OSTI

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A LOW TEMPERATURE IRRADIATION VEHICLE
FOR EBR-II FEASIBILITY DESIGN STUDY

by

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by

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ABSTRACT

This report presents the results of studies and evaluations which were conducted investigating the feasibility of a low temperature irradiation vehicle (LTIV) for possible installation as a test facility in the Experimental Breeder Reactor II (EBR-II). The EBR-II, a 60 MWt fast reactor located at the Idaho Nuclear Engineering Laboratory (INEL), is a versatile test facility providing a high fast neutron flux environment for conducting irradiation experiments on a variety of fuel and structural materials. The reactor's metallic-fueled core is cooled with sodium which enters the core at $\sim 700^{\circ}\text{F}$ and exits at $\sim 883^{\circ}\text{F}$. A variety of test holes and test locations are available. However, continuous access to the core test samples is only possible by utilizing a modified control-rod channel. In order to meet the low temperature sample irradiation requirement ($\sim 550^{\circ}\text{F}$), a separate packaged loop, cooled with liquid lithium in its own closed-circuit coolant system, which is independent and isolated from the reactor coolant, was selected as the reference design. A re-entrant test configuration located in a modified EBR-II control-rod channel contains the irradiation test capsules. The lithium annular linear induction pump (ALIP), lithium-to-air heat exchanger, surge tank, and associated loop piping are external to the reactor and mounted on the vessel lifting superstructure located above the reactor. Flexible metal hoses connecting the ex-reactor and in-reactor loop sections were required so that the in-reactor loop could be lifted out of the core during fuel handling operations without disconnecting the coolant lines. Evaluations of various configurations and performance studies were conducted on the feasibility of the LTIV loop concept, with the results reported herein. Based on these results, it is concluded that the LTIV can be designed, fabricated, and installed in EBR-II without any foreseeable difficulties and that its irradiation performance would be such that the facility would become a valuable test bed for a variety of material irradiation research programs.

I. SUMMARY

A low temperature irradiation vehicle (LTIV) has been conceptually designed and its feasibility studied for potential installation in the Experimental Breeder Reactor-II (EBR-II) located at the Idaho Nuclear Engineering Laboratory near Idaho Falls, Idaho. The LTIV was intended as a multipurpose irradiation test facility in which a variety of nonfuel material samples could be irradiated at a controlled temperature in a high energy neutron flux environment. The self-contained packaged loop would be placed in one of the EBR-II control-rod positions and would have its own closed-circuit cooling system which would be independent from that of the reactor. Features of this facility include the capability to test samples at lower temperatures than the EBR-II sodium inlet temperature of 700°F, isolation from the reactor coolant, double containment for protection from possible loop failures, an independent control of coolant temperature, and coolant flow and coolant chemistry control. These features would allow several types of experiments [e.g., fusion materials and light water reactor (LWR) materials irradiation] to be conducted at temperatures lower than achieved in the past. This report summarizes the results of the feasibility assessments which have been conducted to date.

II. INTRODUCTION

A. Overview of EBR-II

The Experimental Breeder Reactor II (EBR-II) is a sodium-cooled, fast neutron, unmoderated reactor that is located at the Idaho Nuclear Engineering Laboratory ~ 40 miles west of Idaho Falls, Idaho.[1] The maximum power level of EBR-II is 62.5 MWt with the sodium coolant entering the reactor core at 700°F and exiting at 883°F. The reactor core (which may contain irradiation experiments) is a hexagonal assembly, 30.2 in. (767 mm) across flats, of hexagonal subassemblies. Each individual subassembly is 2.290 in. across flats and is 91.36 in. in total length with a centrally located 13.5 in. long fuel region. Stainless-steel axial reflector regions are located above and below the fuel. In one typical configuration (see page 7 of Ref. 1) two additional rows of unfueled solid steel reflector assemblies of similar

dimensions surround the core with an additional seven to nine rows beyond the reflector region of hexagonal, depleted-uranium blanket subassemblies.

Of the total of 127 subassembly core positions, 14 may be occupied by control, safety or experimental subassemblies. These subassemblies are 1.908 in. across flats and move within hexagonal channels of the same radial dimensions as the regular fuel assemblies. The control- and safety-rod drives are mounted outside the reactor vessel at the operating floor with the drive units being removable from the core region during refueling operations. Several of these control/safety channels which extend all the way up from the core through the reactor vessel cover, primary tank cover, and rotating shield plugs to the operating floor are available for use as experimental holes.

The EBR-II is a pool-type reactor and therefore the core and blanket subassemblies are contained within a reactor vessel which in turn is immersed in sodium within a 26 ft diameter by 26 ft high primary tank. The reactor vessel is immediately surrounded by a neutron shield of borated graphite contained within cylinders. The primary tank also contains the entire primary cooling system which includes two centrifugal pumps (4500 gpm at 50 psi head), a sodium-to-sodium shell-and-tube heat exchanger, an auxiliary pump for shutdown cooling, a fuel handling system, and a fuel storage basket for 75 subassemblies. The primary system contains 87,000 gal of sodium.

For more details about the EBR-II facility see Ref. 1 or the EBR-II System Design Descriptions.[2] A presentation of the requirements for conducting experiments in EBR-II can be found in the most recent EBR-II Experiment Guide.[3]

B. Facility Description

Based on the requirements for a multipurpose test vehicle that could irradiate material specimens at temperatures independent of the reactor, an in-pile experimental loop was selected that could be inserted into an existing control-rod thimble through the small rotating plug and reactor-vessel cover. This facility, with the test specimens cooled by liquid lithium, was named

the low temperature irradiation vehicle (LTIV). The major ex-reactor components of the facility (e.g., pump, heat exchanger, and surge tank) would be mounted above the reactor on the reactor vessel cover lifting mechanism support structure. The in-reactor portion of the loop would be elevated above the reactor core during fuel handling (to prevent interference with the fuel handling operation) and during reactor transient experiments (to maintain constant test conditions) by an elevator system. The lifting requirements will be facilitated by connecting the ex-reactor components to the in-reactor loop with doubly contained flexible metal hoses which will allow the test specimens to be continuously cooled.

The in-reactor LTIV loop, of re-entrant flow design, consists of a series of four nested tubes (i.e., test container, flow divider, flow housing, and guide tube) which provides space for the inner test sample capsules, downflow and upflow of the lithium coolant, and an argon gas gap for insulation between the loop and the EBR-II environment. The in-reactor tubes, of standard Birmingham wire gage (which is usually referred to as BWG) are of stepped design to take advantage of the increased volume in the upper control-rod channel. The tubing material selected was 304 stainless steel which is compatible with lithium at the temperatures of interest. The overall length of the in-reactor portion of the LTIV loop was ~ 38.6 ft.

The development of a lithium pump and a lithium-to-air heat exchanger would be required for this LTIV concept although based on preliminary assessments there exists considerable experience in both design areas. A dual Transient Reactor Test Facility (TREAT) annular linear induction pump (ALIP) configuration would probably be adequate to meet the LTIV facility's minimum pumping capacity and head requirements. A commercial heat exchanger vendor has been found who is willing to provide the heat exchanger to the required specifications. Several other specialized components and/or systems will be needed. These include, among others, a handling machine and transporter, a loop filling and draining system, a facility control and instrumentation system, and a loop lithium sampling and purification system.

A summary of some of the specific design and performance features of the LTIV packaged loop are provided in Table I.

C. Potential Benefits of Facility

The LTIV facility fits nicely into the long-range test plans of the EBR-II complex. It is the intent that this packaged loop would not have any serious impact on the plant operations or its plant capacity factor. One of the major objectives of the engineering work to be performed in the future would be to examine the loop's installation, maintenance, normal operation, removal, and installation of in-reactor tubes and samples to minimize the effect of the LTIV on EBR-II plant operations.

There are several programs which could benefit from the availability of an experimental irradiation capability in a packaged loop such as provided by the LTIV facility. The fusion materials test program would be a logical candidate for utilizing EBR-II's high neutron flux at controlled conditions. There also exists a need for such an irradiation test facility in the LWR research and development program. Test samples of vessel and other structural material would use the controlled LTIV environment to study nil-ductility transition (NDT) effects due to the high-energy neutron fluxes available in EBR-II. Some examples of the types of experiments which could be conducted in the packaged LTIV loop, while not considered to be all inclusive, are listed below:

1. Normal and off-normal testing of fusion program materials at the high-energy neutron flux levels, temperatures, irradiation damage levels required to establish operating limits.
2. Irradiation of representative LWR vessel and structural materials to study irradiation damage caused by high-energy neutrons available in EBR-II.
3. Special irradiation age accelerated testing of fusion and fission reactor component materials (i.e., pump insulation) at conditions at or exceeding those expected during component lifetimes.
4. Lithium-technology materials compatibility experiments using a modified LTIV sample capsule.
5. Arms control applications requiring irradiation tests.

D. Report Structure

This report on the design feasibility and performance characteristics of a low temperature irradiation vehicle (LTIV) for installation at EBR-II is structured as follows. A summary of the major aspects of the conceptual design are provided in Sect. I. The supporting background information on EBR-II and the potential benefits of the facility are presented in Sect. II. In Sect. III, the test and programmatic requirements imposed on the LTIV system design are provided. These requirements include experimental as well as operational and safety elements. The details of the LTIV facility as currently defined are provided in Sect. IV with the supporting feasibility performance analyses that were conducted summarized in Sect. V. Finally, in Sect. VI, recommendations for future work are provided with a preliminary design and development schedule and the associated resource requirements provided in Sect. VII. Ancillary information and supporting data are presented in the Appendices.

III. TEST AND PROGRAMMATIC REQUIREMENTS

A. Experimental

The experimental or test requirements that were imposed on the loop design during this feasibility phase were essentially taken from the fusion materials irradiation test program as developed for previous test programs or facility design assessments.[4,5] The materials test assembly must contain a sufficient volume so that appropriate materials test specimens can be irradiated under controlled temperature and neutron environment. The test assembly must accommodate adequate temperatures and provide a sufficient lifetime to achieve the desired neutron fluence goals. Appropriate cooling of the test assembly must be provided for temperature control. Various types of test specimens will be required to be incorporated into the assembly including the possibility of having a quick removal and reinsertion capability.

The specific fusion materials requirements that were used as a basis for the LTIV design have been tabulated in Table II. These experimenters' requirements were generated in conjunction

with the proposed materials irradiation test assembly (MITA) which was planned for insertion in EBR-II.[5] The test requirements tabulated in Table II are, in general, quite achievable with the exception of the temperature requirements (see Requirements 2.3 and 2.4 in Table II) and possibly the fluence goal (see Requirements 2.1 and 2.2). The low temperature range of 200°C (391°F) at the test section does not appear possible due to the loop flow rate capacity and heat exchange characteristics of the LTIV design. The high test temperature range upper limit of 500°C (931°F) and the long-term upper limit goal of 1200°C (2191°F) were not evaluated for application in EBR-II. In this initial feasibility study, the focus was on achieving, in EBR-II, a low-temperature testing capability (i.e., lower than the 700°F sodium inlet temperature). Therefore no detailed calculations were performed at the high-temperature range.

The fluence requirement range of 0.5×10^{22} to 10.0×10^{22} n/cm² with a maximum fluence of 15.0×10^{22} n/cm² may require some extra long irradiation times in EBR-II. In Table III, the irradiation times have been presented for the Table II recommended fluence range. These irradiation time estimates were calculated with a typical EBR-II fast neutron flux of 1.89×10^{15} n/cm² obtained in control rod position 5A3 during run 162A. As seen from the times calculated, assuming no sample intermediate reconstitution, several hundred full power days may be required to achieve the fluence goals. Furthermore, because the lifetime limit for cold-worked stainless steel in EBR-II is 10×10^{22} n/cm², to attain the high fluence limit of 15×10^{22} n/cm² may require an in-reactor loop which is constructed of low swelling alloys (e.g., HT9).

B. Operational

The operational requirements imposed on the LTIV facility design were obtained primarily from Ref. 5. The major operational related items have been tabulated in Table IV. In addition, EBR-II specific operational requirements which will be required can be found in the EBR-II Experiments Guide.[6]

Most of the operational requirements as listed in Table IV are quite general and can be easily accommodated in the LTIV design. The requirement for rapid reconstitution of irradiated

specimens (see Item 3.1 in Table IV) was interpreted to mean removal and reinsertion during a typical reactor refueling (~ 30 days). This requirement led to a LTIV loop configuration which will have a test region independent and separate from the lithium coolant. Direct access to the samples will be provided by a top closure design.

The operating requirements to minimize the operating time that the specimens are at less than design conditions (see Item 3.2 in Table IV) and not to exceed the design flux and temperature (see Item 3.3 in Table IV) requires that test conditions are maintained during the lifetime of the specimen's irradiation. During periods of reactor refueling it is required to lift the loop out of the core so that the small rotating plug can index to the fuel assemblies. Also during planned transient experiments it is planned to lift the loop out of the core region so as not to subject the specimens to abnormal neutron flux and temperature levels. Both of these requirements dictate that the in-reactor loop be lifted (~ 6 ft) with no interruption in loop cooling. This will require a LTIV loop which has an elevator for lifting and is connected to the ex-reactor components with flexible coolant hoses.

C. Safety

The safety requirements or criteria, which will dictate to a large degree the design features of the packaged LTIV facility, were taken from the requirements established for a similar packaged loop designed several years ago for EBR-II application.[7] Safety issues concerned with design, fabrication, installation, and operation of the LTIV at EBR-II will be the principal focus in any future engineering effort. The safety requirements presented in Table V then should be considered as only the initial framework from which the detailed safety criteria will evolve as the design progresses. As typical of most design-development projects, various trade-off studies will be conducted around these general safety requirements, design features, fabrication problems, and operational variables in an attempt to optimize the design.

The safety considerations which were taken primarily from the Ref. 7 design report are tabulated in Table V. These safety requirements will form the basis for future trade-off

evaluations and will no doubt be revised and possibly the list enlarged as required to ensure that the facility conforms to the high standards of safety presently applied to the EBR-II.

IV. DESCRIPTION OF FACILITY

A. Overall Configuration

The overall configuration of the low temperature irradiation vehicle (LTIV) evolved from a series of feasibility studies (see Sect. V). In addition, information from previous work performed on a proposed package loop for EBR-II[7] and the engineering effort on the In-core Instrumentation Test Facility (INCOT)[8] was utilized in this initial feasibility design phase. The LTIV is designed to perform irradiation of small (nonfueled) structural specimens in canisters at temperatures independent of the bulk EBR-II sodium temperature. The facility consists of essentially four major components or systems:

1. In-core irradiation test thimble,
2. In-reactor loop,
3. Ex-reactor loop system, and
4. Auxiliary support systems.

The overall concept of the LTIV is shown schematically in Fig. 1. A conceptual plan view of the LTIV concept looking down from above the reactor is shown in Fig. 2.

The in-core irradiation test thimble and holder will be located in the radial center of the in-reactor loop (see Fig. 1). The test thimbles will essentially be small (~ 1.0 in. diameter by up to ~ 1 ft long) canisters which will contain the test specimens. The holder as presently envisioned will be basically a tree or stalk which is supported at the top of the reactor and extends down through the reactor to locate the canisters in the core region. In order to achieve the quick turnaround requirement (see Item 3.1 in Table IV) the test thimbles and holder will be removable

through the top loop closure without removal of the entire in-reactor loop. The central test region containing the test capsules will be enclosed in an argon gas atmosphere.

The in-reactor loop consists of a series of nested concentric tubes which are mounted on the reactor head at the EBR-II operating floor (see Figs. 1 and 2). In Fig. 3, the arrangement of a control-rod channel installed loop is shown (INCOT loop) which illustrates how the LTIV will be located in EBR-II. Lithium coolant enters and exits the in-reactor loop at the operating floor level. As Fig. 1 indicated, the in-reactor loop will be connected to the ex-reactor loop by means of flexible metal hoses. The details of the in-reactor LTIV loop are provided in Sect. IV.B.

As seen in Fig. 1, the ex-reactor LTIV system consists of an electromagnetic pump, an air-to-lithium heat exchanger, and a lithium expansion tank. These temperature control components are mounted on the reactor vessel cover lifting mechanism support structure. This support structure is located directly above the control-rod channel penetrations in the reactor floor (see Fig. 2). As indicated in Fig. 1, the temperature control system is mounted on a hinged panel for easy access to the control-rod drives located within the lifting mechanism support structure. Another concept of locating the coolant temperature control system on a moveable cart was considered and rejected (see Sect. V). For the details of the ex-reactor LTIV loop, see Sect. IV.C.

Auxiliary loop support systems would also be required to provide services to the irradiation facility. As Fig. 2 illustrates, an elevator and lifting drive system would be required to lift the in-reactor loop from the core region during reactor refueling and during planned reactor transients. Facility test instrumentation, loop control, and plant protection systems will also be required and a dedicated LTIV control station on the EBR-II operating floor established. Also needed will be a lithium loop filling and draining capability as well as a lithium chemistry sampling and purification system (e.g., cold and hot traps). A handling and shipping cask for transporting the in-reactor samples and loop would also be necessary in order to safely shield and transport the specimens and loop. The need for this equipment, their requirements, and specifications have not been determined in this initial study.

B. In-reactor Test Section

The in-reactor LTIV loop consists of a series of four nested tubes which surround the centrally located test region. As illustrated in Fig. 3, the in-reactor loop extends through the reactor's rotating plugs and shielding into the sodium-filled EBR-II reactor tank. The in-reactor loop is ~38.6 ft long and, consistent with the dimensions of the control-rod channel, has an upper section with an outer guide tube 2.5 in. in diameter and a lower section with a slightly smaller guide tube diameter of 2.225 in. The in-reactor loop is connected to the ex-reactor loop by means of flexible steel hoses which allow the in-reactor loop to be lifted without disconnecting it from the ex-reactor loop during refueling and during planned transients. The major feature of the in-reactor loop is the centrally located test hole where test capsules containing specimens to be irradiated can be inserted. Figure 4 illustrates conceptually a typical test capsule. The in-reactor test loop also is characterized by two annular regions for lithium coolant inlet and egress separated by a flow divider. An outer annular argon gas filled region is provided for insulation purposes to reduce the flow of heat between the loop and the EBR-II environment. The in-reactor loop is supported from the top at the reactor floor elevation and has a top closure for removal of the test capsules without having to drain the loop or remove it from the reactor. An elevator and loop lifting mechanism will be provided at the top for removal of the loop from the core.

The dimensions and physical characteristics of the in-reactor tubes and annuli are provided in Table VI. These tube dimensions were established after a series of thermohydraulic calculations where tube dimensions were assumed and the loop temperatures and pressure drop calculated (see Sect. V). Standard BWG tube sizes were selected in order to reduce fabrication costs and delivery times. Type 304 stainless steel was selected for the in-reactor tubing. It is compatible with the lithium coolant at the temperatures of interest.[9,10] This structural material has also been extensively used in previous EBR-II in-reactor test loops[8] and a wealth of design information exists on this material's properties and performance in an irradiation environment. As seen in Table VI, a total of four concentric tubes comprise the LTIV in-reactor geometry. A stepped tube design has been selected to capitalize on the increase in radial dimension of the control-rod channel in the axial direction (see Fig. 1). Different dimensions were selected for the three outer

tubes (i.e., flow divider, flow housing, and guide tube) in the two axial regions (see Table VI), allowing the use of an insulated flow divider in the upper reactor region. As discussed in Sect. V, this feature greatly improved the thermal performance of the loop.

The upper region in the stepped tube design configuration has considerably more radial room than the lower region due to the EBR-II control-rod guide tube design (see Table VI). In earlier LTIV concepts (see Sect. V), most of the extra radial room was taken up by a large argon insulation gap (130 mils). The flow housing tube O.D. in the latest LTIV design was increased from 2.000 in. to 2.125 in. reducing the argon insulation gap to 67.5 mils in the upper region. This allowed the flow divider to be moved out to an O.D. of 1.75 in.

The insulated upper flow-divider design finally selected consists of two concentric tubes sandwiched together around an argon gas space. Keeping with the design philosophy of using "standard" BWG tubing if at all possible the outer flow-divider tube is 1.75 in. O.D. by No. 16 gage (65 mils thick), with the inner flow-divider tube being 1.50 in. O.D. by No. 19 gage (42 mils thick). This translates into a flow divider argon insulation gap of 60 mils. The upper region upcomer flow region remains the same as the previous design gap value of 92.5 mils but because of the larger diameter the upcomer flow area is actually slightly larger (0.535 in.^2 versus 0.499 in.^2). In this latest design the area of downcomer in the upper region is somewhat reduced from the previous uninsulated design (0.348 in.^2 versus 0.390 in.^2). The downcomer gap is now 83 mils compared to the downcomer gap in the upper region of the previous design of 92.5 mils.

The upper LTIV in-reactor loop region has not been completely designed as yet, however, an example of how this region may look conceptually is provided in Fig. 5. This upper region configuration has a terminal box for bringing out the test instrumentation leads. Also shown are the bellow seals required for interfacing with EBR-II and for providing for the thermal expansion between the loop tubes and the top-loop closure for removing the test holder from the central test hole. Although shown in Fig. 5, a terminal box may not be required. Therefore this region will require further design evaluation if the concept is pursued in the future. However, the experience

obtained on previous designs (e.g., see Ref. 8) will be quite valuable and no major problems in this area are expected.

