as-polished" condition showed no sign of attack of the stellite, stainless steel or brazement on either the lithium-exposed or back side of the valve seat. The "etched" condition showed no second phase or IGA in the brazement or at the boundaries between the brazement and the base metal. The stainless steel and stellite parent metals also showed no attack. The center of the specimen looks identical to the edges with no porosity or second phase in the brazement, or abnormal structure in the stellite or stainless steel.

Specifically, the brazement appeared to be of uniform thickness throughout. Figure 100 shows a 10X as-polished photograph of the seat. Figure 101 shows a small flaw extending into the stellite. The brazement runs at about a 60° angle to the flaw, from right to left. The photo is at 500X and shows the as-polished surface. Although this crack was observed in

FIGURE 100. Photomicrograph of Stellite Valve Seat - 10X.

FIGURE 101. Photomicrograph of Flaw in Non-Lithium Side of Stellite Valve Seat - 500X.

one of the four sections, it appeared to be localized and was not on the sealing surface of the valve seat. This type of cracking in the HAZ of the brazement is rather common with stellite and warrants no further investigation.

Figure 102 shows the stellite-lithium interfaces at 500X, as polished. No lithium attack is evident. Figure 103 shows the interior of the brazement at 500X, as polished. Figure 104 shows the lithium interface at 500X in the as-polished condition and lack of any lithium attack on either side of the braze, in the braze metal, or in either the stainless steel or the Stellite. Figure 105 shows the stellite at 500X, etched in glyceresia again showing absence of lithium attack. Figure 106 shows the center of the brazement etched at 500X - note the lack of porosity or second-phase formation. Figure 107 shows the lithium interface at 500X, etched, again showing absence of attack in either metal, brazement or at either metal-brazement juncture.

In contrast to the valve seat examined previously (valve body test specimen), the brazement in this valve showed no second-phase precipitation and no attack by the lithium. One can conclude that with a Ni4 brazement made using a qualified brazing procedure where thermal/time conditions preclude the formation of second phase precipitation, the brazement will give satisfactory service in 270°C lithium.

Hoke Valve Assembly

The valve seat of the Hoke valve was examined under 10X magnification after 5500 hours of 270°C lithium service. No evidence of lithium attack was found. Therefore, destructive examination of this valve was not pursued.

C. PUMP THROAT

After ~9500 hours of operation the MSA Style V a-c electromagnetic pump was removed from the ELS chemistry loop for destructive examination.

FIGURE 102. Photomicrograph of Stellite/Lithium Interface at 500X, as Polished.

FIGURE 103. Photomicrograph of Interior of Brazement at 500X, as Polished.

HEDL 8503-071.19

FIGURE 104. Photomicrograph of Brazement/Lithium Interface at 500X, as Polished.

FIGURE 105. Photomicrograph of Stellite/Lithium Interface at 500X, as Polished.

FIGURE 106. Photomicrograph of Center of Brazement at 500X, as Polished.

HEDL 8503-071.20

FIGURE 107. Photomicrograph of Brazement/Lithium Interface at 500X, Etched.

The duct tube was sectioned for metallographic analysis. Examination of the brazed region showed a continuous joint, with no non-wetted areas. Some interaction of the braze with both the copper and stainless steel was seen, but this was of limited extent--characteristic of a properly brazed joint. Grain boundary precipitates extended about one quarter of the way into the duct tube wall. This is presumably a combined effect of the cold work and heating during brazing. The lithium-exposed surface opposite the braze, as well as in other regions of the duct tube, showed neither bulk corrosion nor intergranular attack. Figure 108 shows a section through the brazed area, along with a more highly magnified view of the duct surface exposed to lithium. Figure 109 shows micrographs of the interior and exterior surfaces in the round section of the duct tube. As can be seen, the surfaces are indistinguishable. No discernable effect of lithium at 270°C is present even after 10,000 hours of service. The duct wall was examined at other locations in the deformed region, with the same results.

The conditions under which the Experimental Lithium System chemistry loop pump operated are generally considered to be quite mild for 300 series stainless steels. The fact that no degrading effects were observed after examination of this pump confirms this appraisal. Low-nitrogen lithium at 270°C does not pose any apparent problems for pump integrity. The fact that not even incipient cracking was detected suggests that these results can be extrapolated to longer times; but caution should be exercised, particularly if more severe temperature or stress-cycle regimes are involved.