C. Ex-reactor Loop System

The ex-reactor loop system is physically located above the reactor with the major loop cooling components (i.e., heat exchanger and pump) mounted on the vessel cover lifting mechanism support structure. Figures 1 and 2 show conceptually the location of these components. In addition, instrumentation and auxiliary support equipment will have to be provided. In the next several subsections, a description of these items will be presented. Because the design of the LTIV is only in the feasibility state, these descriptions are quite sketchy. Enough work has been done to ensure that the loop design is possible. However, additional design and layout work is required to fill in the design details.

1. Flexible Metal Hose

A key element in the LTIV design is the application of flexible metal hoses which are required in order to lift the in-reactor loop ~ 6 ft out of the core without the disruption of the flow of lithium coolant. The hose would be needed to connect the permanently installed ex-reactor loop components to the moveable in-reactor loop. Two lithium coolant transport hoses (an inlet hose and an exit hose) would be required, each about 15 to 20 ft long. There is some precedent for using this type of design approach as it was also proposed in an earlier 1969 EBR-II packaged sodium-loop study.[7]

The service requirements for this LTIV application would be for transporting ~ 10 gpm of liquid lithium at ~ 700°F maximum temperature and at ~ 100 psia. The tubing material specified would be 321 stainless steel (or equivalent) and the tubing size would be ~ 1 in. O.D. These requirements translate into a reasonable lithium flow velocity of 5 to 6 ft/s depending on the tube wall thickness ultimately chosen [e.g., 16 BWG gage (0.065 in. wall) or 13 BWG gage (0.095 in. wall)]. For safety requirement purposes (see Sect. III), a double-wall

tube system (for leak detection and containment) along with an outer protective metal armor sheath is required. Provision for wrapping the flexible tubing with trace heating elements and thermal insulation has also been identified as design requirements. End fittings for standard weld connections to the test equipment would also have to be provided.

In order to assess the feasibility of using flexible metal hoses in the planned LTIV application, the above design information was supplied to 14 flexible metal tubing vendors. A request for their capability and interest in supplying this hosing was requested. Of the 14 hose vendors contacted, seven companies expressed an interest and willingness to bid on the application. In Appendix A the list of these interested vendors is provided for future reference.

The use of flexible hoses will require that each hose be supported and confined in a raceway or supported in such a way so as to restrict movement to only the known and desired directions. The hose motion may be somewhat complicated for not only is the up and down movement necessary but also some sideward movement is required as the fixed heat exchange equipment is on a hinged panel to allow access to the control-rod drives. A duplicate mockup of the hose system may be required to test and check out the hose motion and design clearances.

2. Annular Linear Induction Pump (ALIP)

The LTIV lithium coolant pump is located outside the reactor and is mounted on the vessel cover lifting mechanism on a hinged panel. As Fig. 1 illustrates, the pump is in the cold leg of the ex-reactor loop and takes lithium from the heat exchanger discharge and supplies it to the in-reactor loop. Although several types of pumps could be selected for this application, as the pump size is not of primary concern, an Einstein-Szilard-type of annular linear induction electromagnetic pump (ALIP) was chosen for this initial study. Lithium being a liquid metal lends itself nicely to such a design with this type of pump's operational and design characteristics being well-understood.[11]

The lithium pumping requirements for the LTIV packaged loop were established after several detailed thermal-hydraulic calculations of the LTIV system. These analyses along with several assessments of annular linear induction pump (ALIP) performance with lithium at the reference LTIV conditions are presented in Sect. V. The intent during this feasibility evaluation study phase was not to design nor select the final pump but rather to determine and confirm that a pump exists or would be easily adapted to the LTIV conditions. It was desirable also to have a pump which has reliability and performance experience and has a proven fabrication history. Based on these considerations, the pump selection process focused on the Mark-II ALIP used in the TREAT testing program.

In Table VII, the TREAT ALIP size and characteristics are tabulated with an illustration of the pump shown in Fig. 6. Pump performance data in Table VII are presented for both a single pump operation or a dual pump configuration (two pumps operating in series) with sodium as a coolant. In Sect. V, a model to correct or predict this pump's performance with lithium application has been developed.

Based on the performance analyses conducted with a computer model of the LTIV system (see Sect. V), it appears that the dual TREAT ALIP configuration would be adequate for LTIV application. A wealth of experience on fabricating and operating the present TREAT ALIP has been generated over the years in the TREAT testing program at ANL-East. One potentially negative feature is that this pump requires an external silicone oil coolant to remove heat from the pump coils. Several high temperature coil materials exist however (e.g., see Ref. 7) so that with a proper pump redesign the elimination of this external coolant requirement for the coils should not be an insurmountable problem. Also the requirements of the LTIV facility are not too extreme and several other off-the-shelf electromagnetic (EM) pump designs were found to be available which could provide the performance that is required for LTIV operation.

3. Lithium-to-Air Heat Exchanger

The LTIV facility heat exchanger is located on the vessel cover lifting support structure and it is planned to remove the test heat from the lithium coolant with building air. It is planned to dump ~ 15 kW of test region heat by the use of a blower or fan directly to the EBR-II containment building. The EBR-II building ventilation/cooler system will remove it from the building for ultimate transfer to the outside environment.

The major service requirement of the lithium-to-air heat exchanger would be to remove ~ 15 kW of heat from ~ 9 gpm of flowing molten lithium. The inlet lithium temperature to the heat exchanger is expected to be ~ 470°F with the outlet temperature being ~ 448°F. The lithium pressure is expected to be ~ 100 psia. Inside EBR-II building air at ~ 80°F would be available for cooling the lithium with the air being discharged directly to the building. The heat exchanger material of construction would be 304 stainless steel (or equivalent). End fittings for standard weld connections to the loop piping would also be required. The need for a quality assurance plan and a leak detection and containment plan for the heat exchanger has been identified. The application of all applicable codes and standards would also be needed for this nuclear research program.

To determine the feasibility of obtaining a commercially available heat exchanger for LTIV application, the above requirements were sent out to 25 heat exchanger vendors for their interest in supplying a heat exchanger. One company (Xchanger, Inc., Hopkins, MN) submitted a quotation for their Model LC-16 heat exchanger (26 in. by 26 in. by 36 in. high). A drawing of this heat exchanger assembly is provided in Fig. 7 with the heat exchanger specifications provided in Appendix B.

In the proposed heat exchanger design, the lithium would flow horizontally through finned tubes. The fins are rectangular plates with a matrix of die-extruded tube collars. A sheet metal casing provides rigidity to the finned-tube assembly prior to expansion. After assembly, the tubes are expanded into fin collars, giving a gap-free connection. The tube and fin material was

specified as type 304L stainless steel with a required heat exchange capacity of 61,878 Btu/h. The lithium side pressure loss through the exchanger was given as 0.3 psi. The air side cooling flow requirements were specified as 2050 scfm at a pressure loss of 0.2 in. of water. The air flow through the exchanger would be in a vertical upward direction. The heavy-duty air cooling fan is driven by a 1/4 HP, 230/460 V AC three-phase motor. More details about the proposed LTIV heat exchanger system can be found in Appendix B.

D. Instrumentation

Instrumentation will be required to provide information to the loop control system and the loop protection system, as well as for the data acquisition system. During this initial feasibility phase of the LTIV design, no effort was expended on the type or number of sensors that may be required. Nevertheless, it is felt that the conditions and requirements posed by this facility will not require any instrumentation development effort. Trade-off studies will no doubt be required in order to establish the instrumentation needs for the facility. Extensive sensor instrumentation, control methods and plant protection experience exists from previous EBR-II and other ANL experimental programs and studies to insure that the LTIV will be adequately instrumented (e.g., see Refs. 7 and 8).

E. Loop Handling Equipment

An important aspect of this proposed packaged loop for EBR-II application is design and development of the equipment and procedures needed to insert and remove the loop and associated test specimens safely and efficiently from the reactor. Furthermore, systems and requirements will have to be specified for filling the facility with lithium coolant and providing a supply of argon cover gas. As was the case with the facility instrumentation needs, during this feasibility phase of the LTIV study no detailed engineering effort was expended in this design area. The LTIV design and conditions, however, are not that much different from EBR-II test in-reactor experiments conducted previously that one can be confident that loop handling problems and issues will not be insurmountable.

Again a wealth of experience from previous EBR-II programs exists. It is expected that the handling equipment designed and built for these programs could be utilized almost directly or with slight modification to this LTIV application. The In-core Instrumentation Test Facility (INCOT) elevator and drive system[8] could be used to raise the in-reactor loop the ~ 80 in. needed to clear the tops of the other reactor subassemblies and allow rotation of the shield plugs for fuel handling and during planned operational reactor transients. Also the direct overhead withdrawal and remote-handling system designed and built to remove INCOT experiments[12] could be adapted or modified for LTIV application. This handling system consists of the handling container (i.e., coffin) for the test assembly, a control system, a shielded operator's booth, special shielding components, and several remotely operated extension tools.

Other specialized handling systems will be required for filling and draining the lithium coolant as well as providing the argon cover gas to the facility surge tank and in-reactor assembly terminal box. The argon gas systems and associated instrumentation and controls are conventional off-the-shelf equipment. The lithium handling and purification equipment is not as conventional as the argon systems, however, there exists an adequate experience base from which these lithium systems can be designed. The large lithium heat transfer test loop [containing 3.8 m^3 (1000 gal) of lithium] built and operated at the Hanford Engineering Development Laboratory (HEDL) is a recent example of the lithium test loop experience base (see Ref. 13). This full-scale mockup of the Fusion Materials Irradiation Test (FMIT) Facility achieved over 16,000 h of safe and reliable operation. Experience from this test loop provides important data on lithium system operation, performance, and reliability which is directly applicable to the LTIV test program.

V. FEASIBILITY ANALYSIS

This $\sim$ six month feasibility analysis effort concentrated on establishing an irradiation facility concept that would meet most, if not all, of the requirements specified in Sect. III. Initially the focus was on the selection of the coolant with the ex-reactor loop configuration being dictated by characteristics of each of the coolants. With the selection of liquid lithium as the reference LTIV coolant, the feasibility effort shifted to that of evaluating the packaged loop's

thermal-hydraulic performance. Centermost in this process was to determine the availability of an EM pump which could be suitable for the lithium conditions of the LTIV loop. In order to assess the thermal-hydraulic performance of the LTIV, it soon became apparent that a computer code model was required. Therefore, a FORTRAN language computer code was developed which simulated the thermohydraulic behavior of the LTIV in reactor and ex-reactor loop sections. This computer code called TMOLL (thermohydraulic model of lithium loop) was then used to perform optimization and parametric sensitivity studies. In these calculations, major or controlling variables were perturbed around a reference value and their effect on the loop performance determined.

In the following subsections the results of these feasibility studies and calculations are presented and discussed. Evident in this presentation is the evolutionary nature of these calculations. As the studies progressed and improvements and changes were made to the TMOLL model, the calculational results also varied somewhat from the earlier predictions. Also new information, data, and design parameters were factored into the conceptual design as the study progressed.

A. Selection of Coolant

The selection of the coolant for the LTIV packaged loop focused on coolants compatible with the EBR-II sodium coolant. This major consideration eliminated the use of the more common coolants such as: water, air, and organics (e.g., DOWTHERM™, Therminol®, MutiTherm®). The focus for a suitable facility coolant, therefore, centered primarily on the liquid metals. In addition, the inert helium gas was assessed because of its rather good heat transfer properties (for a gas) and its low neutron activation cross section.

In Table VIII, a comparison of properties for some of the more common liquid metals is tabulated. These data were taken from Ref. 14 and address the thermophysical properties of Na, K, NaK, PbBi, and lithium. The excellent heat removal characteristics of these coolants are evident from the low Prandtl numbers (ratio of momentum diffusivity to thermal diffusivity) for

each of the coolants. The melting points of each of these coolants are low enough to meet the $\sim 550^{\circ}\text{F}$ test temperature requirement (see Table I).

While not shown in Table VIII, the activation characteristics of each of these liquid metals are important and were considered. The NaK alloy selected for evaluation was the near eutectic 22 wt % Na, 78 wt % K rather than the more activation prone (due to the higher Na content) 56 wt % Na, 44 wt % K alloy. As will be discussed below, the lithium liquid metal coolant has very low activation cross sections which can be greatly reduced further or almost eliminated by use of lithium where the Li-6 isotope has been removed.

1. NaK Coolant Considerations

The initial packaged loop considered for application was cooled with NaK. A schematic of this facility is illustrated in Figs. 8 and 9. The in-reactor loop physical characteristics of the tubes and region volumes and surface areas are tabulated in Table IX. In Table X, a summary of the NaK-cooled loop operating conditions and parameters is presented.

As shown in Figs. 8 and 9, the NaK-cooled concept is quite similar to the reference LTIV configuration in Fig. 1. However, because of the lead shielding requirements, it makes the mounting of the ex-reactor components on the vessel cover lifting mechanism support structure unfeasible. Instead it was proposed that the ex-reactor components would be contained on a cart which would be located on a rail system installed on the EBR-II operating floor. The plan would be, as Figs. 8 and 9 indicate, to move the heavily shielded temperature control cart containing the heat exchanger, pump, and surge tank to the in-reactor loop where the connections to the in-reactor loop would be made. When the in-reactor loop is to be raised from the core (e.g., for reactor refueling or for planned transients), the NaK would be drained into the bladder-type surge tank, the disconnect would be made, and the temperature control cart moved back from the in-reactor loop.

The in-reactor loop configuration, the dimensions of which are presented in Table IX, is also essentially the same as the Table VI reference design. However, in this early design, nonstandard BWG tubes were selected and the tubes were uniform and not stepped to conform to the EBR-II control rod variable radial geometry in the axial direction. The test space provided in this initial concept is also slightly smaller than that ultimately selected in the LTIV design. As seen in Table IX, the test container had an O.D. of only 0.875 in. (test volume 133 cm³ for the 13.5 in. core length) versus the 1.000 in. O.D. (test volume of 174 cm³ for 13.5 in. core length) for the reference LTIV test container in Table VI.

In Table X, the feasibility scoping results are presented for the NaK packaged loop. The NaK alloy selected was that with the low 22% Na composition (see Table VIII) in an attempt to reduce the neutron activation and resulting coolant radioactivity. The total NaK inventory was estimated to be 1.5 to 2.0 gal. The total heat removal rating was determined to be 16 kW (gamma heating plus EBR-II heat transfer) which was calculated assuming a gamma heating rate of 6 W/g of stainless steel with the test section having a 50% stainless-steel volume fraction. A rough sizing estimate was made for the mobile temperature control cart, the NaK-to-air heat exchanger, and the shielding requirements (see Table X).

Based on an infinite cycle activation ORIGEN computer code calculation for the operating conditions, an activity level of 0.96 Ci/g of NaK was estimated.[15] Based on a rough-scoping-type of shielding calculation, a lead thickness of 2 to 3 in. would be required around ex-reactor piping and components. This translates into a total shielding weight of ~ 10 tons to be supported.

Other operational parameters and features of the NaK loop are provided in Table X. This concept would plan to use the existing INCOT/INSAT handling cask but would require that the coolant lines be disconnected to lift the in-core section during refueling. The ability to tolerate planned EBR-II transients would rely on the ability to program and control the test temperature with coolant flow and/or heat removal adjustment. The test vehicle removal would require an operator bagging-type action in disconnecting the coolant lines after these lines have

been drained and flushed with argon gas to remove trace amounts of radioactive NaK. Removal time of the in-reactor loop was estimated as requiring several hours.

Based on the NaK coolant activity level and the associated potential shielding and handling problems, other packaged loop concepts for EBR-II application were explored. These are described in the next two subsections.

2. Helium Gas Coolant Assessment

The feasibility of a helium gas cooled facility was explored as an alternative to the NaK-cooled concept. The low neutron activation cross section and its compatibility with reactor sodium and building air are favorable helium attributes. Furthermore, other than hydrogen gas, helium possesses some of the best gas thermal properties. In this scoping study the heat removal performance of helium was evaluated over a loop system pressure which ranged from 1 atm (14.7 psia) to 40 atm (588 psia). The focus of this preliminary assessment was on the in-reactor conditions with no attempt made to evaluate the other ex-reactor conditions or equipment (e.g., heat exchanger, blower, etc.). The study assumed the in-reactor test section geometry and dimensions (see Table IX). A lower test temperature requirement of 500°F (260°C) was selected as representative of the limiting condition (highest heat load). All calculations were performed with an assumed helium test section velocity of 200 ft/s (61 m/s) and at a total heat removal rate of 11.7 kW (based on a gamma heat generation of 3.77 W/g stainless-steel).

The results of this helium-type system are presented in Table XI. As Table XI indicates, the low pressure helium case (i.e., 14.7 psia) is unacceptable yielding a temperature rise across the test section of over 4000°F. In order to achieve a 100°F temperature rise across the test section, which is achieved in the NaK system, a helium system pressure of 588 psia (40 atm) is required. The penalty in pressure drop caused by the higher helium mass flow rate at the increase in system pressure is evident in Table XI.

This pressurized system then suffers from a relatively large frictional pressure drop (~ 130 psi) due to its high mass flow rate that is required to remove the test heat and structural heat generation. Furthermore, it introduces a potentially large volume of helium gas into the EBR-II core region with associated safety implications. This helium-cooled concept was therefore dropped from further design consideration.

3. Liquid Lithium Coolant Evaluations

With the problems identified in the previous sections with NaK and He as coolant candidates for the EBR-II packaged loop, the search was focused on liquid lithium. Lithium is the rarest and lightest of the alkali metals and is found just below sodium in the periodic table. As the comparison of properties in Table VIII indicates, it possesses excellent heat transport and thermodynamic properties. Lithium's melting temperature ($\sim 354^{\circ}\text{F}/179^{\circ}\text{C}$), while high compared to the other liquid metals, is still below the target 200°C test temperature. A brief survey was made of the advantages and disadvantages of selecting lithium for the loop coolant with the major findings summarized in Table XII. The major lithium issues are summarized in Table XIII with detailed lithium property and operational information found in Refs. 9, 10, 13, and 14.

As indicated in Table XII, lithium advantages include the previously mentioned excellent thermal properties. Being an alkali metal it is compatible with liquid sodium and has acceptable corrosion rates with 304 stainless steel at the lower test temperature range of the facility. With lithium being a solid at room temperature, lithium leaks should freeze upon contact with outer cold surfaces. However, as Table VIII indicates, lithium has a heat of fusion almost six times that of sodium so that its freezing rate could be somewhat slower than sodium. Since lithium is planned to be used extensively in the fusion program, its application in this fusion materials irradiation program would provide valuable operating experience.

There are several obvious potential disadvantages with using lithium as a coolant in this proposed irradiation facility (see Table XII) which, while subjective, must nevertheless be

addressed. The first potential problem is that the neutron activation of lithium produces tritium which is a particularly difficult isotope to contain because of its mobility. Table XIII summarizes the properties of tritium and, as indicated, an ORIGEN calculation for an infinite-cycle activation yielded a value of ~ 19 Ci/g of lithium.[15] This activity is due almost entirely to the (n,α) reaction with the Li-6 isotope. Large quantities of lithium depleted in the Li-6 isotope exist from the fusion program and use of it was suggested by D. Smith[16] as a solution to the tritium activation problem. Elimination of Li-6 and its very high neutron cross section (940 barns) would also eliminate any concerns for potential reactivity insertion problems in EBR-II if a loss-of-lithium coolant accident occurred. With the tritium activity problem removed, the only remaining activation concern would be caused by the activation of trace impurities in the lithium and loop corrosion products. Purification and filtration of the initial lithium fill and lithium cleanup during loop operation should eliminate these concerns and therefore the ex-reactor shielding requirements are expected to be minimal.

While lithium is the least reactive of the alkali metals in the liquid state, it is still quite reactive with moisture and it oxidizes in air. At high temperatures (500 to 800°C), lithium reacts with hydrogen to form the hydride LiH. Near or above the melting point, lithium may ignite in air and burn intensely. Lithium is the only alkali metal to react with nitrogen and in the presence of moisture reacts exothermically even at ordinary temperatures. As with all liquid metals, handling of lithium must be done with special safety measures and precautions. Molten lithium may burn with an intense flame when brought into contact with moist human skin and therefore personnel protection against molten lithium leakage and splattering must be provided.

Compared to the other liquid metals (i.e., sodium and NaK), there is a limited amount of experience with lithium in the operation of heat transfer loops. The high melting point of lithium ($\sim 180^\circ\text{C}$) which is considerably above room temperature requires that trace heaters must be provided and special procedures invoked for filling and draining the loop. However, the rather recent HEDL experimental lithium system (ELS) which operated in the early 1980s has provided a wealth of lithium test loop information. Table XIV summarizes some of the highlights of this four year test program which at the time was the largest lithium loop in the world. The

lithium sampling and analytical chemistry techniques developed under this HEDL program along with impurity control methods should be extremely valuable in this packaged lithium loop design effort. Also the lithium corrosion rates and loop material of construction suitability in lithium as well as equipment reliability data will provide the information needed to insure the success of the program.

B. Preliminary Lithium Loop Scoping Analyses

As described in the previous section, a lithium cooled packaged facility is being proposed for use in EBR-II to study the effects of neutron irradiation on fusion reactor materials. A series of preliminary scoping analyses have been conducted investigating the design feasibility and performance characteristics (e.g., pressure drop and coolant flow rate capability).

The general features of this facility are shown schematically in Figs. 1 through 4 and Table XV. As these figures and table indicate, the concept consists of essentially two parts: (1) an in-reactor portion containing two annuli regions for lithium coolant inlet and egress with a central cavity for the test capsules or canisters and (2) an ex-reactor portion which consists of the lithium coolant pump and a lithium-to-air heat exchanger. Figure 10 presents the dimensional data of the in-reactor section with the physical characteristics tabulated in Table XVI. Note that in this design, the test region has been somewhat enlarged over the previous design in Table IX. In the in-reactor section, an argon-filled gas gap is provided to minimize the heat transfer from the core sodium to the test specimens. The concept as presently envisioned has the ex-reactor components mounted above the reactor floor on the cover lifting mechanism support superstructure (see Fig. 2). The low temperature (i.e., less than the EBR-II inlet sodium temperature) feature with the capability to independently keep the material samples at design conditions during refueling and planned transients requires that the in-reactor test section be raised about 6 ft to an out-of-core elevation while remaining connected to the ex-reactor components. As illustrated in Fig. 1, to fulfill this lifting requirement, this concept will require the use of doubly contained flexible stainless-steel tubing for connecting the in-reactor section to the ex-reactor components.

The success of this concept depends upon the removal of ~ 15 kW of heat generated in the in-core test regions and structures with a minimum of temperature rise across the test specimens. Therefore, this parametric study was conducted to evaluate the effect of various in-reactor tube sizes and spacing on system pressure drop and resulting lithium-coolant pump capacity. A parametric calculation was performed in which the lithium flow rate was varied over a range of 2 to 20 gpm and the pressure drop determined. Three design cases, each with a different in-reactor set of tube dimensions, were examined. The study assumptions and results are presented below.

1. Thermal Analysis

In Table XV, the thermal and hydraulic design conditions that were assumed in this study are presented. The lithium mass flow rate through the test region needed for the removal of ~ 15 kW of heat generated in the core region (i.e., from test specimens and structure) was calculated as a function of the lithium temperature rise from the simple energy balance:

$$m = Q/(C_p \cdot \Delta T) \quad (1)$$

where:

- m = lithium mass flow rate, lb/h,
- Q = total heat removed, Btu/h,
- C_p = heat capacity, Btu/lb-°F, and
- ΔT = temperature rise across test, °F.

Figure 11 presents a plot of Eq. (1) over the lithium flow rate range expected. As indicated in Fig. 11, the temperature rise across the test specimens will be relatively modest [e.g., ~20°F (11°C)] at a lithium flow rate of about 10 gpm (631 cc/s).

2. Hydraulic Analysis

a. Hydraulic Model

The estimation of the pressure drop was based on the facility design features as presented in Figs. 1 through 4 and 10 and the design data presented in Table XV. The pressure drop calculation used the simple Fanning friction factor based expression:

$$\Delta P = (4fG^2L)/(2g\rho De) \quad (2)$$

where:

- ΔP = pressure drop, lb/ft²,
- f = Fanning friction factor, dimensionless,
- G = mass velocity, lb/(h)(ft²),
- L = length, ft,
- g = acceleration of gravity, ft/h²,
- ρ = density, lb/ft³, and
- De = equivalent diameter, ft,

and the friction factor (f) is evaluated for turbulent flow in smooth tubing from Ref. 17:

$$f = 0.0014 + 0.125/(Re)^{0.32} \quad (3)$$

where:

- Re = Reynolds Number = $(De \cdot G)/\mu$ and
- μ = viscosity, lb/ft-h.

b. In-reactor Pressure Drop

In the hydraulic analysis of the test facility, three design cases of the in-reactor tubes were investigated which explored various tube sizes and gap spacings. These three cases were:

Case 1--Original Nonstandard Tubing Design

Case 2--Continuous Straight Standard Tubing Design

Case 3--Stepped Standard Tubing Design

The dimensions and physical characteristics of the in-reactor tubes and spacings are provided in Tables XVI, XVII, and XVIII. Case 1 represents the in-reactor design dimensions based on a design similar to the design in Table IX. Figure 10 illustrates the radial in-reactor tube and annular gap spacing for this case. In Table XVI, the physical characteristics of this design are tabulated. The fact that the flow divider and flow housing tubes were not of a standard tubing size suggests that a savings in fabrication cost and ordering time could be realized by going to a design with standard BWG size tubing.

In Case 2, both the flow divider and the flow housing were selected based on standard ferrous tubing sizes as provided in Ref. 18 for condenser and heat exchanger tubing. These BWG tube sizes for the flow divider and flow housing tubes retained the tube wall thicknesses as close as possible to those of the nonstandard Case 1 design. The Case 2 in-reactor design dimensions are tabulated in Table XVII. As a comparison of the dimensions in Tables XVI and XVII indicate, the use of standard tubing (with acceptable thicknesses) results in a greatly reduced downcomer flow gap and flow area which as the hydraulic calculations indicated was not off-set by the increased upcomer flow gap. To overcome this pressure drop penalty, a stepped standard design (Case 3 described below) was considered.

Case 3 considered standard BWG tubing sizes for the flow divider and flow housing tubes but takes advantage of the increased cross-sectional area in the upper in-reactor region caused by the larger outer guide tube. Therefore, it was assumed that these two tubes also

were stepped at the same axial location as the guide tube (see axial lengths given in Table XV) in the current EBR-II CTI/CTX test section design currently being designed at ANL-East. Table XVIII provides the physical characteristics for this packaged loop design.

The pressure drops were calculated for the in-reactor region for the three cases described above using Eqs. (2) and (3) over the lithium flow rate range of interest. The pressure drop results are tabulated in Table XIX. Evident from the Table XIX results is the pressure drop penalty caused by the reduced downcomer gap (e.g., comparing Case 1 with Case 2). The pressure drop benefit of the stepped tube design is also evident (e.g., compare Case 2 with Case 3). The stepped tube design (Case 3) while introducing some additional fabrication complexities has an in-reactor pressure drop comparable to the nonstandard tube design (Case 1).

c. Ex-reactor Pressure Drop

The ex-reactor pressure drop estimate results as a function of lithium flow rate are shown in Table XX. The lack of design definition of the ex-reactor components and their layout configuration precludes an accurate estimation of the ex-reactor pressure drop. To obtain a pressure drop it was estimated that the total ex-reactor pressure drop was 20% of the Case 1 in-reactor pressure drop in Table XIX.

The pressure drop for the metallic flexible tubing was obtained using the turbulent frictional pressure drop model of Sect. V.5. To correct for the roughness introduced by the corrugations as recommended in the "rule of thumb" given in Ref. 19, a factor of three was applied to the pressure drop in a comparable size standard steel pipe. The selection of the flexible metal tubing size was based on a consideration of the flow velocity through various assumed tubing sizes. Figures 12 and 13 show the relationship between lithium flow velocity in the tube as a function of lithium flow rate in gpm for various tubing diameters. Figure 12 is for No.16 BWG gage tubing (0.065 in. wall) with the results presented in Fig. 13 for the larger wall thickness (i.e., 0.095 in. wall) No. 13 BWG gage tubing. Assuming the thicker wall design of No. 13 BWG (0.095 in. wall) as being more conservative, a 1-in. O.D. tubing wall was selected

for the flexible tubing size. As Fig. 13 indicates, at the ~ 10 gpm reference loop flow rate, the tube velocity is ~ 6 ft/s. The 1-in. O.D. flexible metal tubing became the reference size with the total length required (e.g., inlet and exit) estimated at 40 ft.

The pressure drop for the remainder of the ex-reactor loop components (see Column 3 in Table XX) was obtained by subtracting the pressure drop estimate for the flexible metal tubing from the total ex-reactor loop pressure drop. The values for the components pressure drop are felt to be sufficient to cover the pressure losses in the pump, heat exchanger, inlet and exit losses, and turning losses.

d. Total Loop Pressure Drop

The overall loop pressure drops for the three cases were estimated as a function of lithium flow rate with the results tabulated in Table XXI. The in-reactor pressure drops were taken from Table XIX with the ex-reactor pressure drop taken from Table XX. As noted in Table XX, the ex-reactor pressure drops were obtained by multiplying the Case 1 in-reactor pressure drop by 0.20. A more detailed ex-reactor pressure drop estimate awaits a better design definition, location and layout of the pump heat exchanger components.

3. Stress Analysis

A major consideration in the design of the components is the selection of tube thickness for the various tubes which comprise the in-reactor test section. Of these the flow divider will experience the highest stress due to the largest pressure differential existing from the inlet to the outlet of the in-reactor section. Therefore, a simple calculation was made which estimated the tangential stress in the flow divider tube.

The estimation of the tangential stress due to the pressure differential across the flow divider used the Ref. 20 expression for a thin-walled cylinder:

$$S_t = (pD)/(2t) \quad (4)$$

where:

- S_t = tangential stress, psi,
- p = pressure differential, psi,
- D = tube diameter, in., and
- t = tube wall thickness, in.

The evaluation of the flow divider tangential stress using the Eq. (4) model was conducted over a range of pressure drops typical of the in-reactor predictions presented in the previous section. Using the Case 1 flow divider dimensions, the parametric results are shown in Fig. 15. As the Fig. 15 results indicate, the predicted tangential stresses caused by the pressure differential are about an order of magnitude below the 16 kpsi creep stress limit for 304 stainless steel. Therefore, the flow divider wall thickness of 0.0625 in. is acceptable for this application.

4. Scoping Study Conclusions

A preliminary assessment has been made of the hydraulic conditions in the proposed loop. Considered in this investigation were the temperature rise requirements of the lithium coolant, the pressure drop for both the in-reactor and ex-reactor portions of the loop facility, the pump performance requirements, and the resulting stresses created in the flow divider due to the anticipated flow created pressure differential.

Three design cases with various standard and nonstandard tubing were selected for evaluation of the resulting loop in-reactor pressure drop. The first case (Case 1) considered nonstandard tubing for the various in-reactor tube components. In the second case (Case 2) continuous standard gage tubing was considered for the in-reactor tubes and the pressure drop evaluated. For the last design situation (Case 3) standard gage tubing was considered but a stepped configuration was assumed in an attempt to reduce the pressure drop. A stepped tubing design (i.e., Case 3) will be required to meet the requirement to minimize the temperature rise across

the test specimens [e.g., $\sim 20^{\circ}\text{F}$ (11°C)], and the requirement to utilize standard gage tubing. A lithium flow rate of ~ 10 gpm (631 cc/s) will provide the necessary cooling to achieve the nearly isothermal test specimen temperature condition.

The loop ex-reactor pressure drop has also been estimated as a function of lithium coolant flow rate. However, because this portion of the facility is conceptual and has not been physically laid out, the pressure drop estimates are more uncertain. A total ex-reactor pressure drop of 20% of the Case 1 in-reactor pressure drop was assumed. Accounting for the rather well-known flexible metal tubing pressure drop resulted in what was felt to be a conservative pressure drop for the remainder of the ex-reactor system (i.e., pump, heat exchanger, turning and expansion/contraction losses). The ex-reactor pressure losses are felt to be conservative but need to be more accurately calculated once the design is better-defined.

The pressure differentials expected in the in-reactor test section design have also been evaluated. For the limiting case of the flow divider the tangential stresses introduced by the expected lithium coolant flow rate are well within the creep limit of the tube material and wall thickness planned for the LTIV flow divider.

C. ALIP Performance Models

The EM pump head and flow rate requirements are determined from the total loop pressure drop versus lithium flow rate relationship given in Table XXI. In Fig. 14, the pressure drop as a function of lithium flow rate is plotted for the three in-reactor design cases. Also shown are the pump head versus flow rate for three typical EM annular linear induction pumps (ALIP) used in sodium application. The EBR-II 0.5 in. ALIP pump is described in Refs. 21, 22, and 23 with the performance data from Fig. 3 of Ref. 22.

The other two pump head curves shown in Fig. 14 represent the TREAT ALIP EM pump configurations described in Refs. 24 and 25. The pump performance curves with 315°C sodium are shown in Fig. 16 and are from Ref. 25 for a single pump and for two pumps in series. The

TREAT ALIP is shown schematically in Fig. 6. Note that for its application in the TREAT reactor, mineral oil was required for cooling the coils. It remains to be seen whether for this application that this extra coil cooling will be necessary. In Table VII, the design characteristics for the TREAT ALIP which were developed for sodium application are provided.

From the pressure head curves and the ALIP performance curves plotted in Fig. 14, the lithium flow rate can be inferred. With a single TREAT ALIP and assuming the Case 1 or Case 3 in-reactor design configuration, a lithium flow rate of about 10 gpm is expected. For the smaller EBR-II ALIP, a lithium flow rate of about 8 gpm for these designs would be achieved. Assuming the dual TREAT ALIP configuration, a lithium flow rate of ~ 13.5 gpm seems possible.

1. Lithium ALIP Model 1

The performance curves for the pumps shown in Fig. 16 for the 40 amps 'B' phase current operation were those obtained for 315°C sodium rated application. It was believed that these performance curves (i.e., pump head versus flow rate were conservative as it was expected that the ALIP performance would increase as sodium was replaced with the higher electrical resistivity lithium. In fact, this assertion was not true and the ALIP performance actually would decrease as sodium was replaced with lithium coolant. As stated in Ref. 26:

"Generally, a high electrical resistivity not only reduces pump efficiency but prevents the use of induction pumps; a high density and viscosity leads to a high hydraulic loss and limits the liquid velocity which can be employed, so increasing the pump duct section and hence pump size and cost generally."

To assess the extent of this ALIP performance degradation, an estimate was made for the given ALIP design, as presented in Ref. 7, using a rather detailed calculational model which replaced the sodium regions with lithium. The results are presented below where the pump performance factor as determined for this one ALIP design and flow condition was applied to the loop flow situation.

The ALIP preliminary design presented in Ref. 7 was for a previously proposed packaged loop for EBR-II. It was based on pumping 35 gpm of 1200°F sodium with a head of 75 psi. This pump was about 60 in. long with an O.D. of 3.28 in. The pump was of re-entrant design with the I.D. of the inner flow tube being 0.625 in. and the outer flow region annulus having an I.D. of 1.790 in. and an O.D. of 1.988 in. The container and flow channels of the pump were constructed of 316 stainless steel with the flux laminations being Hiperco 27 and the coil conductors being SS-clad Zr copper. The electrical insulation material was Sauerisen Cement No. 8. All of the materials selected were for operation at 1200°F which eliminated the need for external pump cooling.

Although the ALIP of Ref. 7 was somewhat larger than required in the LTIV facility it nevertheless had a rather detailed pump performance model which was taken from Refs. 27 and 28. Therefore, to assess the implications on ALIP performance, this ALIP model was employed with 500°F (260°C) lithium substituted for 1200°F sodium wherever appropriate. Table XXII presents the physical properties for the two coolants with the major parameter difference being the electrical resistivity (i.e., 13.75 $\mu\Omega$ -in. for sodium and 19.29 $\mu\Omega$ -in. for lithium) which increased by a factor of ~ 1.40 . The lithium resistivity value was taken from Ref. 14.

In Table XXIII, the comparison of ALIP performance parameters for sodium and lithium coolants, which were calculated for the Ref. 7 ALIP using the model from Refs. 27 and 28, is presented. As indicated in Table XXIII, the increased liquid resistance factor of ~ 1.40 (conductivity decrease of $\sim 30\%$) resulted in an output pressure decrease at 35 gpm to $\sim 74\%$ (71.7 to 53.3 psi). The output pump power decreased to $\sim 75\%$ (1091 to 821 W) with the pumping efficiency decreasing somewhat from 15.4 to 14.1% .

The ALIP performance curves for the TREAT and small 0.5 in. I.D. EBR-II pumps as presented in Fig. 14 were adjusted for lithium operation using the 0.74 factor as obtained using the ALIP model of Ref. 7 as adjusted with the Table XXIII results. In Fig. 17, the estimated pump head versus flow rate are shown for the two ALIPs along with the situation of two

TREAT ALIPs operating in series (TREAT dual ALIP head). The three pressure drop cases identified in Fig. 17 are the same as identified previously in Fig. 14.

Comparing the ALIP performance curves (see Figs. 14 and 17) for the Case 3 pressure drop situation shows that the effect of replacing sodium by lithium was to reduce the flow rate capability that can be expected for the facility by a factor of about 0.85. In the case of the TREAT dual ALIP operation, the lithium flow rate at the Case 3 design point dropped from 13.5 to 11.6 gpm. For the single TREAT ALIP application, the design point flow rate dropped from 10.6 to 9.0 gpm with the EBR-II 0.5 in. ALIP flow rate changing from 7.7 to 6.5 gpm.

The remaining ALIP design uncertainty is the question of whether high temperature coil material will be required for the 260°C (500°F) temperature application and if it is, how this different pump material will affect pump performance. In the TREAT ALIP design as stated in Ref. 29, the field coils were constructed of flat ribbon-wound pancake coils of fully anodized EC aluminum. A maximum operating temperature of about 260°C was anticipated with this design; however, a reference was cited (Ref. 30) where this type of conductor has been wound without interleaving insulation and has been successfully operated as the primary of a 60-cycle, one-phase, 230 V AC stepdown transformer at 425°C for over 500 h without malfunction or failure. If this material proves inadequate (i.e., pump requires external coil cooling), high temperature coil material developed for the 0.5 in. EBR-II ALIP (e.g., Glidcop ribbon coated with glass frit as presented in Ref. 22) may be required. The effect of this material design change on the TREAT ALIP performance, however, would have to be assessed.

For lithium pump Model 1 the two TREAT ALIP performance curves shown in Fig. 17 were polynomial fitted using the Speakeasy computer code of Ref. 31. The polynomial expressions for the 40 amp operation pump performance in lithium are presented below:

Single TREAT ALIP Operation

$$\Delta P_{\text{pump}} = 61.281 + 2.4325e-02m - 6.1212e-02m^2 + 9.2730e-04m^3 \quad (5)$$

Dual TREAT ALIP Operation

$$\Delta P_{\text{pump}} = 103.69 - 0.7010m - 2.3267e-02m^2 - 1.4928e-03m^3 \quad (6)$$

where m is the lithium inlet to the downcomer flow rate in gpm units and ΔP_{pump} is the pump head in psi units.

The resulting four coefficients for each of the lithium pumps [see Eqs. (5) and (6)] were then used in the thermal-hydraulic TMOLL (thermohydraulic model of lithium loop) computer model described in Appendix D.

2. Lithium ALIP Model 2

In pump Model 1 based on the TREAT ALIPs (i.e., single and dual), the pump pressure head versus flow rate for the 40 amp and 315°C sodium operation were corrected for lithium coolant and the resulting pressure head versus lithium flow rate incorporated into the TMOLL computer code. It was pointed out in Ref. 32 that for long-term continuous operation the TREAT ALIPs should be operated at a current no greater than 30 amps. In addition more recent references were obtained which cast doubt on the lithium electrical resistivity value that was used in the Model 1 pump performance analysis.

In light of these two above revelations the ALIP model used in the TMOLL computer code (see Sect. V.D) was reassessed for TREAT ALIP operation with lithium. These modifications to the original pump Model 1 were implemented into the TMOLL computer code and resulted in an improved pump Model 2.

a. Lithium Electrical Resistivity

In the above pump Model 1, a value for lithium electrical resistivity of 19.29 $\mu\text{ohms-in.}$ (49 $\mu\Omega\text{-cm}$) at 500°F (260°C) was used as the basis for the sodium-to-lithium

pump performance conversion. The source of this lithium resistivity was the 45.25 $\mu\text{ohm-cm}$ at 230°C value tabulated in the Liquid Metals Handbook (see page 41 of Ref. 14). The liquid metals handbook referenced source for this value was a 1905 article by Bernini (see Ref. 33).

More recent references indicate that the electrical resistivity for liquid lithium is only about half the Ref. 33 value at the 230°C temperature. In Table XXIV, several of these resistivity correlations are tabulated along with their original reference sources. These reference sources were not actually obtained but were found in other reports: Correlations 1 and 3, presented in Table XXIV, were cited in Ref. 11 with Correlation 2 cited in Ref. 10. Based on the rather good agreement among these three rather recent independent sources, the earlier Ref. 33 lithium resistivity value must be in error.

In Appendix C (Fig. C.5), the resistivity of lithium and sodium are plotted over the low temperature range of interest for LTIV application. The lithium resistivity curve is the Correlation 2 relationship in Table XXIV and was selected as it represents somewhat of an average of the three correlations. The electrical resistivity in $\Omega\text{-m}$ with T in °C for sodium, ρ_{Na} , was taken from Ref. 10:

$$\rho_{\text{Li}} = 8.14\text{e-}08 + 2.27\text{e-}10T + 2.99\text{e-}13T^2 \quad (7)$$

The source of this expression for sodium was Ref. 34 with the electrical resistivity values essentially in agreement with those values tabulated by Golden and Tokar (see Ref. 35). The Speakeasy computer code of Ref. 31 was used to determine the best polynomial fit for the lithium Correlation 2 in Table XXIV. The expression for the lithium electrical resistivity (ρ_{Li}) in units of $\mu\Omega\text{-cm}$ with T in °C was determined to be:

$$\rho_{\text{Li}} = 17.2 + 5.24\text{e-}02T - 4.46\text{e-}05T^2 \quad (8)$$

which was also used in the Model 2 pump performance model.

b. Modified TREAT ALIP Pump Head Curves

The performance curves for the TREAT ALIPs with both single and dual 315°C sodium operation were provided in Ref. 25 and are shown in Fig. 16. All previous LTIV loop performance studies were based on the highest 40 amp current operation. To be on the conservative side in light of the 30 amp limit specified in Ref. 32--the 25 amp current pump head relationships curves of Fig. 16 were selected for LTIV application.