FIGURE 108. Section Through the Braze Region of the HEDL Chemistry Loop Pump Duct (50X).

a) Interior Surface (400X)

b) Exterior Surface (400X)

FIGURE 109. Sections from the Circular Region of the HEDL Chemistry Loop Pump Duct.

XI. REFERENCES

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A P P E N D I X A

ELS VALVE LIST

ELS VALVE LIST

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
3"-POV-1	Main Loop	Lithium	1200	375	Block	Bellows Sealed Sliding Gate	Valcor	H4-30326	Single-Acting Pneumatic	Masoneilan	A	SH 1 B-5	Full Cycle Required
3"-MOV-2	Main Loop	Lithium	1200	375	Throttle	Bellows Sealed Sliding Gate	Valcor	H4-30326	Single-Acting Pneumatic	Masoneilan	A	SH 1 B-5	
1"-POV-3	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 C-6	
1"-MOV-4	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Motor	Precon	201	SH 1 D-2	See Failure Log
1"-POV-5	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NO	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 D-4	
1"-MOV-6	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Motor	Precon	201	SH 1 D-4	See Failure Log
1"-POV-7	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 D-4	
1/2"-MOV-8	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Motor	Precon	201	SH 1 D-3	See Failure Log
1/2"-POV-9	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 D-3	
1/2"-MOV-10	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Motor	Precon	201	SH 1 E-3	See Failure Log
1"-HOV-11	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	N/A	N/A	N/A	SH 1 D-2	
1"-POV-12	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NO	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 E-2	
1/2"-POV-13	Dowtherm® System	Dowtherm	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	N/A	Deleted
1/2"-POV-14	Dowtherm System	Dowtherm	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	N/A	Deleted
1/2"-MOV-15	Dowtherm System	Dowtherm	1200	2500	Throttle	Plug-Poppet	Nupro	SS-12UW-16PBW	Motor	Precon	201	N/A	Deleted
6"-POV-16	Cold Trap Cooling	Air	---	---	Throttle	Butterfly	Keystone	Fig. 122-066	Single-Acting Pneumatic	Keystone	723 ACT 756-000	SH 1 D-2	No. Reassigned
1-1/2"-MOV-17	PTI Cooling	Air	392	200	Throttle	Bellows Sealed Butterfly	Nupro	304-24 VFO	Motor	Bodine	---	SH 1 D-3	Too Coarse
1/4"-HOV-18	Dowtherm System	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	N/A	Deleted
1/2"-HOV-19	Dowtherm System	Dowtherm	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW	Hand Operated	N/A	N/A	N/A	Deleted
1"-HOV-20	Lithium Fill Line	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Hand Operated	N/A	N/A	SH 1 D-5	

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Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
1/4"-HOV-21	Feed & Bleed	Argon	900	400	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 1 B-6	No. Reassigned
1/4"-HOV-22	Vacuum Supply	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 2 E-3	No. Reassigned
1"-POV-23	Argon Supply	Argon or Vacuum	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 E-7	Deleted
2"-POV-24	Vacuum Supply	Argon or Vacuum	392	14.7	Block	Bellows Sealed Angle Gate	Torr Vacuum Products	RVS-22VA	Single-Acting Pneumatic	Torr Vacuum Products	RVS-22VA	SH 2 E-4	
4"-POV-25	Vacuum Supply	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-4000V-P	Double-Acting Pneumatic	MDC	GV-4000M-P	SH 2 E-4	
1"-POV-26	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NO	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 D-7	
1"-POV-27	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NO	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 D-7	Deleted
4"-POV-28	Vacuum Supply	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	Thermionics	G-4000-P	Double-Acting Pneumatic	Thermionics	G-4000-P	N/A	Deleted
1"-POV-29	Vacuum Break	Argon or Vacuum	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 D-8	
1"-POV-30	Vacuum Break	Argon or Vacuum	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 D-6	
24"-POV-31	Ventilation	Air	---	---	Throttle	Butterfly	WHC	H3-43628 SH 3	Single-Acting Pneumatic	Powerstroke	331-2686	N/A	See H3-43628
24"-POV-32	Ventilation	Air	---	---	Throttle	Butterfly	WHC	H3-43628 SH 3	Single-Acting Pneumatic	Powerstroke	331-2686	N/A	See H3-43628
24"-POV-33	Ventilation	Air	---	---	Throttle	Butterfly	WHC	H3-43628 SH 3	Single-Acting Pneumatic	Powerstroke	331-2686	N/A	See H3-43628
1/4"-PKV-34	Ventilation Control Air	Air	200	400	Pressure	Hand Regulator	Norgren	11-002-001	Hand Operated	N/A	N/A	N/A	Inside Control Cabinet 1
1/2"-HOV-35	Chemistry Loop	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Hand Operated	N/A	N/A	SH 1 E-2	
1/2"-HOV-36	Chemistry Loop	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Hand Operated	N/A	N/A	SH 1 E-2	
1/2"-HOV-37	Chemistry Loop	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Hand Operated	N/A	N/A	SH 1 E-2	
1/2"-HOV-38	Main Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Hand Operated	N/A	N/A	SH 1 B-5	
1/2"-HOV-39	Argon Supply	Argon	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-8PBW	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-HOV-40	Argon Supply	Argon	900	600	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	N/A	Deleted