The Speakeasy computer program[31] polynomial curve fits were obtained for the single and dual TREAT ALIP operation in 315°C sodium at 25 amps from Fig. 16. The polynomial expressions for the 25 amp operation pump performance in 315°C sodium are presented below:

Single TREAT ALIP Operation

$$\Delta P_{\text{ref}} = 49.548 - 0.216920m - 0.047328m^2 + 1.1548e-03m^3 \quad (9)$$

Dual TREAT ALIP Operation

$$\Delta p_{\text{ref}} = 86.290 - 0.27949m - 0.07533m^2 + 9.4791e-04m^3 \quad (10)$$

where m is the lithium inlet to the downcomer flow rate in gpm units and ΔP is the pump head in psi units. As described below, these reference sodium pump head versus flow rate relationships became the basis for pump Model 2.

c. Revised Pump Model 2

In the pump Model 1 described previously, a simple ALIP design model found in the literature was used to convert the existing known 1200°F sodium pump head design prediction to the 500°F LTIV lithium condition. From this calculation a conversion factor was

generated for application to the TREAT ALIP pump head curves. This approach is obviously an approximation but as it turns out was reasonably accurate because of the resistivity value for lithium that was assumed. As stated on page 34 of Ref. 11:

"If the flux density and the voltage acting on the liquid metal circuit remain constant, then for a given flow rate the pressure developed by an EM pump will be inversely proportional to the resistivity."

This approximation seems to check with the pump Model 1 analysis which generated a correction factor of ~ 0.74 using the ALIP design model. This agrees with the ~ 0.71 factor based on the inverse of the electrical resistivity ratio assumption.

Clearly the above factor (i.e., 0.74) based on 1200°F sodium does not account for the resistivity of the 315°C TREAT ALIP sodium. However, when one assumes the inverse approximation and the correct lithium resistivity value at 500°F ($\sim 260^\circ\text{C}$) (see Fig. C.5 in Appendix C) a correction factor of ~ 0.64 results. Therefore the previous results were $\sim 15\%$ nonconservative (e.g., $0.74/0.64$) in predicting the TREAT ALIP pump head with lithium at typical LTIV temperatures. The erroneous lithium resistivity value, which was higher than the correct resistivity, tended to compensate for the use of the higher 1200°F sodium temperature rather than the 315°C TREAT ALIP temperature.

The TMOLL computer pump model (see Sect. V.D) has been modified to reflect the above inverse resistivity relationship assumption. In addition to the desired pump head curve versus flow rate as expressed with the four polynomial coefficients [e.g., either Eqs. (9) or (10)] the resistivity of the reference liquid metal (ρ_{Na}) is also provided in the input as the fifth entry in the pump head coefficient array. For sodium at 315°C, a resistivity value of $18.29 \mu\Omega\text{-cm}$ is determined from Eq. (7). A subroutine which calculates the lithium electrical resistivity as a function of temperature has been incorporated into the TMOLL model. Presently Correlation 2 in Table XXIV as expressed by Eq. (8) has been employed although, in principle, any relationship can be easily implemented.

The TMOLL iterative calculation remains essentially the same as before except after the pump pressure head, Δp_{Na} is calculated at the loop flow rate from the input polynomial coefficients it is corrected for the resistivity of lithium. A call to the lithium resistivity subroutine (LIREs) along with the calculated inlet downcomer lithium temperature (assumes the pump is on the cold leg) provides the needed lithium electrical resistivity (ρ_{Li}). The LTIV pump head, Δp_{pump} , is then calculated assuming the inverse resistivity relationship:

$$\Delta p_{pump} = \Delta p_{Na} \rho_{Na} / \rho_{Li} \quad (11)$$

If it is desired to not correct the input pump head versus flow rate relationship, then a zero reference electrical resistivity must be provided in the pump head coefficient array.

D. Optimization of In-reactor Tube Dimensions

The TMOLL computer program was used to investigate the performance benefits of an insulated upper flow divider. The LTIV geometry and initial conditions were identical to those used and reported in the Appendix D study (see Table D1) with the exception of the radial geometry in the upper region and that the iterative lithium flow option was selected. Two cases were simulated with the insulated flow divider design:

1. Operation of LTIV with a single TREAT ALIP and,
2. Operation of LTIV with two (or dual) TREAT ALIPs.

Both cases used input polynomial curve fits to the pump heads as described in Sect. V.C for estimating the lithium loop operation.

1. Insulated Upper Flow Divider

The upper region in the stepped tube design configuration has considerably more radial room than the lower region due to the EBR-II control rod guide tube design. In the loop

design of Case 3 (in Sect. V.B) (see Table XVIII), most of the extra radial room was taken up by a large argon insulation gap (130 mils). In this latest LTIV design, the flow housing tube O.D. was increased from 2.000 to 2.125 in. reducing the argon insulation gap to 67.5 mils in the upper region. This allowed the upper region flow divider to be moved out to an O.D. of 1.75 in.

The insulated upper flow-divider design finally selected consists of two concentric tubes sandwiched together around an argon gas space. Keeping with the design philosophy of using "standard" BWG tubing if at all possible the outer flow-divider tube was 1.75 in. O.D. by No. 16 gage (65 mils thick) with the inner flow-divider tube being 1.50 in. O.D. by No. 19 BWG gage (42 mils thick). This translates into a flow-divider argon insulation gap of 60 mils. The upper upcomer flow region remains the same as the Case 3 in Sect. V.B at a design gap value of 92.5 mils but because of the larger diameter the upcomer flow area is actually slightly larger (0.535 in.^2 versus 0.499 in.^2). In this latest design the downcomer in the upper region is somewhat reduced from the previously presented Sect. V.B uninsulated Case 3 design (0.348 in.^2 versus 0.390 in.^2). The downcomer gap is now 83 mils compared to the downcomer gap in the upper region of the previous design of 92.5 mils. The physical characteristics of this insulated upper flow-divider design have been tabulated in Table VI.

The TMOLL model presently considers the flow divider to be a solid with a given thermal conductivity (although a different value can be input for the upper and lower regions). To account for the insulation gap, a heat transfer film coefficient of $3.44 \text{ Btu/h/ft}^2/\text{°F}$ was calculated assuming the 60 mils gap was filled with 1 atm argon ($k = 0.0172 \text{ Btu/h/ft/°F}$). For conservatism to account for thermal radiation and heat conduction through spacers this coefficient was reduced $\sim 12\%$ and an equivalent thermal conductivity of $0.05447 \text{ Btu/h/ft/°F}$ was calculated and input into TMOLL for the 1.75 in. O.D. by 1.416 in. I.D. upper flow divider.

2. Single TREAT ALIP Operation

The TMOLL input for the simulation of the LTIV insulated upper flow-divider design is, with the exception of the insulated flow divider and lithium flow option, as presented

in Table D1 in Appendix D. The selection of the flow search hydraulic option described previously in Appendix D was chosen. The Model 1 pump head curve [see Eq. (5)] for the single TREAT ALIP lithium operation was employed. A polynomial curve fit was obtained from the scoping study in Sect. V.B (see Table XX) for the external LTIV pressure drop, ΔP_{ex} , in psi units and with the lithium flow rate m , in gpm units:

$$\Delta P_{ex} = -0.38193 + 0.33385m + 0.088823m^2 - 4.8858e-04m^3. \quad (12)$$

The TMOLL output calculational results for the single ALIP operation yielded a converged lithium flow rate of 9.093 gpm which is slightly lower than the 10 gpm lithium loop flow rate used in the previous uninsulated study. The in-reactor pressure drop of 47.5 psi is, as expected then, comparable to the 53.2 psi pressure drop calculated in the Appendix D study.

The major improvement in thermal performance introduced by the insulated upper region flow divider can be obtained from a comparison of the inlet downcomer temperature required to achieve the desired 550°F loop bottom temperature. The uninsulated upper flow divider required an inlet downcomer lithium temperature of 388°F (see Table D2 in Appendix D). With the insulated upper flow divider, on the other hand, an inlet downcomer lithium temperature of 448°F is required to achieve the 550°F loop bottom temperature. Therefore the insulated upper flow-divider design provides a larger and more acceptable loop operation margin over the 355°F lithium freeze point.

In Figs. 18 and 19 the axial lithium temperatures and pressures in the loop downcomer and upcomer regions are presented for the single ALIP operation case. The axial pressure profile seen in Fig. 19 is referenced to an assumed downcomer inlet pressure of 100 psi.

3. Dual TREAT ALIP Operation

The TMOLL input for the simulation of the insulated upper flow-divider loop design with dual TREAT ALIP operation was identical to that for the single pump case except for

the pump head curve. The pump head curve for the dual TREAT ALIP operation with lithium was Eq. (6) for pump performance Model 1. The pump head curve polynomial coefficients were determined using the Speakeasy program (see Sect. V.C). The Eq. (12) ex-reactor loop pressure drop versus flow rate relationship was assumed for this dual TREAT ALIP case.

The TMOLL output for the insulated upper flow-divider design with dual ALIP operation was obtained for the lithium flow iteration option. The converged lithium loop flow rate was found to be 11.8 gpm with the total loop pressure drop estimated to be 89.7 psi. In Figs. 20 and 21 the major lithium temperature and pressure results are plotted.

The improvement in loop thermal performance over the single pump results are seen by comparing the results for the single ALIP operation (Fig. 18) with those obtained for the dual ALIP operation study (Fig. 20). The increase in lithium flow rate results in the inlet downcomer temperature increasing from the single ALIP operation temperature of 448 to 488°F. The temperature differential (i.e., between downcomer inlet to upcomer outlet) has been reduced from ~23 to ~16.9°F. This improvement in loop thermal performance could be reflected in a reduction in the 550°F loop bottom temperature yet still retaining a 100°F temperature margin between the downcomer inlet temperature and the lithium freezing point.

4. Summary and Conclusions

The loop performance improvement due to the presence of an insulated flow divider in the upper region of the in-reactor loop was investigated. Two cases were studied and compared to the uninsulated results of Appendix D. In the first case a single TREAT ALIP loop operation situation was assumed. The TMOLL calculation resulted in an increase in lithium downcomer inlet temperature from 388°F for the uninsulated design to 448°F for the insulated flow divider design. This insulated design temperature condition is ~100°F above the lithium freezing point and is felt to represent an adequate operating temperature margin.

In the second case that was analyzed, a dual TREAT ALIP operation situation was assumed and the loop performance calculated with the TMOLL computer model. A further increase in inlet lithium downcomer temperature to 488°F was realized.

Based upon the results reported herein it is concluded that an insulated upper flow divider appears necessary to provide the required operating temperature margin ($\sim 100^\circ\text{F}$) above the lithium freezing point. An additional loop operating temperature margin is available if a second TREAT ALIP is employed. A reduced loop operating temperature below the reference 550°F level is an alternate option to take advantage of the improved thermal performance capability introduced by the second pump.

E. Parametric Sensitivity Results

The TMOLL (thermal model of lithium loop) computer program described in Appendix D was used to assess the thermohydraulic performance of the low temperature irradiation vehicle (LTIV) with a change in several parameters around the reference set of conditions. In this sensitivity analyses the basic stepped tube design (Case 3 in Sect. V.B) remained the same except in the upper region (upper 233.64 in.) where the solid stainless-steel flow divider was replaced with an insulated flow divider design in Sect. V.D. This design was taken as the new reference design configuration. In Table VI these reference design dimensions are tabulated. The thermal and hydraulic performance of the LTIV was evaluated assuming both a single TREAT ALIP operation as well as assuming dual TREAT ALIP operation using the Model 1 pump performance model (see Sect. V.C).

The basic purpose of this study was to explore the sensitivity of the LTIV operational conditions to the variation of several parameters or design assumptions. The reference set of LTIV conditions and resultant TMOLL computer model calculational predictions around which the analysis was made are provided in Table XXV. The major objective of the study was to infer the influence of design condition assumptions on LTIV performance parameters (i.e., lithium flow

rate, inlet and outlet in-core lithium temperatures). In this study the parameters studied (i.e., varied) included:

1. Test Section Steel Volume Fraction,
2. Gamma Heating Rate,
3. Test Temperature,
4. Ex-reactor Pressure Drop, and
5. EBR-II Heat Exchange.

The results of varying these parameters around the Table XXV set of reference conditions are tabulated and discussed below.

1. Test Section Stainless-steel Volume Fraction

The gamma heat generated within the 13-in. long loop test section region depends upon the amount of steel present within the 1-in. O.D. sample capsule. To investigate the sensitivity to this parameter the 0.50 reference stainless-steel volume fraction was varied between 0.25 and 1.00. The TMOLL results for this parametric variation are tabulated in Table XXVI.

As the Table XXVI results indicate, the stainless-steel volume fraction had a relatively small effect on the converged LTIV lithium flow rate. This insensitivity is due to the very small physical property variation over the narrow temperature range that was predicted. As indicated in Table XXVI, the gamma heat generation varied from 10.29 kW at the 0.25 vol fraction to 15.09 kW at the 1.00 vol fraction situation. All of the change in gamma heating, of course, occurred in the downcomer region. This range of gamma heating translated into a lithium inlet-to-the-downcomer temperature variation of 37.8°F for the single TREAT ALIP case and 23.8°F temperature variation for the dual TREAT ALIP case.

2. Gamma Heating Rate

The next parameter varied was the gamma heating rate in the test section. In Ref. 36, the EBR-II row No. 5 (where control rod channels are located) stainless steel (SS) gamma heating rate varied from 3.77 W/(gram of SS) to 6.00 W/(gram of SS). The reference gamma heating rate was 4.62 W/(gram of SS) (see Table XXV). In order to cover the gamma heat rate range that might be encountered in the LTIV, the gamma heat rate was varied from 3.0 to 8.0 W/(gram of SS) and TMOLL calculations performed.

Results of the gamma heat rate variation are presented in Table XXVII. With the gamma heating present within all of the in-core tubes, the gamma heating affected both the downcomer as well as the upcomer heat generation quantities. The total gamma heat generation range was calculated to vary from 7.73 kW at the lower 3.0 W/g heat generation level to 20.59 kW at the highest 8.0 W/g heat generation level. The wide variation in lithium in-core loop temperatures that were predicted by TMOLL are evident in Table XXVII. Again as was the case with the previous parametric calculations, the small lithium physical property temperature dependency resulted in small lithium flow rate variations for the two pump situations that were assumed in this study.

3. Test Temperature

The test temperature is an important parameter from an experimenter's standpoint as it is a figure-of-merit which will be used to judge the performance of the LTIV. As low a temperature as possible is desirable, to give the experimenter the flexibility needed in order to perform as wide a range of experiments as possible. The test temperature in this study was actually the lithium temperature at the bottom of the in-core loop where the downcomer and upcomer combine at the same temperature. This temperature is generally about 10°F above the downcomer in-core lithium temperature nearest the test specimens. In the present TMOLL model, the radial temperature drop from the test specimen to the in-core downcomer lithium is not calculated.

The test temperature effect was evaluated over a temperature range of 250°C (481°F) to 316°C (600°F). The reference test temperature (see Table XXV) was 550°F (288°C). The lowest assumed test temperature of 250°C represents a target for low temperature fusion materials irradiation experiments.

The results of the test temperature parametric study are shown in Table XXVIII. The insensitivity to lithium flow rate is again evident. As Table XXVIII indicates, this lack of flow rate effect translates into an almost constant in-core and total pressure drop. The almost direct relationship between test temperature (i.e., loop bottom temperature) and loop inlet and outlet lithium temperatures is also quite evident in the Table XXVIII results. Also of note in the Table XXVIII results, are the inlet lithium temperatures required to attain the fusion test target 250°C temperature. The 376.4°C inlet temperature for 250°C case with the single pump operation appears to be unacceptable considering that the lithium melt temperature is 354°F. To provide a sufficient operating envelope at the very minimum, a dual pump configuration appears to be required.

4. Ex-reactor Pressure Drop

One of the larger uncertainties in the present LTIV facility design is the ex-reactor pressure drop. This, of course, is because the layout and selection of the piping and equipment is very preliminary. Therefore, to study the effect of the ex-reactor pressure drop on LTIV performance this pressure drop was varied by $\pm 25\%$ from the reference values. In order to accomplish these calculations, a set of polynomial coefficients for each pressure drop versus flow rate curve was generated and input into the TMOLL model.

Results of the ex-reactor pressure drop effect on the LTIV thermal and hydraulic performance are tabulated in Table XXIX. The influence that the ex-reactor pressure drop has on the overall loop performance was not great, considering the wide range of the change that was assumed. Over the $\pm 25\%$ ex-reactor pressure drop range, the lithium inlet temperature variation was less than 10°F for the single TREAT ALIP situation and less than 5°F for the dual TREAT

ALIP configuration. This is due to the fact that the ex-reactor pressure drop contributes only about 17% to the total system pressure drop.

5. EBR-II Heat Exchange

The TMOLL computer model used to perform the previous sensitivity calculations was found to have an error in the heat exchange calculation between the LTIV upcomer lithium and EBR-II. The heat conduction across the outer insulation argon gas filled insulation gap (e.g., gap D and gap E shown in Table VI) was not being calculated correctly. The heat exchange model between EBR-II and the LTIV in-reactor loop was corrected and a revised LTIV reference set of performance conditions was generated.

In addition, parametric calculations were made investigating the sensitivity of the LTIV thermohydraulic performance to the effects of changing heat exchange variables between EBR-II and the LTIV. Varied in these TMOLL computer calculations were the value of the argon gas gap thermal conductivity as well as the value for the thermal emissivity of the insulation surfaces in the thermal radiation model. Results of these investigations are presented below.

a. Revised Reference LTIV Thermohydraulic Performance

The heat exchange model between EBR-II and the LTIV lithium in the TMOLL model, was modified from that used in the previous TMOLL calculations. In the previous model, the heat transfer across the insulation gap was not being calculated correctly. This oversight was corrected by adding the conduction component through the argon gas gap to the existing thermal radiation component. The heat transfer was assumed to be parallel with the total heat exchange across the insulation gap to be the sum of the two individual heat transfer processes (i.e., $q_{tot} = q_{rad} + q_{con}$). An overall gap heat transfer coefficient was, therefore, determined as the sum of the individual coefficients (i.e., $h_{tot} = h_{rad} + h_{con}$). The present model assumes a temperature independent argon thermal conductivity and neglects the effects of natural convection within the gas insulation gap.

The re-evaluation of the LTIV thermohydraulic performance used the geometry and loop configuration data developed previously and is shown in Table VI. The reference argon thermal conductivity (i.e., $k_{\text{arg}} = 0.0172 \text{ Btu/h/ft/}^{\circ}\text{F}$) and the thermal surface emissivity values (i.e., $\epsilon_1 = \epsilon_2 = 0.79$) used previously were again assumed (see below for sensitivity effect).

The results of the TMOLL predictions for the revised reference LTIV design configuration are tabulated in Table XXX. Also provided for comparison are the previous reference conditions. As indicated in Table XXX, for the single TREAT ALIP operation, the revised TMOLL model results in an $\sim 7^{\circ}\text{F}$ drop in the converged in-reactor inlet lithium temperature. For the dual TREAT ALIP case, the lithium inlet temperature reduction was only $\sim 4^{\circ}\text{F}$ when compared to the previous values. The changes in the other thermal-hydraulic predictions (i.e., lithium flow rate, pressure drop, and heat exchange with EBR-II) were all relatively minor between the original and revised references as seen in Table XXX.

b. Heat Exchange with EBR-II Sensitivity Study

In the previous LTIV thermohydraulic performance sensitivity study, the variation of the important heat exchange parameters between EBR-II and the LTIV in-reactor loop were not assessed. In this study, using the above modified TMOLL model, the influence of the variation in several thermal assumptions on the LTIV performance was determined. As described in the previous section, the heat exchange model across the argon insulation gap (see Items 8 and 14 in Table VI) considered two processes: 1) thermal radiation and 2) thermal conduction. In one sensitivity set of TMOLL calculations, then, the value of the thermal emissivity of the two insulation gap annular surfaces were varied about the reference conditions. In the other sensitivity calculation, the value of the argon thermal conductivity was varied with the other conditions held constant (i.e., emissivity). The EBR-II axial temperature profile on the outside surface of the LTIV loop was taken from Fig. D1 in Appendix D. The results of the two heat exchange parametric studies are presented in Tables XXXI and XXXII.

The results for the effect of the surface emissivity on LTIV performance are shown in Table XXXI. The emissivity values that were used ranged from $e = 0$ (no thermal emittance) to $e = 1.0$ (black body). The emittance data typical for steel surfaces vary over a wide range of values--depending upon the surface condition and temperature history and level. In Table XXXIII, taken from Ref. 37, several examples are provided. The reference emissivity taken for LTIV was 0.79 although as Table XXXIII indicates a somewhat lower value could probably be justified.