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
1/4"-H0V-41	Argon Supply	Argon	900	400	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-H0V-42	Argon Supply	Argon	900	600	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-H0V-43	Argon Supply	Argon	900	400	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-H0V-44	Argon Supply	Argon	900	600	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-H0V-45	Argon Supply	Argon	900	600	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	SH 1 F-8	Deleted
1/4"-H0V-46	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4UW-TSW	Hand Operated	N/A	N/A	SH 1 E-8	
1/4"-H0V-47	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4UW-TSW	Hand Operated	N/A	N/A	SH 1 E-8	
1/4"-H0V-48	Argon Supply	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 1 D-8	
1/4"-H0V-49	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	SH 1 D-8	
1"-H0V-50	Fire Suppression	Argon	---	1000	Block	Ball	Worcester	R11	Hand Operated	N/A	N/A	SH 1 B-8	
1"-H0V-51	Fire Suppression	Argon	---	1000	Block	Ball	Worcester	R11	Hand Operated	N/A	N/A	SH 1 B-8	
1"-H0V-52	Fire Suppression	Argon	---	1000	Block	Ball	Worcester	R12	Hand Operated	N/A	N/A	N/A	DFC No. ELS-221
1"-H0V-53	Argon Supply	Argon	---	1000	Block	Ball	Worcester	R10	Hand Operated	N/A	N/A	SH 1 A-8	
1/4"-H0V-54	Chemistry Loop	Argon or Vacuum	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 1 D-3	
1/2"-H0V-55	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-80W-T5W	Hand Operated	N/A	N/A	SH 2 E-4	
1/4"-H0V-56	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	SH 1 F-8	Deleted
1/4"-H0V-57	Gas Sampling	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	N/A	Deleted
1/4"-H0V-58	Gas Sampling	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	SH 1 B-6	No. Reassigned
1/2"-PRV-59	Feed & Bleed	Argon	---	---	Pressure Control	Metering	Research Control	78S	Single-Acting Pneumatic	Research Control	A% TRIM	SH 1 B-6	
1/4"-CV-60A	Feed & Bleed	Argon	---	---	Check	Swing Check	Jenkins	117A	N/A	N/A	N/A	SH 1 C-6	
1/2"-POV-60B	Feed & Bleed	Argon	---	---	Block	Bellows Sealed Swing Gate	Huntington	GVAP-062V	Double-Acting Pneumatic	Huntington	GVAP-062V	SH 1 B-7	

[illegible]

A-6

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
3/8"-HOV-76	Fire Suppression	Argon	---	1000	Block	Ball	Worcester	R8	Hand Operated	N/A	N/A	SH 1 B-8	
1"-HOV-77	Chemistry Loop	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Hand Operated	N/A	N/A	SH 1 C-3	
1"-HOV-78	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 E-3	
-79	Not Used												
-80	Not Used												
-81	Not Used												
-82	Not Used												
-83	Not Used												
-84	Not Used												
-85	Not Used												
1"-POV-86	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 E-4	
1"-POV-87	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 E-4	
1"-POV-88	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 E-4	
1/2"-POV-89	Feed & Bleed	Argon	---	---	Block	Bellows Sealed Swing Gate	Huntington	GVAP-062V	Double-Acting Pneumatic	Huntington	GVAP-062V	SH 1 B-6	
1/4"-PRV-90	Cold Trap Control Air	Air	---	250	Pressure Control	Hand Regulator	Masoneilan	77-40	Hand Operated	N/A	N/A	N/A	West Wall of Module 101
1/4"-PRV-91	324C Control Air	Air	---	---	Pressure Control	Hand Regulator	Parker	06E14C16AA	Hand Operated	N/A	N/A	N/A	Back of Control Cabinet 4
-92	Not Used												
-93	Not Used												
-94	Not Used												
-95	Not Used												
-96	Not Used												
-97	Not Used												
-98	Not Used												
1-1/2"-HOV-99	Vacuum Supply	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V	Hand Operated	N/A	N/A	SH 2	DFC No. ELS-211
2"-SV-100	Vacuum Supply	Vacuum	---	---	Anti-Suckback	Bellows Sealed Angle Gate	Leybold-Heraeus	273 05-1	Electrical & Vacuum	Leybold-Heraeus	273 05-1	SH 2 D-8	

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
1"-HOV-101	Vacuum Supply	Vacuum	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Hand Operated	N/A	N/A	SH 2 E-5	
4"-HOV-102	Vacuum Supply	Vacuum	392	14.7	Throttle	Bellows Sealed Swing Gate	Thermionics	G-4000-H	Hand Operated	N/A	N/A	SH 2 D-5	
1-1/2"-POV-103	Vacuum Supply	Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	---	SH 2 D-4	
1/4"-HOV-104	Vacuum Supply	Vacuum	850	500	Meter	Bellows Sealed Leak Valve	Varian	951-5100	Hand Operated	N/A	N/A	SH 2 C-4	
1-1/2"-POV-105	Vacuum Supply	Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	Normally Closed	SH 2 B-6	
1-1/2"-POV-106	Vacuum Supply	Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	Normally Closed	SH 2 B-7	
1-1/2"-POV-107	Vacuum Supply	Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	Normally Closed	SH 2 C-6	
1-1/2"-POV-108	Vacuum Supply	Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	Normally Closed	SH 2 C-7	
1-1/2"-POV-109	Vacuum Supply	Argon or Vacuum	250	14.7	Block	Bellows Sealed Angle Gate	Varian	951-5090	Single-Acting Pneumatic	Varian	Normally Closed	SH 2 C-8	
2"-POV-110	Equalization	Argon or Vacuum	392	14.7	Block	Bellows Sealed Angle Gate	Torr Vacuum Products	RVS-22VA	Single-Acting Pneumatic	Torr Vacuum Products	Normally Closed	SH 1 F-7	
1/2"-POV-111	Vacuum Supply	Argon or Vacuum	---	---	Root	Bellows Sealed Swing Gate	Huntington	GVAP-062V	Double-Acting Pneumatic	Huntington	GVAP-062V	SH 2	DFC No. ELS-208
1-1/2"-HOV-112	Vacuum Supply	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V	Hand Operated	N/A	N/A	SH 2 E-2	
1-1/2"-HOV-113	Vacuum Supply	Argon or Vacuum	392	14.7	Root	Bellows Sealed Swing Gate	MDC	GV-1500V	Hand Operated	N/A	N/A	SH 2	
-114	Not Used												
-115	Not Used												
-116	Not Used												
-117	Not Used												
-118	Not Used												
-119	Not Used												
1"-HOV-120	Argon Supply	Argon	---	1000	Block	Ball	Worcester	R12	Hand Operated	N/A	N/A	SH 1 B-8	
1/4"-PRV-121	Argon Supply	Argon	200	400	Pressure Control	Hand Regulator	Norgren	11-002-001	Hand Operated	N/A	N/A	SH 1 D-8	
-122	Not Used												
-123	Not Used												