As the results of Table XXI indicate, for the complete emissive range going from zero to black body radiation, the inlet lithium temperature varied about 25°F for the single TREAT ALIP case to about 15°F for the dual TREAT ALIP operation case. This rather weak sensitivity can be attributed to the fact that although heat is gained from EBR-II in the lower section of the LTIV loop it is lost in the upper sections (see Fig. D1). This is noticeable in the dual ALIP Case 1E result in Table XXXI where heat is actually lost to EBR-II. The higher lithium temperatures that were achieved result in a smaller temperature differential for heat gain with EBR-II in the lower loop sections and a larger temperature differential for heat loss in the upper loop sections.

Note also that for Case 3E (Table XXXI) the results are quite similar to those for the original LTIV reference shown in Table XXX. This situation was for an assumed emissivity of 0.55, which is slightly lower than the 0.79 reference emissivity. As Table XXXIII indicates, the 0.55 emissivity value under the somewhat lower LTIV temperature conditions could probably be justified.

The effect of argon thermal conductivity on the thermal conduction across the insulation gaps in the in-reactor LTIV loop is shown in Table XXXII. In order to infer the effect of gap conductance the argon thermal conductivity was varied from zero times k_{ref} to $10k_{ref}$. The zero times k_{ref} calculation (Case 1F in Table XXXII) represents the zero heat transfer by thermal conduction situation. This is essentially the original reference condition presented in Table XXX. The higher argon thermal conductivity situations (Cases 3F through 5F in Table XXXII)

were selected to bracket a possible increase in gap conductance due to other processes (e.g., natural convection, conduction through gap spacers, etc.).

As the parametric study results of Table XXXII indicate, except for the $10k_{ref}$ case (Case SF) the influence of lithium temperature, while significant, is nevertheless probably acceptable for the single ALIP case. Operation of the LTIV with a single ALIP of the TREAT design would still have a 56°F temperature margin over the 354°F lithium melting temperature. For the dual TREAT ALIP cases, it appears even the $10k_{ref}$ case (Case 5F) would be more than acceptable as the lithium temperature was ~91°F above the 354°F melt temperature. Again the lower lithium temperatures required for the single TREAT ALIP account for its greater heat loss sensitivity. The lower lithium flow rate in the case of the single ALIP operation also is responsible for the greater heat exchange that was predicted.

F. Reference Design

In the previous TMOLL parametric studies, the calculations were performed using an ALIP performance model based on operating a standard TREAT ALIP either singly or dually at a current of 40 amps (Model 1 in Sect. V.C). In Ref. 32, it was noted that for continuous operation the TREAT ALIP should be operated at a current no higher than 30 amps. Therefore, in Sect. V.C, a pump model (Model 2) was developed which was based on a conservative performance current of 25 amps. In addition, this model incorporated an improved temperature dependent correlation for the electrical resistivity of lithium and a better knowledge of the role that the resistivity plays in the pump performance was utilized. This pump performance model (e.g., Model 2 in Sect. V.C) was used to recalculate the LTIV thermohydraulic reference conditions.

The pump model used in these TMOLL computer code calculations (e.g., Model 2 in Sect. V.C) has been modified to reflect a better understanding of the role that the liquid electrical resistivity plays in the ALIP performance. The approximation that the pump head at a given flow rate varies inversely with the electrical resistivity of the fluid being pumped was assumed in the

revised pump model. It was also discovered that the value that was employed in previous LTIV studies (i.e., pump Model 1) for the lithium electrical resistivity was from a 1905 study (see Ref. 4). Based upon more recent studies, this lithium electrical resistivity could be high by a factor of almost two. A lithium resistivity versus temperature correlation which was felt to represent the average of the more modern existing data (see Correlation 2 in Table XXIV in Sect. V.C) was selected for LTIV application.

Previous LTIV assessments using the erroneous lithium resistivity value were determined to be still qualitatively correct. This conclusion was based on the compensating effect that the previous pump model had in mitigating the effect of the high lithium resistivity value although the resulting correct model is more complicated than just improving a single factor involved in the analysis.

1. LTIV Performance

The fore mentioned pump model changes were implemented and the TMOLL computer code was used to evaluate the thermal-hydraulic performance of the LTIV loop. The TREAT ALIP performance curves for the 25 amp current operation (see Fig. 16 in Sect. V.C) were polynomial fitted and the coefficients were generated for TMOLL application [see Eqs. (9) and (10) in Sect. V.C]. The lithium electrical resistivity versus temperature relationship was assumed to be that of Correlation 2 in Table XXIV. The LTIV TMOLL computer model calculations were performed for both a single TREAT ALIP operation as well as for a dual TREAT ALIP operation with the results summarized in Table XXXIV. In these calculations the loop physical characteristics describing the design with an upper insulated flow divider of Table VI was employed. Also tabulated in Table XXXIV, for comparison purposes, are the results for TREAT ALIP operation at the 40 amp current condition that were obtained in the previous study (i.e., see the revised reference conditions in Table XXX).

As the comparison of LTIV results in Table XXXIV indicate, the reduced TREAT ALIP current condition of 25 amps translates into a marked reduction in LTIV performance. In

fact, based on the predicted inlet lithium temperature of 352.8°F for the single pump case, at 25 amps this operating condition would be impossible based on the ~354°F lithium freezing/melting temperature. The dual TREAT ALIP operation while seriously degraded from the 40 amp current case results in an inlet lithium LTIV temperature of 434.1°F which should have an acceptable (but somewhat close) operating margin above the lithium freezing temperature.

2. Conclusions

The TMOLL predictions of the LTIV loop performance with the revised pump model were obtained for the TREAT ALIP operation at a reduced 25 amp current. This operating condition, reduced from the previous 40 amp current, was recommended for continuous loop operation in Ref. 32. The TMOLL results indicate that at 25 amp operation the performance of the LTIV with a single TREAT ALIP will not be possible. For this case the low pump head and, hence, low lithium flow rate that was generated required an inlet lithium temperature below the lithium freezing point. Operation of the LTIV with a dual TREAT ALIP configuration appears possible with the inlet lithium temperature of 434.1°F predicted. However, this ~80°F operating margin is near the minimum that may be allowable and ways of obtaining more pumping capability (e.g., larger ALIP designs) should probably be investigated.

VI. RECOMMENDATIONS FOR FUTURE WORK

It is anticipated that the development of this concept will require an extensive out-of-pile testing program. This research and development program will no doubt include a full-scale thermal-hydraulic proof test loop for establishing the performance, operability, and reliability of the individual LTIV components. A separate facility mocking up the EBR-II control-rod drive elevator system would also be needed to check out the removal and insertion problems of the in-reactor loop. Some of the individual components and their associated development requirements are discussed below.

A. Facility Location and Layout

The location of the ex-reactor components and their layout relative to the existing EBR-II structures and equipment requires further study. The present thinking is that the location of the LTIV lithium-to-air heat exchanger, lithium pump, lithium surge tank, and other ancillary components (e.g., lithium purification system) would be mounted on the reactor vessel cover lifting mechanism superstructure. This superstructure is located directly above the EBR-II core region on the operating floor. The layout and location of LTIV equipment on the superstructure in such a manner so as to prevent interference with existing equipment requires additional study. The location selection is, of course, dependent upon several factors which include, among others, the control-rod channel location selected for the LTIV, the motion and support requirements for the flexible metallic connecting hose, and the need to provide access to the control-rod drives and equipment located within the superstructure envelope.

The availability of a mockup of the control-rod elevator and LTIV support will be needed to study various installation problems. The motion and clearances between the EBR-II structures and the LTIV coolant lines requires check out in a full-scale out-of-reactor facility.

It is presently envisioned that the ex-reactor equipment installed on the vessel cover lifting mechanism superstructure will be mounted on a moveable panel. This equipment panel would be on hinges which would allow the equipment panel to swing away from the superstructure allowing access to the centrally located EBR-II control-rod drives. The necessity for requiring this feature and the requirements should be explored. It may be that with proper location of the LTIV ex-reactor equipment that this requirement can be eliminated or modified. A fixed and immovable ex-reactor equipment installation would reduce considerably the design problems with the flexible coolant lines.

B. Pump Development

The feasibility calculations of the LTIV indicated that an ALIP system consisting of two TREAT size units would provide adequate performance. There is not the space and size restrictions or requirements that are usually associated with in-reactor test loops. Therefore the individual TREAT ALIP size of 3.75 in. O.D. by 26 in. long (see Table VII) should not be a problem. Another ALIP design with improved pumping performance might be a consideration if increased testing requirements are invoked. However, the availability of the proven TREAT ALIP design and operating experience makes it a leading candidate for LTIV application.

The only major drawback of the TREAT ALIP design is that the present design requires a secondary coolant (e.g., mineral oil) to cool the pump coils. In the TREAT ALIP design, the field coils were constructed of flat ribbon-wound pancake coils of fully anodized EC aluminum. A maximum operating temperature of about 260°C will be required. This is above the ~150°C limit presently in effect for TREAT application. If the present coil material proves inadequate (i.e., external cooling required for coil cooling), high temperature coil material (e.g., Glidcop ribbon coated with glass frit) may be required. The effect of this material design change on the TREAT ALIP performance characteristics, however, would have to be assessed.

An alternate mechanical pump design could be considered for this LTIV application. Experience with mechanical liquid metal pumps exists (e.g., see Refs. 38 and 39) and their application to this lithium packaged loop should be practical. Also other types of EM pump designs exist (e.g., helical-rotor, flat linear induction pump)[11] with several vendors offering commercially available EM pumps in a size suitable for LTIV application.[40] In any event, whatever pump design is selected for LTIV deployment, a prototype pump would have to be built and prooftested in an out-of-reactor lithium facility.

C. Seals and Connections

Reliance would be placed on previous EBR-II test loop experience in selecting the low pressure seals and connections that are required in a packaged loop of this design. Seals between the in-core tube and the rotating plug have been designed and tested in the past for the INCOT test program. A seal between the lithium coolant and the argon gas in the in-reactor upper tube region will be required in order to prevent lithium vapors from collecting in the upper plenum. Several expanding bellows will be required to provide for differential thermal expansion effects between the various tubes in the loop. Various lithium-piping connections will be required with their design requiring testing also before installation in the facility.

D. Lithium Purification System

Although the lithium purification methods and systems experience which exists from previous lithium test loop operating programs is not as extensive as that for sodium, there nevertheless exists an adequate knowledge base from which to specify procedures and select equipment for lithium purification. The large lithium heat transfer loop[13] has generated a wealth of valuable experience in operating a lithium heat transfer facility. The lithium purification and filter systems developed in this program and the procedures for operating solid filters, plugging meters, and hot and cold traps with their associated heat exchangers will be directly applicable to the LTIV program. A dedicated out-of-reactor lithium test facility would also be invaluable in acquiring the necessary lithium technology and loop operating information needed to select, design, and operate the in-reactor LTIV facility.

E. Loop Handling and Filling Equipment

A test out-of-reactor lithium loop would also be extremely valuable in assessing the lithium handling and loop filling requirements for the LTIV. Again the HEDL experience obtained during the four years of operating the experimental lithium system as described in Ref. 13 would be directly applicable to the LTIV program. Establishing the piping and component insulation and

trace heating requirements and determining the proper lithium filling and draining procedures would be essential elements of any out-of-reactor test program.

The reliability of all handling operations could be established in a prototype elevator assembly test stand. The removal and insertion procedures needs to be developed and checked out before installation in the reactor. The irradiated in-reactor test samples and loop require the use of shielded containers. The use of an existing EBR-II test coffin would be anticipated but the feasibility of this approach would have to be determined when the design is further along.

F. Flexible Metal Hose

The use of flexible metal hose for coolant lines between the in-reactor and ex-reactor loops would have to be studied and its engineering suitability determined. The potential hazard associated with a flexible metal hose failure would require a proof test program to establish the reliability of the commercially available tubing. With a doubly contained tubing system, leak detectors for sensing a lithium leak would require testing. The flexible tubing support system and motion control during in-reactor loop lifting would also require checkout testing in the elevator test stand.

G. Heat Exchanger

An out-of-reactor lithium test facility would provide the ideal test bed for verifying experimentally the performance of the air-to-lithium LTIV heat exchanger. Although the size of this exchanger is not crucial and the performance requirements are neither difficult nor special, there, nevertheless, are several unique design features which would require experimental verification. To provide emergency protection in the event of a lithium leak will require the presence of quick acting dampers on the air side to contain the lithium and isolate the system. The control system and sensors for regulating the heat exchange and lithium flow rate in conjunction with the lithium pump and air blower would require evaluation and proof testing.

VII. SCHEDULE AND RESOURCE REQUIREMENTS

Based on the completed feasibility assessment and scoping calculations that were conducted, a schedule and resource estimate has been made for developing, building, and installing a single LTIV facility at EBR-II. These estimates of time, money, and manpower are, of course, very preliminary but have been based upon the ANL experience of the engineering efforts on similar test facilities. These estimates are, therefore, felt to be reasonable and attainable assuming the usual uncertainty bounds of +20%.

In Fig. 22 the schedule is presented for the development of the fusion materials irradiation test vehicle. The entire program from start of conceptual design until start up of the testing in EBR-II is expected to take 20 months. As seen in Fig. 22, because of the just completed rather extensive feasibility study, only a short two month conceptual design phase is indicated. The development, engineering, and design effort is projected to require 12 months with an overlapping procurement, fabrication, and assembly phase of 12 months. Since it is planned to construct a full-scale prototype out-of-reactor test loop, the shakedown and pre-operational testing in EBR-II will be minimal.

The projected resources required to meet the LTIV development schedule in Fig. 22 are shown in Table XXXV. A total cost of the engineering effort is estimated to be \$2648K. Cost and manpower breakdown estimates for the tasks identified in Fig. 22 are also shown in Table XXXV. A total of 84 man-months of engineering staff time, 18 man-months of designer time, and 36 man-months of technician time are indicated. Equipment costs (i.e., materials and fabrication) are estimated to be \$900K.

VIII. ACKNOWLEDGMENTS

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APPENDIX A
INTERESTED FLEXIBLE METAL TUBE VENDORS

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INTERESTED FLEXIBLE METAL TUBE VENDORS

American Boa, Inc.
P. O. Box 1301
Cumming, GA 30130
Ph: 404 889-9400
Fax: 404-8894661

Anamet, Inc.
698 S. Main St.
P.O. Box 2618
Waterbury, CT 06725
Ph: 203-574-8500
Fax: 203-573-1505

Hyspan Precision Products, Inc.
1685 Brandywine Ave.
Cula Vista, CA 91911
Ph: 619-421-1355
Fax: 619-421-1702

Parker Hannifin Corp., Parflex Div.
1300 N. Freedom St.
Ravenna, OH 44266
Ph: 216-296-2871
Fax- 216-296-8433

Swagelok Co.
31400 Aurora Rd.
Solon, OH 44139
Ph: 216-349-5934
Fax: 216-349-5843

Universal Metal Hose Co.
2133 S. Kedzie Ave.
Chicago, IL 60623-3393
Ph: 800-638-4673
Fax: 312-277-0727

Senior Flexonics, Inc.
300 East Devon Ave.
Bartlett, IL 60103
Ph: 708-837-1811
Fax: 708-213-3025

APPENDIX B
LTIV LITHIUM-TO-AIR HEAT EXCHANGER SPECIFICATIONS

LTIV LITHIUM-TO-AIR HEAT EXCHANGER SPECIFICATIONS

PERFORMANCE	PROCESS MEDIA	SERVICE MEDIA SIDE
Fluid Circulated	Lithium	Air
Volumetric Flow Rate	9.0 g/min	2050.0 scfm
Mass Flow Rate	2285.7 lbm/h	9224.3 lbm/h
Total Entering Vapor		9224.3 lbm/h
Noncondensibles		
Fluid Vaporized or Condensed		
Temperature In	471.0°F	80.0°F
Temperature Out	444.8°F	108.0°F
Inlet Pressure		14.7 psia
Velocity	0.8 ft/s	702.8 ft/min
Pressure Loss	0.3 psig	0.2 in. of water
Fouling Factor	0.0010 h-ft ² -°F/Btu	0.0001 h-ft ² -°F/Btu
Total Heat Exchanger: 61,878 Btu/h		
Media Properties		
Thermal Conductivity	25.3369 Btu/h-ft-°F	0.0154 Btu/h-ft-°F
Specific Heat	1.0338 Btu/lbm-°F	0.2400 Btu/lbm-°F
Viscosity	1.2345 lbm/ft-h	0.0457 lbm/ft-h
Density	31.6640 lbm/ft ³	0.0718 lbm/ft ³
Construction		
Design Temperature	800.0°F	Not Applicable
Design Pressure	150.0 psig	Not Applicable
Test Pressure	300.0 psig	Not Applicable
Flow Direction	Horizontal	Vertical Up
ASM Drawing No.: Approx. Weight:		
Fin-Tube Core: 304L Tube/304 Fin		Exhaust Hood: Galvanized Steel
Connections		
Process Inlet - 1 in. pipe stub		
Process Outlet - 1 in. pipe stub		
Mechanical Equipment		
Fan Diameter: 16 in.		Motor Size: 1/4 hp
Number of Fans: 1		Number of Motors: 1
Number of Blades: 3		Motor Speed: 1725 rpm
Blade Material: Aluminum		Motor Electrical: 230/460 V AC 60 Hz 3 ph
Fan Speed: 1725 rpm		Motor Enclosure: TIFC, STD. DUTY
Fan Guard: Coated Carbon Steel		Venturi Frame: Coated Carbon Steel
NOTES: These specifications supersede any which are different on drawing.		

APPENDIX C

LITHIUM PHYSICAL PROPERTY CORRELATIONS

The temperature dependent liquid lithium physical property data tabulated in Ref. C1 have been used to develop correlations for use in the loop design. The following physical properties were found tabulated in the reference source at four temperatures (i.e., 400, 600, 800, and 1000°F):

- Heat Capacity (Btu/lb-°F),
- Thermal Conductivity (Btu/h-ft-°F),
- Viscosity (lb/ft-h), and
- Density (lb/ft³).

These physical property data are plotted in Figs.C1 through C4 at the four temperatures using a straight line plotting program.

The Speakeasy program (Ref. C2) was used to obtain third-order polynomial fits to the four point temperature data for each of the lithium physical properties. Table C1 presents these program listings and coefficients that were obtained. The extremely good fit that was obtained (e.g., COR=1 and very small RES values for all of the cases) suggests that the reference tabulated data points (see property values in Table C1) represent already smooth and fitted data.

In addition to the above four physical lithium properties, the electrical resistivity of lithium and sodium over the temperature range of interest was also obtained and plotted in Fig. C5. The lithium resistivity, ρ_{Li} , curve is that from Ref. C3 and represents somewhat of an average correlation of the existing data (see Table XXIV):

$$\rho_{Li}(\mu\text{ohms-cm}) = 17.2 + 5.24\text{e-}02 T - 4.46\text{e-}05 T^2$$

The electrical resistivity in Ωm with T in $^{\circ}\text{C}$ for sodium, ρ_{Na} , was taken from Ref. C4:

$$\rho_{\text{Na}}(\text{ohms-m}) = 8.14\text{e-}08 + 2.27\text{e-}10T + 2.29\text{e-}13T^3.$$

The source of this expression for sodium was Ref. C5 with the electrical resistivity values essentially in agreement with those values tabulated by Golden and Tokar (see Ref. C6).

REFERENCES

- C1. M. Necati Ozisik, Basic Heat Transfer, McGraw-Hill Book Co., Inc., New York, NY (1977).
- C2. "Lectures on Speakeasy," Speakeasy Manual, Speakeasy Computing Corp., Chicago, IL (1984).
- C3. "The Electrical Resistivity of Lithium and Sodium-Potassium Alloy," Pratt & Whitney Aircraft, PWAC-349 (1961).
- C4. V. A. Maroni, E. J. Cairns, and F. A. Cafasso, "A Review of the Chemical, Physical, and Thermal Properties of Lithium That are Related to Its Use in Fusion Reactors," Argonne National Laboratory Report, ANL-8001 (March 1973).
- C5. "The Electrical Resistivity of Sodium, Potassium, Rubidium, and Cesium in the Liquid State," Pratt & Whitney Aircraft, PWAC-376 (1962).
- C6. G. H. Golden and J. V. Tokar, "Thermophysical Properties of Sodium," Argonne National Laboratory, ANL-7323 (August 1967).

APPENDIX D

TMOLL COMPUTER CODE

A steady-state computer model has been developed which simulates the thermal and hydraulic behavior of the lithium coolant in the in-reactor portion of the LTIV facility. This model, called TMOLL (thermohydraulic model of lithium loop), describes the axial and radial LTIV geometry in general terms which provides the user the flexibility to vary tube dimensions, region axial lengths and number of axial nodes. This computer model is essentially a formalization of the calculations performed in the preliminary scoping analysis in Sect. V.B. The major calculational results from TMOLL include the lithium axial temperature distribution, the heat exchange between EBR-II and the LTIV, and the pressure drops in the downcomer and upcomer flow annuli. The axial EBR-II sodium temperature distribution and core gamma heat rate along with physical property data are input into the program. Temperature dependent lithium properties can be employed as an option (see Appendix C). The program output includes all of the input data as well as a summary of the major calculational results. Extensive output data are also available in the form of axial tabular output. Several axial parameters are also made available in a tabular format (as an option) for later use as input to a plotting program.