<u>Valve No.</u>	<u>System</u>	<u>Service</u>	<u>Design Temp (°F)</u>	<u>Design Pressure (psi)</u>	<u>Function</u>	<u>Valve Type</u>	<u>Manufacturer</u>	<u>Model</u>	<u>Operator Type</u>	<u>Manufacturer</u>	<u>Model</u>	<u>EFD Sheet /Zone</u>	<u>Remarks</u>
-124	Not Used												
-125	Not Used												
-126	Not Used												
-127	Not Used												
-128	Not Used												
-129	Not Used												
1"-HOV-130	Valve Test Manifold	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW- 16PBW	Hand Operated	N/A	N/A	SH 1 E-1	
1"-HOV-131	Valve Test Manifold	Lithium	1200	2500	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW- 16PBW	Hand Operated	N/A	N/A	SH 1 D-1	
1/2"-HOV-132	Valve Test Manifold	Lithium	1200	2500	Throttle	Bellows Sealed Plug-Poppet	Nupro	SS-12UW- 8PBW	Hand Operated	N/A	N/A	SH 1 E-1	
1"-POV-133	Valve Test Manifold	Lithium	1200	375	Block	Bellows Sealed Y-Pattern Globe	Sargent	75001-001	Single-Acting Pneumatic	Sargent	71501-003	SH 1 D-1	Test Valve
1"-POV-134	Valve Test Manifold	Lithium	800	150	Block	Bellows Sealed Modified Plug	Hoke	N9039- V16Y43	Single-Acting Pneumatic	Fisher Control	667	SH 1 D-1	Test Valve
1"-POV-135	Valve Test Manifold	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW- 16PBW	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1 D-1	Test Valve
-136	Not Used												
-137	Not Used												
-138	Not Used												
-139	Not Used												
-140	Not Used												
-141	Not Used												
1/4"-HOV-142	Feed & Bleed	Argon	900	600	Root	Bellows Sealed Plug-Poppet	Nupro	SS-4UW	Hand Operated	N/A	N/A	SH 1 E-5	
1/4"-HOV-143	Gas Sampling	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 1 E-5	
1/2"-CV-144	Argon Supply	Argon	300	2500	Check	Bellows Sealed Poppet	Nupro	SS-8CPA2-3	N/A	N/A	N/A	SH 1 C-8	
1"-PRV-145	Argon Supply	Argon	175	300	Pressure Control	Hand Regulator	Norgren	R12-400- NNLA	Hand Operated	N/A	N/A	SH 1 B-8	
1/2"-HOV-146	Vacuum Supply	Vacuum	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW-TSW	Hand Operated	N/A	N/A	SH 2 E-2	
-147	Not Used												
-148	Not Used												

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
-149	Not Used												
1"-POV-150	Argon Supply	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-12UW-16PBW	Single-Acting Pneumatic	Nupro	Normally Open	SH 1 D-7	
1"-HOV-151	Argon Supply	Argon	---	1000	Block	Ball	Worcester	R10	Hand Operated	N/A	N/A	SH 1 A-8	
1/2"-HOV-152	Argon Supply	Argon	---	1000	Block	Ball	Powell	---	Hand Operated	N/A	N/A	SH 1 A-8	
1/2"-HOV-153	Argon Supply	Argon	---	1000	Block	Ball	Worcester	R9	Hand Operated	N/A	N/A	SH 1 A-8	
1/2"-HOV-154	Argon Supply	Argon	---	1000	Block	Ball	Worcester	R11	Hand Operated	N/A	N/A	SH 1 A-8	
3/8"-HOV-155	Ventilation Dampers	Air	---	400	Block	Ball	Crane	2330TF	Hand Operated	N/A	N/A	N/A	
3/8"-HOV-156	Ventilation Dampers	Air	---	400	Block	Ball	Crane	2330TF	Hand Operated	N/A	N/A	N/A	
1/2"-HOV-157	Ventilation Dampers	Air	---	400	Block	Ball	Crane	930TF	Hand Operated	N/A	N/A	N/A	
1/4"-HOV-158	Ventilation Dampers	Air	200	400	Pressure Control	Hand Regulator	Norgren	11-002-013	Hand Operated	N/A	N/A	N/A	No. Reassigned
1/4"-HOV-159	Lockup	Air	---	---	Pressure Control	Metering	Auto Ponents	F208-C7	Hand Operated	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-160	Lockup	Air	---	---	Pressure Control	Metering	Auto Ponents	F208-CT	Hand Operated	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-161	Lockup	Air	---	---	Block	Plug	Dahl Co	TU0 111	Hand Operated	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-162	Lockup	Air	---	400	Check	Vertical Lift	Fairbanks	0612	N/A	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-163	Bottle Air Supply	Air	350	500	Block	Plug	Hoke	4251F4Y	Hand Operated	N/A	N/A	N/A	
1/4"-HOV-164	Bottle Air Supply	Air	350	500	Block	Plug	Hoke	4251F4Y	Hand Operated	N/A	N/A	N/A	
1/2"-HOV-165	Bottle Air Supply	Air	---	---	Relief	TBD	Teledyne	C6-6378-4-1/2-2	N/A	N/A	N/A	N/A	
1/4"-HOV-166	Lockup	Air	---	400	Check	Vertical Lift	Fairbanks	0612	N/A	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-167	Lockup	Air	---	400	Check	Vertical Lift	Fairbanks	0612	N/A	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-168	Lockup	Air	--	400	Check	Vertical Lift	Fairbanks	0612	N/A	N/A	N/A	N/A	See H-3-43601
1/4"-HOV-169	Lockup	Air	---	400	Check	Vertical Lift	Fairbanks	0612	N/A	N/A	N/A	N/A	See H-3-43601