The TMOLL program can be operated in either of two calculational modes: 1) with a constant lithium loop flow or 2) in an iterative lithium flow rate mode. In the first option, the lithium flow rate is provided as input and a single calculation is made of the loop conditions. The second type of iterative calculation requires a pump pressure head and ex-reactor loop pressure drop versus lithium flow rate relationship. With this input information, and starting from an assumed initial lithium flow rate, the lithium flow rate which just balances the pump pressure with the total loop pressure losses (within a given error, ϵ) is determined.

In the following sections a brief description of the TMOLL program is provided. A sample problem is provided as an example of the input requirements and the typical results that are obtained.

A. General Model Description

The starting point for the TMOLL calculation is at the bottom of the loop where the temperature of the downcomer and upcomer are assumed to be known (i.e. input parameter) and identical. With an assumed lithium mass flow rate, the energy balances for the lithium in the downcomer and upcomer are solved at each prescribed axial node as the calculation marches up the loop. Four distinct axial regions are considered: a lower region below the core, a core region, an intermediate region above the core, and an upper region. The first three regions all have identical geometry outside the central test container tube with the option of having a different upper region geometry which is required to describe a stepped tube design. Gamma heating in the steel is considered in the axial core region with an average gamma heating rate (in W/g) specified in the input. The energy exchange between the EBR-II sodium upper reactor region and the outer lithium upcomer annulus is calculated considering thermal radiation and thermal conduction across the outer argon insulation gap, the resistance of the flow housing and the thermal resistance of the lithium film on the inside of the flow housing. The energy transfer between the upcomer lithium and the downcomer lithium considers the thermal resistance of the flow divider as well as the temperature drop across the lithium films on either side of the flow divider. The pressure drop due to friction is also calculated for each axial downcomer and upcomer segment with the values summed to obtain the total integrated in-reactor pressure drop. Separate subroutines are provided to calculate the liquid metal heat transfer film coefficients, friction factors and incremental frictional pressure drop. A third subroutine estimates the physical properties of lithium as a function of temperature if this option is specified.

The TMOLL program can be run with either a known lithium flow rate or the lithium flow rate may be determined based on the converged pressure losses and pump head pressure gain. The pump head pressure model is described in the previous section (i.e., Model 2) and can be lithium temperature dependent (i.e., through the use of electrical resistivity function) if desired. Presently the ex-reactor loop pressure drop must also be provided as a function of lithium flow rate.

The output from the TMOLL program is quite extensive and includes a complete listing of all of the input data and control options that were user selected (e.g., variable lithium properties, axial results, plot data). The major integrated calculational results are also summarized. These results include inlet downcomer and exit upcomer lithium temperatures as well as pressure drops in each flow region, total heat transferred from EBR-II, heat transferred to the upcomer, heat transferred to the downcomer and the total gamma heat generated in the core region. As an option, axial lithium temperatures, heat fluxes, physical property values and flow parameters (e.g., Reynolds number, friction factors, film coefficients) are available in tabular output. Some of these axial parameters have been outputted to another file in a tabular format for transfer to an ANL-East plotting program (i.e., OSPPS).

A FORTRAN listing of the TMOLL computer program is provided in Appendix E.

B. Input Requirements

The TMOLL program is structured with no separate input file required to execute the program. This means that input changes must be made directly to the model's FORTRAN listing. The listing must therefore be recompiled before each separate run. As the program is quite short (~1500 lines with four subroutines), this introduces no major problem as the compilation time is usually less than a minute. All input parameters are defined in the first several pages of the TMOLL listing (see Appendix E). Comment statements have been liberally provided in the listing, in most cases, to clearly define the input parameters and program control options.

1. Geometry

The basic TMOLL program is based on the loop in-reactor configuration described in Sect. IV. A total of five concentric tubes comprise the loop in-reactor geometry. To account for the possibility of incorporating a stepped tube design into the loop concept (see Sect. V.B), allowance was made for considering two different tube geometries in the axial direction. In the axial direction there are four distinct regions: a lower region below the core, the core region,

an intermediate region above the core, and finally an upper region. All four regions must have the same inner sample capsule and test container diameters. The three lower regions have the same diameters for the remaining three tubes (i.e., flow divider, flow housing, and guide tube). The upper region may have a different set of diameters for these three tubes to allow the incorporation of a stepped tube loop design.

The TMOLL model allows a different thermal conductivity value to be used for the upper and lower flow-divider axial regions. This feature provides the capability to simulate an insulated upper region flow divider by allowing an "average" gas-type conduction thermal resistance across the sandwich-type flow divider gap to be input.

The lengths of each of the four axial regions (i.e., lower, core, intermediate, and upper) are specified in inch units. Also specified as input are the number of axial nodes (fixed point) in each of these regions. A maximum of 100 nodes (total) is presently the limit that can be specified. However, this limit can be easily changed if required.

Four other dimensions are required as input to the TMOLL program. These axial distances are required in the EBR-II sodium sink (or source) temperature determination. These axial locations, referenced from the bottom of the loop, and expressed in inch units are: distance to the bottom of the top reactor cover, distance to the top of the top reactor cover, distance to the bottom of the small rotating plug, and distance to the top of the small rotating plug. As identified below, EBR-II temperatures must be provided at these axial locations.

2. Temperatures and Initial Conditions

Probably the two most important parameters required in the TMOLL code are the lithium temperature (in °F) at the bottom of the loop and the loop lithium flow rate in gallons per minute (gpm). The bottom loop lithium temperature is that temperature which represents the common downcomer and upcomer temperature. It is the starting temperature for the thermal calculation and at the typical EBR-II gamma heating rates is pretty close to the test sample lithium

core temperatures (within $\sim 10^{\circ}\text{F}$). The loop volumetric flow rate (in gpm) is assumed to be at this bottom lithium temperature.

If the flow rate iterative calculation option is selected, an assumed lithium flow rate is still required as the initial calculational guess. In this option, polynomial coefficients are required as a function of lithium flow rate for the pump head and ex-reactor pressure drop. A pressure differential epsilon (i.e., pressure differential between pressure losses and pressure pump head) is required as input along with a maximum number of iterations limit for this calculational option. The converged lithium flow rate is determined based on an extrapolation iterative routine or algorithm which is employed to determine the zero of the implicit functional problem.

The EBR-II sink/source temperatures are also input. The EBR-II sodium inlet temperature (e.g., 700°F) is applied to the lower loop region. The outlet sodium temperature, in $^{\circ}\text{F}$, from the EBR-II core is also provided (e.g., 883°F). The sink temperature in the loop core region is obtained by a linear interpolation between these inlet and outlet temperature values. The outlet EBR-II core temperature is assumed to exist up to the bottom of the top reactor cover. The temperature at the top of the top reactor vessel cover (e.g., 700°F) is input with linear interpolation again applied over the top reactor vessel cover axial region. The temperature at the top of the top reactor cover is assumed to exist all the way up to the bottom of the small rotating plug. The last EBR-II temperature required is the value at the top of the small rotating plug (e.g., 80°F). Across this plug, linear interpolation of the bottom and top temperatures are conducted. The top of the small rotating plug temperature is applied from this axial location to the top of the loop.

Other initial input parameters are associated with the gamma heating and the thermal radiation model. The average gamma heat rate (in the units of W/g of stainless steel) is required along with the volume fraction of stainless steel in the test capsule core region. This heating rate is applied only over the axial core region with the heating rate calculated for the test container, flow divider, and flow housing tubes as well as the test capsule. This heat generation is removed by both the downcomer as well as the upcomer flowing lithium. The thermal radiation

model across the argon outer insulation gap requires the value for the inner and outer stainless-steel emissivities which are also provide as input.

The absolute pressure level in the lithium coolant at the inlet to the in-reactor loop downcomer region is a parameter which is also required in the initial input data set. This pressure level along with the calculated incremental pressure drop is used to determine the absolute pressure level within the in-reactor loop.

3. Physical Property Data

Thermophysical data are needed in the thermal and hydraulic models in order to describe the lithium coolant, stainless-steel structure tubes, and the argon gas in the outer insulation gap. For the lithium coolant an option is available (see control options below) to have these properties calculated as a function of temperature directly by the program. Typical temperature dependent lithium physical property correlations are presented in Appendix C. All of these properties are assumed to be in English units with for lithium and argon needed are values for density, thermal conductivity, heat capacity and viscosity. In addition an electrical resistivity temperature dependent correlation is necessary for the lithium flow rate iteration calculation along with the reference resistivity value for the supplied pump pressure head relationship. The stainless-steel property table, of course, does not require a value for viscosity, however, a different value for the thermal conductivity of the upper region's flow divider may be specified in order to treat the design case where an insulated upper flow divider is incorporated into the loop design.

4. Control Options

Four program control options must be selected or specified by the user. These parameters, in fixed point format, decide whether to: 1) iterate on the lithium flow rate, 2) print out a detailed axial output of results, 3) create a plot file for future input into a plotting program, and 4) consider the lithium properties to be temperature dependent or constant. A zero signifies

a yes answer for each of the four options. The plotting file is printed out into a separate output file (i.e., fort.9) whereas the axial tabular results are merely an extension of the standard TMOLL output file (i.e., fort.7). The temperature dependent lithium properties are determined in a separate subroutine--based upon the supplied polynomial fits (e.g., see Appendix C).

For the situation where the lithium flow rate iteration option is selected, a nonzero flow rate must still be supplied for the initial guess. A maximum number of iterations (typically 25 although most calculations require ~ 5 iterations for convergence) is also required along with the pressure differential convergence criteria (e.g., ϵ of typically 0.01 psi). The pressure differential (e.g., difference between pressure losses and pump pressure head) is determined after each calculational sweep through the loop model.

Rather than go through the detail specification of the input data that is available from the TMOLL program, a sample problem along with its input is provided in Sect. E of this appendix.

C. TMOLL Model Description

The steady-state TMOLL model solves an energy balance at each axial node, starting at the loop bottom, marching up in one sweep to the top of the loop, as defined by the input geometry. The lithium flows are assumed to be counter current with the loop inlet loop lithium stream assumed to be the inner downcomer with the lithium flowing upward in the exiting upcomer stream. A frictional pressure drop is calculated over each axial node in both the downcomer and upcomer flow paths. Arrays are provided for storage of most of the axially nodal dependent calculational results for later printing if desired. Presently the size of these arrays are limited to 100 axial entries for each space dependent parameter.

When the lithium flow iteration option is invoked, the pressure differential between pressure losses and pump head is determined and compared to the ϵ convergent criterion. If the calculated differential exceeds the absolute value of ϵ , then a new loop lithium flow rate is

estimated and the thermal-hydraulic calculational sweep through the loop is repeated. The new lithium flow rate estimate is based on an extrapolation method for determining the zero of the implicit functional. This calculational iterative process is repeated until convergence is obtained or the number of iterations exceeds the maximum number as specified in the input.

The initial model calculations determine the needed geometric information (e.g., surface areas, volumes, flow areas) based on the input tube diameters and axial region lengths. The lithium volumetric flow rate is converted to a mass flow rate (e.g., in units of lb/h) which is treated as a constant throughout each single sweep calculation. Various other initialization calculations are performed (e.g., interpolating the EBR-II temperatures at each axial node, and redistributing the gamma heat generation to the downcomer and upcomer flows) and values for the geometry dependent thermal resistances are established.

With the initial geometric and boundary temperature preparation completed, the actual thermal-hydraulic calculations begin starting at the loop bottom with the lower region. The energy balance at each node is solved with the calculation marching up the loop. The heat transfer calculation for each axial node is based on the known temperatures at the bottom of the axial increment. This approximation is felt to be justified based on the gradual change in the temperature as one progresses up the loop. The heat transfer from the known EBR-II temperature to the upcomer lithium considers both thermal conduction as well as thermal radiation across the outer annular argon gap. The thermal resistance of the outer guide tube and flow housing as well as the lithium film on the inside of the flow housing are incorporated in the model. The heat transfer from the upcomer lithium to the adjacent downcomer lithium fluid considers the lithium film resistance on each side of the flow divider as well as the thermal resistance of the flow divider tube. The lithium heat transfer film coefficients are calculated in a separate subroutine (LICOEF). In this model, axial heat transfer is neglected and no radial temperature rise calculation across the sample capsule is attempted. A direct result of the energy balance is the lithium temperatures--which in the case of the downcomer is into the axial segment, and in the case of the upcomer is out of the axial segment.

If temperature dependent lithium are specified they are calculated in a separate subroutine (LIPROP) which incorporates a polynomial curve fit of tabulated literature data (e.g., see Appendix C). The properties are based on the lithium temperatures calculated at the end of the previous axial segment.

The frictional pressure drop across each axial node is calculated for the lithium flowing in both the downcomer as well as in the upcomer. A call to a separate subroutine (LIFRIC) is used to produce the friction factor and the incremental frictional pressure drop. No turning or form losses are calculated presently in the TMOLL model.

In addition to incremental pressure drop and heat transfer, several integrated parameters are determined by summing the incremental quantities. These integrated results include the downcomer and upcomer pressure drop, the total gamma heat generation, and the total heat transferred from EBR-II to the loop. The absolute pressure level at each axial elevation in the in-reactor loop is determined relative to an user supplied pressure at the inlet to the loop downcomer region.

D. Program Output

The output from the TMOLL program consists of several possible options. A standard output consists of a listing of all pertinent input parameters and a summary of results which tabulates the major results (e.g., inlet and outlet lithium temperatures, summary of pressure drops, and a summary of the integrated heat exchanged and gamma heat generation totals). In addition to these summary results, the capability exists (based upon control option selection) to obtain a detailed axial output of the incremental and integrated calculated quantities. These axial results are provided in three tables: one table provides the nodal temperature and heat transfer information for both the downcomer and upcomer flows, the second and third tables provide the axial flow results (i.e., friction factor, pressure drop) and lithium physical property data for the downcomer and upcomer flow channels respectively. The third output option allows the user to write the axial data of temperatures, heat flows, and pressure drops onto a separate file (named

fort.9) for future use in a plotting program. The current plotting program in use in ANL/RE is the ANL/TREAT developed OSPPS program.

Rather than go through the detail specification of the output data that is available than from the TMOLL program, a sample problem along with its output is provided in the next section.

E. Sample TMOLL Problem

The features of the TMOLL program are best illustrated by means of a sample problem. As an example, the Case 3 geometry presented in Sect. V.B. was simulated. This case is the loop with a stepped upper region tube design. A constant lithium loop flow rate of 10 gpm was assumed (i.e., noniteration mode) along with a desired 550°F combined lithium temperature at the bottom of the loop (i.e., downcomer and upcomer temperatures are equal to 550°F at this location). (Note that the 10 gpm flow rate is referenced to this temperature.) The results of the TMOLL calculation are provided in Tables D1 and D2, in Figs. 18 through 24 and Appendix F. The standard and axial tabular output results are printed to file fort.7 (Tables D1 and D2) whereas the axial data required for OSPPS program plotting are printed out to file fort.9 (see listing in Appendix E).

The summary output from the TMOLL calculation is summarized in Tables D1 and D2 which represent the "short" or standard printout. In Table D1, all of the pertinent input data are tabulated. The computer name for each variable are provided in most instances along with its dimensions. At the top of the output the run date and program start time are printed-out. For this calculation 95 axial nodes were used to describe the four axial regions (e.g., 5 in the lower region, 10 in the core region, 40 in the intermediate region, and 40 in the upper region). Also note that three options were activated in the control option selection (i.e., axial prints, plot data and variable lithium properties were selected). The EBR-II environment temperatures and the axial locations at which they occur are also tabulated. As Table D1 illustrates, the gamma heating rate has been specified as 4.62 W/g of stainless steel with the sample capsule's volume fraction assumed to be 0.50.

The standard TMOLL calculational output of results are shown in Table XXVI. The geometry calculational results for each flow region are summarized. These results agree with those tabulated for Case 3 in Table XVIII in Sect. V.B. The summary of major results include the inlet downcomer temperature (388°F), exit upcomer (409°F), total loop pressure drop (53.2 psi), total gamma heat generation [4.06E+04 Btu/h (~ 11.9 kW)] and heat transferred from EBR-II [1.35E+04 Btu/h (~ 4 kW)]. Other heat balance results and lithium mass flow rate information are also provided in this standard output as seen in Table D2.

While the loop design calculations are only in their preliminary stage, the Case 3 stepped tube results, as illustrated in Table D2, are quite interesting. The inlet downcomer lithium temperature must be reduced to ~388°F in order to achieve a sample test temperature of ~550°F. Since this is ~33°F above the lithium melt temperature of 355°F, the reference sample temperature does not appear to be achievable with the present design configuration. One possible solution would be to provide an insulated flow divider between the downcomer and upcomer flows. This design alternative seems feasible at least in the upper region where the stepped tube concept provides some additional area in the radial direction. The potential benefits of an insulated upper flow divider are explored in the next section (see Sect. V.E).

The detailed TMOLL axial thermohydraulic results are provided in Appendix F as determined by the input control parameter selection process (MIT=0). Essentially four tabular sets of information are provided. In the first set, tabulated at each axial node, are the thermal heat balance results for both the downcomer and upcomer flow regions. In the second and third sets of tabular printout, the hydraulic and physical property information are provided for both the downcomer and upcomer, respectively. The fourth set of data tabulates the gamma heating results obtained for the axial core nodes. At the beginning of all four tables, a parameter key is provided defining each parameter along with their dimensional units. The distinct loop axial regions have also been identified for user orientation.

Figures 18 through 24 illustrate the axial TMOLL results as plotted from the plot data printed in file fort.9 as specified by setting control option NIT equal to zero. These plots

used the tabular format of the OSPPS plotting program developed at ANL-East. All of these variables are found in the axial tabular output in Appendix F. The first three figures (Figs. 18 through 20) are temperature plots, with Fig. 18 showing the axial profile of the EBR-II source/sink temperature, and Figs. 19 and 20 showing the lithium axial temperature profiles in the downcomer and upcomer flow regions. Figure 20 is a close-up of Fig. 19 results but focusing just around the loop test sample core region.

Figures 21 and 22 provide the axial traces of the inside (upcomer-to-downcomer) overall film heat transfer coefficient and outside (EBR-II to upcomer) overall film heat transfer coefficient, respectively.

In Fig. 23, the integrated heat transfer from EBR-II to the loop are shown as a function of axial length from the bottom of the loop. The change from a heat gain in the loop to a heat loss at ~ 25 ft from the loop bottom as the EBR-II environment temperature changes to 80°F is evident.

The integrated pressure drop in both the downcomer and upcomer regions are plotted in Fig. 24 as a function of distance from the loop bottom. The change in the pressure drop slope in the downcomer reflects the larger flow annulus in the upper loop region due to the stepped tube design. It should be recognized that these losses shown in Fig. 24 do not reflect the absolute pressure level at each loop elevation. To obtain this absolute pressure level, these drops would have to be referenced to the downcomer pressure value at the inlet elevation.

F. Model Summary

A computer model (TMOLL) has been written which describes the thermohydraulic conditions of the lithium coolant in the in-reactor loop. The downcomer and upcomer lithium flow paths are broken up into discrete axial nodes and the energy balances solved. The heat transfer from the EBR-II environment along with the gamma heat generation within the core region are incorporated into the model. The major results of this steady-state one-dimensional

model are the lithium temperature and pressure drops within the downcomer and upcomer flow annuli for an assumed lithium flow rate and bottom lithium temperature. An iterative calculational option is available which determines the loop lithium flow rate, if desired, that balances the loop pressure losses with the assumed pump pressure head.

The TMOLL computer model results have been presented to illustrate the input data requirements and the type of output results which are obtained. The program represents a calculational capability which allows the designer to assess quickly the effects of loop design modifications on performance. A FORTRAN listing of the TMOLL computer code is presented in Appendix E.