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
1/2"-HOV-170	Main Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW	Hand Operated	N/A	N/A	SH 1 C-5	
1/4"-LUV-171	Lockup	Air	150	150	Air Switch	Sliding Spool	Conoflow	VB-12	Single-Acting Pneumatic	Conoflow	VB-12	N/A	See H-3-43601
1/4"-LUV-172	Lockup	Air	150	150	Air Switch	Sliding Spool	Conoflow	VB-12	Single-Acting Pneumatic	Conoflow	VB-12	N/A	See H-3-43601
1/4"-LUV-173	Lockup	Air	150	150	Air Switch	Sliding Spool	Conoflow	VB-12	Single-Acting Pneumatic	Conoflow	VB-12	N/A	See H-3-43601
1/4"-LUV-174	Lockup	Air	150	150	Air Switch	Sliding Spool	Conoflow	VB-12	Single-Acting Pneumatic	Conoflow	VB-12	N/A	See H-3-43601
1/4"-LUV-175	Lockup	Air	150	150	Air Switch	Sliding Spool	Conoflow	VB-12	Single-Acting Pneumatic	Conoflow	VB-12	N/A	See H-3-43601
-176	Not Used												
-177	Not Used												
-178	Not Used												
1-1/2"-POV-179	RGA Inlet	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V-P	Double-Acting Pneumatic	MDC	GV-1500V-P	SH 1 F-1	
2-1/2"-POV-180	Target Lighting	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	Modified MDC	GV-2500V-P	Double-Acting Pneumatic	MDC	GV-2500V-P	N/A	DFC No. ELS-215
2-1/2"-POV-181	Target Lighting	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	Modified MDC	GV-2500V-P	Double-Acting Pneumatic	MDC	GV-2500V-P	N/A	DFC No. ELS-215
4"-PCV-182	Target RWA	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	Modified Thermionics	G-4000-P	Double-Acting Pneumatic	Thermionics	G-4000-P	N/A	
-183	Not Used												
-184	Not Used												
-185	Not Used												
-186	Not Used												
-187	Not Used												
-188	Not Used												
-189	Not Used												
-190	Not Used												
-191	Not Used												
-192	Not Used												
-193	Not Used												
-194	Not Used												
-195	Not Used												

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
-196	Not Used												
-197	Not Used												
-198	Not Used												
-199	Not Used												
2-1/2"-HOV-200	Thief Sampling	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-2500V	Hand Operated	N/A	N/A	SH 1	See H3-48487
1-1/2"-HOV-201	Thief Sampling	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V	Hand Operated	N/A	N/A	SH 1	See H3-48487
1/4"-HOV-202	Thief Sampling	Argon or Vacuum	600	1000	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4BW-TSW	Hand Operated	N/A	N/A	SH 1	See H3-48487
1/4"-HOV-203	Thief Sampling	Argon or Vacuum	600	1000	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4BW-TSW	Hand Operated	N/A	N/A	SH 1	See H3-48487
1/4"-HOV-204	Thief Sampling	Argon or Vacuum	600	1000	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4BG	Hand Operated	N/A	N/A	SH 1	See H3-48487
1/4"-HOV-205	Impurity	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	N/A	Not Installed
1/4"-SRV-206	Impurity Addition	Argon	300	50	Relief	Bellows Sealed Poppet	Nupro	SS-6R-2F-10	N/A	N/A	N/A	SH 1	See H3-48489
1/2"-POV-207	Gas Sampling	Argon	200	150	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8BK-TSW-91-NC	Single-Acting Pneumatic	Nupro	Normally Closed	SH 1	DFC No. ELS-190-1
1/2"-HOV-208	Gas Sampling	Argon	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-190-1
1/4"-HOV-209	Gas Sampling	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-190-1
1/4"-HOV-210	Gas Sampling	Argon	600	1000	Throttle	Bellows Sealed Plug	Hoke	4112G4Y	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-190-1
1-1/2"-POV-211	Gas Sampling	Argon	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V-P	Double-Acting Pneumatic	MDC	GV-1500V-P	SH 1	DFC No. ELS-190-1
1-1/2"-POV-212	Beam Tube Vacuum	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V	Hand Operated	N/A	N/A	N/A	DFC No. ELS-219
1-1/2"-HOV-213	Beam Tube Vacuum	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V-P	Double-Acting Pneumatic	MDC	GV-1500V-P	N/A	DFC No. ELS-219
6"-HOV-214	Beam Tube	Argon or Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-6000V	Double-Acting Pneumatic	N/A	N/A	N/A	DFC No. ELS-219
6"-HOV-215	Beam Tube	Argon or Vacuum	392	14.7	Block	Bellows Sealed Splash	Modified MDC	GV-6000V	Double-Acting Pneumatic	N/A	N/A	N/A	DFC No. ELS-219
1/4"-HOV-216	Seal Leak Port	Argon	900	400	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4H-TSW	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-206
1/4"-HOV-217	Seal Leak Port	Argon	600	1000	Block	Bellows Sealed Plug-Poppet	Nupro	SS-4BW-TSW	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-206