APPENDIX E
TMOLL COMPUTER CODE FORTRAN LISTING

```

C      PROGRAM TMOL
C      THERMAL-HYDRAULIC MODEL FOR IN-REACTOR LTIV FACILITY IN EBR-II
C      CONTROL ROD CHANNEL. HAS REVISED PUMP HEAD MODEL (6/14/94).
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      THIS CODE CALCULATES THE LITHIUM TEMPERATURE IN THE TWO INPILE LTIV
C      FLOW ANNULI. THE MODEL CONSIDERS GAMMA HEATING IN TEST & STRUCTURES
C      AND THE HEAT GAIN FROM THE EBR-II SODIUM. CALC ALSO ARE THE PRESSURE
C      IN THE DOWNCOMER & UPCOMER AS WELL AS AN ESTIMATE IS MADE FOR
C      THE EXTERNAL LOOP PRESSURE DROP. THE ALIP PRESS HEAD IS CALC
C      AND IF DESIRED A SEARCH IS CONDUCTED FOR THE CONVERGENT FLOW RATE.
C
C      COMMON EDDL,EDDU,EDUL,EDUU,VDL,VDU,PR,VISL,
C      1TKL,SEV,CH,EX
C
C      COMMON DELL,DELC,DELI,DELU,CFRC
C
C      DIMENSION DT(3),DL(7),DU(7),ADT(3),ADL(7),ADU(7),VDT(3),VDL(6)
C      1,VDU(6),GTT(3),GTL(6),GTU(6),HR(100),UO(100),QO(100),UI(100)
C      2,QD(100),QU(100),TU(100),TD(100),Z(100),QGD(100),QGU(100),HT(100)
C      3,QDT(100),QUT(100),QOT(100),QDG(100),QUG(100),QGT(100),TEBR2(100)
C
C      DIMENSION CPD(100),TKD(100),VISD(100),DEND(100),TFRD(100),
C      1GFRD(100),REYD(100),HFD(100),CPU(100),TKU(100),VISU(100),
C      2DENU(100),TFRU(100),GFRU(100),REYU(100),HFU(100),FFD(100),
C      3FFU(100),DELPD(100),DELPD(100),PRESU(100),PTOPD(100),
C      4PTOPU(100),COEF(4),CHD(5),G(25),P(25),PH(25),DP(25),PL(25),RES(25)
C
C      COEF(I) ARE POLYNOMIAL COEFF FOR EXTERNAL LOOP PRESSURE DROP V.S.
C      GPM CURVE
C
C      CHD(I) ARE POLYNOMIAL COEFF FOR PUMP HEAD V.S. GPM CURVE. FIRST
C      SET OF DATA IS FOR TREAT ALIP & SECOND SET IS FOR DUAL TREAT ALIP.
C
C      REF EX-REACTOR PRESS DROP COEFF
C
C      DATA (COEF(I),I=1,4) /-0.38193,0.33385,0.088823,-4.8858E-04/
C
C      COEFFS FOR 25% INCREASE IN REF EX-REACTOR PRESS DROP
C
C      DATA (COEF(I),I=1,4) /-0.3491,0.37481,0.11492,-7.1517E-04/
C
C      COEFFS FOR 25% DECREASE IN REF EX-REACTOR PRESS DROP
C
C      DATA (COEF(I),I=1,4) /-0.20916,0.22699,0.068655,-4.1971E-04/
C
C      PUMP HEAD COEFFS. FOR SINGLE TREAT ALIP(1st @ 40amps,2nd @ 25amps)
C
C      DATA (CHD(I),I=1,4) /61.281,0.024325,-0.061212,9.273E-04/
C      DATA (CHD(I),I=1,4) /36.669,-0.16233,-0.034828,8.4945E-04/
C      DATA (CHD(I),I=1,4) /31.633,-0.1382,-0.030118,7.2995E-04/
C
C      PUMP HEAD COEFFS. FOR SINGLE TREAT ALIP & REF RESISTIVITY (MOHM-CM)
C      DATA (CHD(I),I=1,5) /49.548,-.21692,-.047328,.0011548,18.2573/
C
C      PUMP HEAD COEFFS. FOR DUAL TREAT ALIP(1st @40amps,2nd @ 25amps)
C
C      DATA (CHD(I),I=1,4) /103.69,-0.701,-0.023267,-0.0014928/
C      DATA (CHD(I),I=1,4) /63.856,-0.20783,-0.055624,6.9/68E-04/
C      DATA (CHD(I),I=1,4) /55.097,-0.17831,-0.048106,6.0562E-04/
C
C      PUMP HEAD COEFFS. FOR DUAL TREAT ALIP & REF RESISTIVITY (MOHM-CM)

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C      DATA (CHD(I),I=1,5) /86.29,-.27949,-.07533,9.4791E-04,18.2573/
C      DATA (CHD(I),I=1,5) /86.29,-.27949,-.07533,9.4791E-04,0.000/
C
C      INTEGER IARRAY(3)
C
C      GET DATE & TIME AND PRINT INITIAL INFO
C
C      WRITE(7,80)
C      80 FORMAT(58X,'PROGRAM TMO15'//,48X,
C      1'THERMOHYDRAULIC MODEL OF INREACTOR'//,
C      244X,'LOW TEMPERATURE IRRADIATION VEHICLE (LTIV)',1X/1X/)
C
C      CALL IDATE(IARRAY)
C      WRITE(7,111) IARRAY(2),IARRAY(1),IARRAY(3)
C      111 FORMAT(//,5X,'RUN DATE: ',I3,'/',I3,'/',I4)
C      CALL ITIME(IARRAY)
C      WRITE(7,112) IARRAY(1),IARRAY(2),IARRAY(3)
C      112 FORMAT(5X,'START TIME: ',I3,' HRS',I3,' MIN',I3,' SEC')
C
C      GEOMETRY DEFINITIONS
C
C      CORE & LOWER & UPPER REGION
C
C      DT(1)=O.D. OF SAMPLE CAPSULE, INCHES
C      -I.D. OF ARGON CLEARANCE GAP, INCHES
C      DT(2)=O.D. OF ARGON CLEARANCE GAP, INCHES
C      -I.D. OF TEST CONTAINER, INCHES
C      DT(3)=O.D. OF TEST CONTAINER, INCHES
C
C      ADT(1)=SURFACE AREA OUTER SAMPLE CAPSULE, FT2/FT
C      -SURFACE AREA INNER ARGON GAP A, FT2/FT
C      ADT(2)=SURFACE AREA OUTER ARGON GAP A, FT2/FT
C      -SURFACE AREA INNER-TEST CONTAINER, FT2/FT
C      ADT(3)=SURFACE AREA OUTER-TEST CONTAINER, FT2/FT
C
C      VDT(1)=VOLUME SAMPLE CAPSULE, FT3/FT
C      VDT(2)=VOLUME ARGON GAP-A, FT3/FT
C      VDT(3)=VOLUME TEST CONTAINER, FT3/FT
C
C      LOWER REGION
C
C      DL(1)=I.D. OF DOWNFLOW ANNULUS, INCHES
C      DL(2)=O.D. OF DOWNFLOW ANNULUS, INCHES
C      -I.D. OF FLOW DIVIDER, INCHES
C      DL(3)=O.D. OF FLOW DIVIDER, INCHES
C      -I.D. OF UPFLOW ANNULUS, INCHES
C      DL(4)=O.D. OF UPFLOW ANNULUS, INCHES
C      -I.D. OF FLOW HOUSING TUBE, INCHES
C      DL(5)=O.D. OF FLOW HOUSING TUBE, INCHES
C      -I.D. OF ARGON INSULATION GAP-D, INCHES
C      DL(6)=O.D. OF ARGON INSULATION GAP-D, INCHES
C      -I.D. OF OUTSIDE GUIDE TUBE, INCHES
C      DL(7)=O.D. OF OUTSIDE GUIDE TUBE, INCHES
C
C      ADL(1)=ADT(3)-SURFACE AREA INNER-DOWNFLOW REGION, FT2/FT
C      ADL(2)=SURFACE AREA OUTER-DOWNFLOW REGION, FT2/FT
C      -SURFACE AREA INNER-FLOW DIVIDER, FT2/FT
C      ADL(3)=SURFACE AREA OUTER-FLOW DIVIDER, FT2/FT
C      -SURFACE AREA INNER-UPCOMER REGION, FT2/FT
C      ADL(4)=SURFACE AREA OUTER-UPCOMER REGION, FT2/FT
C      -SURFACE AREA INNER-FLOW HOUSING, FT2/FT
C      ADL(5)=SURFACE AREA OUTER-FLOW HOUSING, FT2/FT
C      -SURFACE AREA INNER-ARGON INSULATION GAP-D, FT2/FT
C      A(6)=SURFACE AREA OUTER-ARGON INSULATION GAP-D, FT2/FT

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C -SURFACE AREA INNER-GUIDE TUBE, FT2/FT
 C ADL(7)=SURFACE AREA OUTER-GUIDE TUBE, FT2/FT
 C
 C VDL(1)=VOLUME DOWNFLOW GAP, FT3/FT
 C VDL(2)=VOLUME FLOW DIVIDER, FT3/FT
 C VDL(3)=VOLUME UPCOMER GAP, FT3/FT
 C VDL(4)=VOLUME FLOW HOUSING, FT3/FT
 C VDL(5)=VOLUME ARGON INSULATION GAP-D, FT3/FT
 C VDL(6)=VOLUME GUIDE TUBE, FT3/FT
 C
 C UPPER REGION
 C
 C DU(1)=I.D. OF DOWNFLOW ANNULUS, INCHES
 C DU(2)=O.D. OF DOWNFLOW ANNULUS, INCHES
 C -I.D. OF FLOW DIVIDER, INCHES
 C DU(3)=O.D. OF FLOW DIVIDER, INCHES
 C -I.D. OF UPFLOW ANNULUS, INCHES
 C DU(4)=O.D. OF UPFLOW ANNULUS, INCHES
 C -I.D. OF FLOW HOUSING TUBE, INCHES
 C DU(5)=O.D. OF FLOW HOUSING TUBE, INCHES
 C -I.D. OF ARGON INSULATION GAP, INCHES
 C DU(6)=O.D. OF ARGON INSULATION GAP, INCHES
 C -I.D. OF OUTSIDE GUIDE TUBE, INCHES
 C DU(7)=O.D. OF OUTSIDE GUIDE TUBE, INCHES
 C
 C ADU(1)=ADT(3)=SURFACE AREA INNER-DOWNFLOW REGION, FT2/FT
 C ADU(2)=SURFACE AREA OUTER-DOWNFLOW REGION, FT2/FT
 C -SURFACE AREA INNER-FLOW DIVIDER, FT2/FT
 C ADU(3)=SURFACE AREA OUTER-FLOW DIVIDER, FT2/FT
 C -SURFACE AREA INNER-UPCOMER REGION, FT2/FT
 C ADU(4)=SURFACE AREA OUTER-UPCOMER REGION, FT2/FT
 C -SURFACE AREA INNER-FLOW HOUSING, FT2/FT
 C ADU(5)=SURFACE AREA OUTER-FLOW HOUSING, FT2/FT
 C -SURFACE AREA INNER-ARGON INSULATION GAP-D, FT2/FT
 C ADU(6)=SURFACE AREA OUTER-ARGON INSULATION GAP-D, FT2/FT
 C -SURFACE AREA INNER-GUIDE TUBE, FT2/FT
 C ADU(7)=SURFACE AREA OUTER-GUIDE TUBE, FT2/FT
 C
 C VDU(1)=VOLUME DOWNFLOW GAP, FT3/FT
 C VDU(2)=VOLUME FLOW DIVIDER, FT3/FT
 C VDU(3)=VOLUME UPCOMER GAP, FT3/FT
 C VDU(4)=VOLUME FLOW HOUSING, FT3/FT
 C VDU(5)=VOLUME ARGON INSULATION GAP-D, FT3/FT
 C VDU(6)=VOLUME GUIDE TUBE, FT3/FT
 C
 C PROBLEM CONSTANTS
 C
 C ONE=1.0000D 00
 C ZERO=0.0000D 00
 C RC=0.173D-08
 C PI=3.1415926D 00
 C HALF= 0.500D 00
 C TWO = 2.000D 00
 C FOUR = 4.000D 00
 C TRANK = 459.7
 C TWEL =12.00D 00
 C SQCF = 144.00D 00
 C PCF=3.412141D 00
 C THRSY = 3.6000D 00
 C SIXTY = 6.0000D 01
 C GAL = 7.480519D 00
 C WCF=453.59237D 00
 C SEV=7.0000D 00
 C CH=0.0250D 00

EX=0.80000D 00
 CFRAD=TWO*TWEL.
 CFRC=(TWO/SQCF)/4.17312D 08
 SH=3.6000D 03
 C
 C INPUT LIQUID LITHIUM PROPERTIES (T= 500F) IN ENGLISH UNITS
 C
 C DENL=31.325
 C TKL = 25.85
 C CPL = 1.0313
 C VISL = 1.195
 C
 C INPUT ARGON GAS PROPERTIES (T= 600F) IN ENGLISH UNITS
 C
 C DENA = 0.0492
 C TKA = 0.0172
 C CPA = 0.124
 C VISA = 0.0905
 C
 C INPUT STAINLESS STEEL PROPERTIES (T =75F) IN ENGLISH UNITS
 C
 C DENS = 498.
 C TKS = 9.0 D 00
 C CPS = 0.1200D 00
 C
 C INPUT UPPER REGION FLOW DIVIDER THERMAL CONDUCTIVITY (BTU/HR/FT/F)
 C
 C TKFD = 0.05500D 00
 C
 C INPUT INITIAL CONDITIONS
 C
 C TEBRL = EBR-II INLET TEMP (DEG.F)
 C TEBRU = EBR-II OUTLET TEMP (DEG. F)
 C TI = LTIV LOWER LOOP LITHIUM TEMP (DEG. F)
 C TTOPC = VESSEL COVER TOP TEMP (DEG. F)
 C TTOPP = SMALL PLUG TOP TEMP (DEG. F)
 C
 C QG = GAMMA HEATING (AVG) IN WATTS/GM
 C VFCAP = VOLUME FRACTION SS IN TEST CAPSULES
 C E1 = EMISSIVITY OF FLOW HOUSING TUBE
 C E2 = EMISSIVITY OF GUIDE TUBE
 C VFLO = INITIAL LTIV LITHIUM FLOW RATE (GPM)
 C PRESI = LI PRESSURE AT DOWNCOMER INLET (PSI)
 C
 C
 C TEBRL=700.0
 C TEBRU=883.0
 C TI = 550.0
 C TTOPC= 700.000D 00
 C TTOPP= 80.000D 00
 C QG = 4.62
 C VFCAP=0.50000D 00
 C E1 = 0.79
 C E2 = 0.79
 C VFLO = 15.0
 C PRESI = 100.0
 C
 C INPUT PROBLEM CALCULATIONAL CONTROL PARAMETERS
 C
 C DEFINE FOUR AXIAL DISTINCT REGIONS WITH FOLLOWING NUMBER OF NODE:
 C NI= LOWER CORE REGION -LOWER REG DIMENSIONS & NO GAMMA HEATING
 C NC= CORE REGION-LOWER REG DIMENSIONS & GAMMA HEATING
 C NI= INTERMEDIATE REGION-LOWER REG DIMENSIONS & NO GAMMA HEATING
 C NU= UPPER REGION-UPPER REG DIMENSIONS & NO GAMMA HEATING

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C   MIT= PRINT PLOT DATA (MIT = 0 YES)
C   NIT= PRINT AXIAL DATA (NIT = 0 YES)
C   MPH= VARIABLE LITHIUM PROPERTIES (MPH = 0 YES)
C   NMAX= MAXIMUM NUMBER OF FLOW ITERATIONS
C   NTYPE= FLOW ITERATION CALC (NTYPE = 0 YES)
C   EPS= PRESSURE DIFFERENCE CONVERGENCE CRITERIA (PSI)
C
C   NL = 5
C   NC = 10
C   NI = 40
C   NU = 40
C   MIT = 1
C   NIT = 1
C   MPH = 0
C   NMAX=20
C   NTYPE=0
C   EPS=0.01
C
C   INPUT GEOMETRY OF LTIV IN-REACTOR
C   (DISTANCES ARE DELTAS OR REGION LENGTHS IN INCHES)
C
C   AXIAL LTIV REGION LENGTHS (INCHES)
C   DDL= LOWER REGION LENGTH
C   DDC= CORE REGION LENGTH
C   DDI= INTERMEDIATE REGION LENGTH
C   DDU= UPPER REGION LENGTH
C
C   AXIAL DISTANCES FROM LOOP BOTTOM (INCHES)
C   DBOTC= DISTANCE TO BOTTOM OF TOP COVER
C   DTOPC= DISTANCE TO THE TOP OF TOP COVER
C   DBOTP= DISTANCE TO BOTTOM OF SMALL PLUG
C   DTOPP= DISTANCE TO TOP OF SMALL PLUG
C
C   DDL = 24.562 D 00
C   DDC = 13.500 D 00
C   DDI = 191.657 D 00
C   DDU = 233.640 D 00
C
C   DBOTC=91.590D 00
C   DTOPC=119.593D 00
C   DBOTP=254.218D 00
C   DTOPP=351.718D 00
C
C   CALC AXIAL DISTANCES RELATIVE TO BOTTOM OF FACILITY IN INCHES
C
C   ZSP = 229.719 D 00
C
C   ZL = DDL
C   ZC = ZL + DDC
C   ZI = ZC + DDI
C   ZU = ZI + DDU
C
C   INPUT RADIAL DIAMETER DIMENSIONS OF LTIV IN INCHES
C
C   DT(1)=1.000D 00
C   DT(2)=1.120D 00
C   DT(3)=1.250D 00
C
C   DL(1)=DT(3)
C   DL(2)=1.370D 00
C   DL(3)=1.500D 00
C   DL(4)=1.685D 00
C   DL(5)=1.875D 00
C   DL(6)=2.000D 00

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DL(7)=2.125D 00
DU(1)=DT(3)
DU(2)=1.416D 00
DU(3)=1.750D 00
DU(4)=1.935D 00
DU(5)=2.125D 00
DU(6)=2.260D 00
DU(7)=2.500D 00
C
C   CALC SURFACE AREAS (DIMENSION IN FT2/FT)
C
C   DO 10 I=1,3
10  ADT(I)=PI*DT(I)/TWEL
C   ADL(1)=ADT(3)
C   DO 12 I=2,7
12  ADL(I)=PI*DL(I)/TWEL
C   ADU(1)=ADT(3)
C   DO 14 I=2,7
14  ADU(I)=PI*DU(I)/TWEL
C
C   CALC VOLUMES (DIMENSIONS IN FT3/FT)
C
C   VOLCF=FOUR*SQCF
C   VDT(1)=PI*(DT(1)**TWO)/VOLCF
C   DO 16 I=2,3
16  VDT(I)=PI*(DT(I)**TWO-DT(I-1)**TWO)/VOLCF
C   DO 18 I=1,6
18  VDL(I)=PI*(DL(I+1)**TWO-DL(I)**TWO)/VOLCF
C   DO 20 I=1,6
20  VDU(I)=PI*(DU(I+1)**TWO-DU(I)**TWO)/VOLCF
C
C   CALCULATE GAP THICKNESS OF MEMBERS IN INCHES & PRINT RADIAL GEOM
C
C   GTT(1)=DT(1)/TWO
C   WRITE(7,28) 1,DT(1),ADT(1),VDT(1),GTT(1)
C   DO 22 I=2,3
C   GTT(I)=(DT(I)-DT(I-1))/TWO
C   WRITE(7,28) I,DT(I),ADT(I),VDT(I),GTT(I)
22  CONTINUE
C   DO 24 I=1,6
C   GTL(I)=(DL(I+1)-DL(I))/TWO
C   WRITE(7,28) I,DL(I),ADL(I),VDL(I),GTL(I)
24  CONTINUE
C   DO 26 I=1,6
C   GTU(I)=(DU(I+1)-DU(I))/TWO
C   WRITE(7,28) I,DU(I),ADU(I),VDU(I),GTU(I)
26  CONTINUE
C
C   CALCULATE INITIAL PARAMETERS FOR THERMAL CALC
C
C   DNL=FLOAT(NL)
C   CNC=FLOAT(NC)
C   UNI=FLOAT(NI)
C   UNU=FLOAT(NU)
C
C   DELL=DDL/(DNL*TWEL)
C   DELC=DDC/(CNC*TWEL)
C   DELI=DDI/(UNI*TWEL)
C   DELU=DDU/(UNU*TWEL)
C
C   ARL=ADL(5)/ADL(6)
C   ARU=ADU(5)/ADU(6)

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      IF (E1 .LE. ZERO .AND. E2 .I.E. ZFRO) THEN
      FEL = ZERO
      FEU = ZERO
      ELSE
      FEL=ONE/(ONE/E1+ARL*(ONE/E2-ONE))
      FEU=ONE/(ONE/E1+ARU*(ONE/E2-ONE))
      END IF

C      HCONL=TKA*TWEL/GTL(5)
C      HCONU=TKA*TWEL/GTU(5)

C
C      DEFINE NODES FOR DO LOOP ITERATIONS
C
      ICI=NL+1
      ICF=NL+NC
      III=ICF+1
      IIF=ICF+NI
      IUI=IIF+1
      IUF=IIF+NU

      G(1)=VFLO
      J=1
      IF (NTYPE .NE. 0) GO TO 255

C
C      BEGIN SEARCH CALC FOR CONVERGED LI LOOP FLOW RATE
C
      DO 501 J=1,NMAX

C      CONVERT LITHIUM FLOW IN GPM TO LBS/HR
C

255 CONTINUE

      IF (MPH .NE. 0) GO TO 201
      CALL LIPROP(TI,CPL,TKL,VISL,DENL)
      CPD(1)=CPL
      TKD(1)=TKL
      VISD(1)=VISL
      DEND(1)=DENL
      CPU(1)=CPL
      TKU(1)=TKL
      VISU(1)=VISL
      DENU(1)=DENL
201 TFR=G(J)*SIXTY*DENL/GAL
      IF (MPH .NE. 0) GO TO 199
      TFRD(1)=TFR/(DEND(1)*SH*VDL(1))
      TFRU(1)=TFR/(DENU(1)*SH*VDL(3))

C
C      CALCULATE LITHIUM HEAT TRANSFER FILM COEFFICIENTS
C
199 CONTINUE
      EDDL=(DL(2)-DL(1))/TWEL
      EDDU=(DU(2)-DU(1))/TWEL
      EDUL=(DL(4)-DL(3))/TWEL
      EDUU=(DU(4)-DU(3))/TWEL

      PR=CPL*VISL/TKL

C      GDL=TFR/VDL(1)
C      GDU=TFR/VDU(1)
C      GUL=TFR/VDL(3)
C      GUU=TFR/VDU(3)

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C      REDL=EDDL*GDL/VISL
C      REDU=EDDU*GDU/VISL
C      REUL=EDUL*GUL/VISL
C      REUU=EDUU*GUU/VISL

C      HDL=(TKL/EDDL)*(SEV+CH*(REDL*PR)**EX)
C      HDU=(TKL/EDDU)*(SEV+CH*(REDU*PR)**EX)
C      HUL=(TKL/EDUL)*(SEV+CH*(REUL*PR)**EX)
C      HUU=(TKL/EDUU)*(SEV+CH*(REUU*PR)**EX)

      CALL LICOEF(1,TFR,GDL,REDL,HDL)
      CALL LICOEF(2,TFR,GDU,REDU,HDU)
      CALL LICOEF(3,TFR,GUL,REUL,HUL)
      CALL LICOEF(4,TFR,GUU,REUU,HUU)

      IF (MPH .NE. 0) DEND(1)=DENL
      CALL LIFRIC(1,DEND(1),REDL,GDL,FF1,DELP1)
      CALL LIFRIC(2,DEND(1),REUL,GUL,FF2,DELP2)
      CALL LIFRIC(3,DEND(1),REDL,GDL,FF3,DELP3)
      CALL LIFRIC(4,DEND(1),REUL,GUL,FF4,DELP4)
      CALL LIFRIC(5,DEND(1),REDL,GDL,FF5,DELP5)
      CALL LIFRIC(6,DEND(1),REUL,GUL,FF6,DELP6)
      CALL LIFRIC(7,DEND(1),REDU,GDU,FF7,DELP7)
      CALL LIFRIC(8,DEND(1),REUU,GUU,FF8,DELP8)

C
C      FOR CONSTANT PROPERTY LITHIUM INPUT FILL UP AXIAL ARRAYS
C
      IF (MPH .EQ. 0) GO TO 198
      DO 196 I=1,IIF
      HFD(I)=HDL
      HFU(I)=HUL
      TFRD(I)=TFR/(DEND*SH*VDL(1))
      TFRU(I)=TFR/(DEND*SH*VDL(3))
      GFRD(I)=GDL
      GFRU(I)=GUL
      REYD(I)=REDL
      REYU(I)=REUL
      CPD(I)=CPL
      CPU(I)=CPL
      TKD(I)=TKL
      TKU(I)=TKL
      VISD(I)=VISL
      VISU(I)=VISL
      DEND(I)=DENL
      DENU(I)=DENL
196 CONTINUE
      DO 195 I=IUI,IUF
      HFD(I)=HDU
      HFU(I)=HUU
      TFRD(I)=TFR/(DEND*SH*VDU(1))
      TFRU(I)=TFR/(DEND*SH*VDU(3))
      GFRD(I)=GDU
      GFRU(I)=GUU
      REYD(I)=REDU
      REYU(I)=REUU
      CPD(I)=CPL
      CPU(I)=CPL
      TKD(I)=TKL
      TKU(I)=TKL
      VISD(I)=VISL
      VISU(I)=VISL
      DEND(I)=DENL
      DENU(I)=DENL
      FFD(I)=FF7

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      FFU(I)=FF8
      DELPD(I)=DELP7
      DELPU(I)=DELP8
195  CONTINUE
      DO 296 I=1,NL
      FFD(I)=FF1
      FFU(I)=FF2
      DELPD(I)=DELP1
      DELPU(I)=DELP2
296  CONTINUE
      DO 396 I=ICI,ICF
      FFD(I)=FF3
      FFU(I)=FF4
      DELPD(I)=DELP3
      DELPU(I)=DELP4
396  CONTINUE
      DO 496 I=III,IIF
      FFD(I)=FF5
      FFU(I)=FF6
      DELPD(I)=DELP5
      DELPU(I)=DELP6
496  CONTINUE
198  IF(MPH .NE. 0) GO TO 197
      HFD(1)=HDL
      GFRD(1)=GDL
      REYD(1)=REDL
      HFU(1)=HUL
      GFRU(1)=GUL
      REYU(1)=REUL
      FFD(1)=FF1
      FFU(1)=FF2
      DELPD(1)=DELP1
      DELPU(1)=DELP2
C
C   CONVERT GAMMA HEATING (W/GM) TO BTU/FT3
C
197  QGE=QG*PCF*WCF*DENS
C
C   ASSUME DOWNFLOW GETS HEAT FROM CAPSULES , TEST CONTAINER & 1/2
C   OF FLOW DIVIDER.  UPCOMER GETS HEAT FROM 1/2 FLOW DIVIDER & HOUSING
C
      VGDC=VDT(1)*VFCAP+VDT(3)+HALF*VDL(2)
      VGUC=HALF*VDL(2)+VDL(4)
      QGDC=QGE*VGDC
      QGUC=QGE*VGUC
C
C   LINEAR EBR TEMP IN CORE REGION
C
      X1=DDL/TWEL
      T1=TEBRL
      X2=(DDL+DDC)/TWEL
      T2=TEBRU
      AA=(T1-T2)/(X1-X2)
      BB=T1-AA*X1
C
C   LINEAR EBR TEMP CONSTANTS IN COVER REGION
C
      XC1=DBOTC/TWEL
      TC1=TEBRU
      XC2=DTOPC/TWEL
      TC2=TTOPC
      AAC=(TC1-TC2)/(XC1-X2)

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      BBC=TC1-AAC*XC1
C
C   LINEAR EBR TEMP CONSTANTS IN SMALL PLUG REGION
C
      XP1=DBOTP/TWEL
      TP1=TTOPC
      XP2=DTOPP/TWEL
      TP2=TTOPP
      AAP=(TP1-TP2)/(XP1-XP2)
      BBP=TP1-AAP*XP1
C
C   CALCULATE AXIAL TEMP DISTRIBUTION
C
      ZIN=ZERO
      TUP=TI
      TDW=TI
C
C   LOWER REGION GEOMETRY & THERMAL RESISTANCE PARAMETERS
C
      RES1=DLOG(DL(7)/DL(6))/TKS
      RES2=DLOG(DL(5)/DL(4))/TKS
      RES3=DLOG(DL(3)/DL(2))/TKS
      IF(TKA .LE. ZERO) GO TO 573
      RES4=DLOG(DL(6)/DL(5))/TKA
573  RLGA=(DL(5)+DL(6))/(FOUR*TWEL)
      IF(TKA .LE. ZERO) THEN
      HCONL=ZERO
      ELSE
      HCONL=(ONE/RES4)/RLGA
      END IF
      RO=DL(7)/(TWO*TWEL)
      ADLO=TWO*PI*RO
      RI=(DL(3)+DL(2))/(FOUR*TWEL)
      RL2=DL(2)/CFRAD
      RL3=DL(3)/CFRAD
      RL4=DL(4)/CFRAD
      REL2=ONE/(RL2*HDL)
      REL3=ONE/(RL3*HUL)
      REL4=ONE/(RL4*HUL)
      ADLI=(ADL(4)+ADL(3))/TWO
C
C   UPPER REGION GEOMETRY & THERMAL RESISTANCE PARAMETERS
C
      REU1=DLOG(DU(7)/DU(6))/TKS
      REU2=DLOG(DU(5)/DU(4))/TKS
      REU3=DLOG(DU(3)/DU(2))/TKFD
      IF(TKA .LE. ZERO) GO TO 574
      REU4=DLOG(DU(6)/DU(5))/TKA
574  RUGA=(DU(5)+DU(6))/(FOUR*TWEL)
      IF(TKA .LE. ZERO) THEN
      HCONU=ZERO
      ELSE
      HCONU=(ONE/REU4)/RUGA
      END IF
      RU=DU(7)/(TWO*TWEL)
      ADUO=TWO*PI*RU
      RK=(DU(3)+DU(2))/(FOUR*TWEL)
      RU2=DU(2)/CFRAD
      RU3=DU(3)/CFRAD
      RU4=DU(4)/CFRAD
      RUL2=ONE/(RU2*HUU)
      RUL3=ONE/(RU3*HUU)
      RUL4=ONE/(RU4*HUU)
      ADUI=(ADU(4)+ADU(3))/TWO