Valve No.	System	Service	Design Temp (°F)	Design Pressure (psi)	Function	Valve Type	Manufacturer	Model	Operator Type	Manufacturer	Model	EFD Sheet /Zone	Remarks
1-1/2"-POV-218	Argon Supply	Argon	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-1500V-P	Double-Acting Pneumatic	MDC	GV-1500V-P	SH 1	DFC No. ELS-200
4"-POV-219	Vacuum Supply	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-4000V-P	Double-Acting Pneumatic	MDC	GV-4000V-P	SH 2	DFC No. ELS-211
1/2"-HOV-220	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-184-1
1/2"-HOV-221	Chemistry Loop	Lithium	900	600	Block	Bellows Sealed Plug-Poppet	Nupro	SS-8UW	Hand Operated	N/A	N/A	SH 1	DFC No. ELS-184-1
6"-POV-222	Vacuum Supply	Vacuum	392	14.7	Block	Bellows Sealed Swing Gate	MDC	GV-6000V-P	Double-Acting Pneumatic	MDC	GV-6000V-P	N/A	DFC No. ELS-219
1/2"-SRV-1	Dump Tank	Argon	300	2500	Relief	Bellows Sealed Poppet	Nupro	SS-8CPA2-3	N/A	N/A	N/A	SH 1 A-6	Deleted
1/2"-SRV-2	Main Surge Tank	Argon	300	2500	Relief	Bellows Sealed Poppet	Nupro	SS-8CPA2-3	N/A	N/A	N/A	SH 1 E-5	
1/2"-SRV-3	Chemical Surge Tank	Argon	300	2500	Relief	Bellows Sealed Poppet	Nupro	SS-8CPA2-3	N/A	N/A	N/A	SH 1 F-4	
2"-SRV-4	Argon Supply	Argon	---	---	Relief	---	Kunkle	Fig 87	N/A	N/A	N/A	SH 1 C-8	
1/2"-SRV-5	Dowtherm System	Dowtherm	300	3000	Relief	Bellows Sealed Poppet	Nupro	SS-8C-25	N/A	N/A	N/A	N/A	
3/4"-SRV-6	Argon Supply	Argon	---	---	Relief	TBD	Kunkle	Fig 87.C	N/A	N/A	N/A	SH 1 C-8	
1"-PRV-1	Argon Supply	Argon	175	300	Pressure Control	Hand Reguiator	Norgren	R12-400-NNLA	Hand Operated	N/A	N/A	SH 1 B-8	
1/2"-PRV-2	Argon Supply	Argon	175	300	Pressure Control	Hand Regulator	Norgren	R17-800-RGLA	Hand Operated	N/A	N/A	SH 1 C-8	
1/2"-PRV-3	Feed & Bleed	Argon	160	250	Pressure Control	Hand Regulator with Shutoff	Matheson	71	Hand Operated	N/A	N/A	SH 1 C-6	
1/2"-PRV-4	Feed & Bleed	Argon	160	250	Pressure Control	Hand Regulator with Shutoff	Matheson	71	Hand Operated	N/A	N/A	SH 1 C-6	
1/2"-PRV-5	Feed & Bleed	Argon	160	250	Pressure Control	Hand Regulator with Shutoff	Matheson	71	Hand Operated	N/A	N/A	SH 1 C-6	

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