```

C
C LOWER REGION
C

TEBR-TEBRL

```
DO 30 I=1,NL
IF(I .EQ. 1 .OR. MPH .NE. 0) GO TO 202
CALL LIPROP(TD(I-1),CPD(I),TKD(I),VSD(I),DEND(I))
VDSL-VSD(I)
TKL-TKD(I)
PR=(CPD(I)*VDSL)/TKL
TFRD(I)=TFR/(DEND(I)*SH*VDL(1))
CALL LICOEF(1,TFR,GFRD(I),REYD(I),HFD(I))
CALL LIFRIC(1,DEND(I),REYD(I),GFRD(I),FFD(I),DELPD(I))
HDL-HFD(I)
CALL LIPROP(TU(I-1),CPU(I),TKU(I),VISU(I),DENU(I))
VDSL-VISU(I)
TKL-TKU(I)
PR-CPU(I)*VDSL/TKL
TFRU(I)=TFR/(DENU(I)*SH*VDL(3))
CALL LICOEF(3,TFR,GFRU(I),REYU(I),HFU(I))
CALL LIFRIC(2,DENU(I),REYU(I),GFRU(I),FFU(I),DELPD(I))
HUL -HFU(I)
REL2=ONE/(RL2*HDL)
REL3=ONE/(RL3*HUL)
REL4=ONE/(RL4*HUL)
202 HR(I)=FEL*RC*((TEBR+TRANK)**FOUR-(TUP+TRANK)**FOUR)/(TEBR-TUP)
HT(I)=HR(I)+HCONL
UO(I)=(ONE/RO)*(ONE/(ONE/(RLGA*HT(I))+RES1+RES2+REL4))
QO(I)=UO(I)*DELL*ADLO*(TEBR-TUP)
UI(I)=(ONE/RI)*(ONE/(RES3+REL3+REL2))
QD(I)=UI(I)*DELL*ADLI*(TUP-TDW)
QU(I)=QO(I)-QD(I)
TU(I)=TUP+QU(I)/(CPL*TFR)
TD(I)=TDW-QD(I)/(CPL*TFR)
```

```
IF(I .EQ. 1) THEN
QDT(1)=QD(1)
QUT(1)=QU(1)
QOT(1)=QO(1)
PRESD(1)=DELPD(1)
PRESU(1)=DELPD(1)
ELSE
QOT(I)=QOT(I-1)+QO(I)
QDT(I)=QDT(I-1)+QD(I)
QUT(I)=QUT(I-1)+QU(I)
PRESD(I)=PRESD(I-1) + DELPD(I)
PRESU(I)=PRESU(I-1) + DELPU(I)
END IF
```

Z(I)=ZIN+DELL

```
ZIN=Z(I)
TUP=TU(I)
TDW=TD(I)
TEBR2(I)=TEBR
```

30 CONTINUE

C
C CORE REGION
C

```
DO 40 I=ICI,ICF
QGD(I)=DELC*QGDC
```

```
QGU(I)=DELC*QGUC
TEBR-AA*ZIN+BB
IF(MPH .NE. 0) GO TO 203
CALL LIPROP(TD(I-1),CPD(I),TKD(I),VSD(I),DEND(I))
VDSL-VSD(I)
TKL-TKD(I)
PR=(CPD(I)*VDSL)/TKL
TFRD(I)=TFR/(DEND(I)*SH*VDL(1))
CALL LICOEF(1,TFR,GFRD(I),REYD(I),HFD(I))
CALL LIFRIC(3,DEND(I),REYD(I),GFRD(I),FFD(I),DELPD(I))
HDL-HFD(I)
CALL LIPROP(TU(I-1),CPU(I),TKU(I),VISU(I),DENU(I))
VDSL-VISU(I)
TKL-TKU(I)
PR-CPU(I)*VDSL/TKL
TFRU(I)=TFR/(DENU(I)*SH*VDL(3))
CALL LICOEF(3,TFR,GFRU(I),REYU(I),HFU(I))
CALL LIFRIC(4,DENU(I),REYU(I),GFRU(I),FFU(I),DELPD(I))
HUL -HFU(I)
REL2=ONE/(RL2*HDL)
REL3=ONE/(RL3*HUL)
REL4=ONE/(RL4*HUL)
203 HR(I)=FEL*RC*((TEBR+TRANK)**FOUR-(TUP+TRANK)**FOUR)/(TEBR-TUP)
HT(I)=HR(I)+HCONL
UO(I)=(ONE/RO)*(ONE/(ONE/(RLGA*HT(I))+RES1+RES2+REL4))
QO(I)=UO(I)*DELC*ADLO*(TEBR-TUP)
UI(I)=(ONE/RI)*(ONE/(RES3+REL3+REL2))
QD(I)=UI(I)*DELC*ADLI*(TUP-TDW)
QU(I)=QO(I)-QD(I)
TU(I)=TUP+QU(I)/(CPL*TFR)
TD(I)=TDW-QD(I)/(CPL*TFR)
QOT(I)=QOT(I-1)+QO(I)
QDT(I)=QDT(I-1)+QD(I)
QUT(I)=QUT(I-1)+QU(I)
PRESD(I)=PRESD(I-1) + DELPD(I)
PRESU(I)=PRESU(I-1) + DELPU(I)
```

```
IF(I .EQ. ICI) THEN
QDG(I)=QGD(I)
QUG(I)=QGU(I)
QGT(I)=QDG(I)+QUG(I)
ELSE
QDG(I)= QDG(I-1)+QGD(I)
QUG(I)= QUG(I-1)+QGU(I)
QGT(I)= QGT(I-1)+QGD(I)+QGU(I)
END IF
Z(I)=ZIN+DELC
```

```
ZIN=Z(I)
TUP=TU(I)
TDW=TD(I)
TEBR2(I)=TEBR
```

40 CONTINUE

C
C INTERMEDIATE REGION
C

TEBR-TEBRU

```
DO 50 I=III,IIF
IF(ZIN .GE. XC1 .AND. ZIN .LE. XC2) THEN
TEBR-AAC*ZIN+BBC
ELSE IF(ZIN .GE. XP1 .AND. ZIN .LE. XP2) THEN
```

```

TEBR=AAP*ZIN+BBP
ELSE IF(ZIN .GT. XC2 .AND. ZIN .LT. XP1) THEN
TEBR= TTOPC
ELSE IF(ZIN .GT. XP2) THEN
TEBR=TTOPP
END IF
IF( MPH .NE. 0) GO TO 204
CALL LIPROP(TD(I-1),CPD(I),TKD(I),VISD(I),DEND(I))
VISL=VISD(I)
TKL=TKD(I)
PR=(CPD(I)*VISL)/TKL
TFRD(I)=TFR/(DEND(I)*SH*VDL(1))
CALL LICOEF(1,TFR,GFRD(I),REYD(I),HFD(I))
CALL LIFRIC(5,DEND(I),REYD(I),GFRD(I),FFD(I),DELPD(I))
HDL=HFD(I)
CALL LIPROP(TU(I-1),CPU(I),TKU(I),VISU(I),DENU(I))
VISL=VISU(I)
TKL=TKU(I)
PR=CPU(I)*VISL/TKL
TFRU(I)=TFR/(DENU(I)*SH*VDL(3))
CALL LICOEF(3,TFR,GFRU(I),REYU(I),HFU(I))
CALL LIFRIC(6,DENU(I),REYU(I),GFRU(I),FFU(I),DELPU(I))
HUL=HFU(I)
REL2=ONE/(RL2*HDL)
REL3=ONE/(RL3*HUL)
REL4=ONE/(RL4*HUL)
204 HR(I)=FEL*RC*((TEBR+TRANK)**FOUR-(TUP+TRANK)**FOUR)/(TEBR-TUP)
HT(I)=HR(I)+HCONL
UO(I)=(ONE/RO)*(ONE/(ONE/(RLGA*HT(I))+RES1+RES2+REL4))
QO(I)=UO(I)*DELI*ADLO*(TEBR-TUP)
UI(I)=(ONE/RI)*(ONE/(RES3+REL3+REL2))
QD(I)=UI(I)*DELI*ADLI*(TUP-TDW)
QU(I)=QO(I)-QD(I)
TU(I)=TUP+QU(I)/(CPL*TFR)
TD(I)=TDW-QD(I)/(CPL*TFR)
QOT(I)=QOT(I-1)+QO(I)
QDT(I)=QDT(I-1)+QD(I)
QUT(I)=QUT(I-1)+QU(I)
PRESD(I)=PRESD(I-1) + DELPD(I)
PRESU(I)=PRESU(I-1) + DELPU(I)
Z(I)=ZIN+DELI

ZIN=Z(I)
TUP=TU(I)
TDW=TD(I)
TEBR2(I)=TEBR
50 CONTINUE

C
C UPPER REGION (CHANGE TO UPPER REGION GEOMETRY)
C

DO 60 I=IUI,IUF
IF(ZIN .GE. XC1 .AND. ZIN .LE. XC2) THEN
TEBR=AAC*ZIN+BBC
ELSE IF(ZIN .GE. XP1 .AND. ZIN .LE. XP2) THEN
TEBR=AAP*ZIN+BBP
ELSE IF(ZIN .GT. XC2 .AND. ZIN .LT. XP1) THEN
TEBR= TTOPC
ELSE IF(ZIN .GT. XP2) THEN
TEBR=TTOPP
END IF
IF( MPH .NE. 0) GO TO 205
CALL LIPROP(TD(I-1),CPD(I),TKD(I),VISD(I),DEND(I))

```

```

VISL=VISD(I)
TKL=TKD(I)
PR=(CPD(I)*VISL)/TKL
TFRD(I)=TFR/(DEND(I)*SH*VDU(1))
CALL LICOEF(2,TFR,GFRD(I),REYD(I),HFD(I))
CALL LIFRIC(7,DEND(I),REYD(I),GFRD(I),FFD(I),DELPD(I))
HDU=HFD(I)
CALL LIPROP(TU(I-1),CPU(I),TKU(I),VISU(I),DENU(I))
VISL=VISU(I)
TKL=TKU(I)
PR=CPU(I)*VISL/TKL
TFRU(I)=TFR/(DENU(I)*SH*VDU(3))
CALL LICOEF(4,TFR,GFRU(I),REYU(I),HFU(I))
CALL LIFRIC(8,DENU(I),REYU(I),GFRU(I),FFU(I),DELPU(I))
HUU=HFU(I)
RUL2=ONE/(RU2*HDU)
RUL3=ONE/(RU3*HUU)
RUL4=ONE/(RU4*HUU)
205 HR(I)=FEL*RC*((TEBR+TRANK)**FOUR-(TUP+TRANK)**FOUR)/(TEBR-TUP)
HT(I)=HR(I)+HCONU
UO(I)=(ONE/RU)*(ONE/(ONE/(RUGA*HT(I))+REU1+REU2+RUL4))
QO(I)=UO(I)*DELU*ADUO*(TEBR-TUP)
UI(I)=(ONE/RK)*(ONE/(REU3+RUL2+RUL3))
QD(I)=UI(I)*DELU*ADUI*(TUP-TDW)
QU(I)=QO(I)-QD(I)
TU(I)=TUP+QU(I)/(CPL*TFR)
TD(I)=TDW-QD(I)/(CPL*TFR)
QOT(I)=QOT(I-1)+QO(I)
QDT(I)=QDT(I-1)+QD(I)
QUT(I)=QUT(I-1)+QU(I)
PRESD(I)=PRESD(I-1) + DELPD(I)
PRESU(I)=PRESU(I-1) + DELPU(I)
Z(I)=ZIN+DELU

ZIN=Z(I)
TUP=TU(I)
TDW=TD(I)
TEBR2(I)=TEBR
60 CONTINUE

C
C ESTIMATE EXTERNAL LTIV LOOP PRESS DROP & TOTAL
C

TOTPRES=PRESD(IUF) + PRESU(IUF)

FY1=G(J)**2
FY2=FY1*G(J)
DELPEX=COEF(1)+COEF(2)*G(J)+COEF(3)*FY1+COEF(4)*FY2
TPLOOP=DELPEX+TOTPRES

C
C CALC ABSOLUTE PRESSURE IN LTIV LITHIUM
C

PTOPD(IUF)= PRESI
DO 160 I=1,IUF
KKK=IUF-I
KK=KKK+1
PTOPD(KKK)=PTOPD(KK)-DELPD(KK)
160 CONTINUE

PBOTL = PTOPD(1) - DELPD(1)
DO 260 I=1,IUF
IF(I .EQ. 1) THEN
PTOPU(1)=PBOTL - DELPU(1)
ELSE

```

```

      PTOPI(I) = PTOPI(I-1) - DELPU(I)
      END IF
160 CONTINUE

      IF (NTYPE .NE. 0) GO TO 502
C
C   DETERMINE NEXT LI FLOW RATE FOR NEXT ITERATION
C
      P(J) = TPLOOP
      PL(J) = CHD(1) + CHD(2) * G(J) + CHD(3) * G(J) ** 2.0 + CHD(4) * G(J) ** 3.0
      IF (CHD(5) .EQ. 0.00) THEN
        PH(J) = PL(J)
        GO TO 412
      ELSE
        CALL LIRES(TD(IUF), RES(J))
        PH(J) = PL(J) * CHD(5) / RES(J)
      END IF
412 DP(J) = PH(J) - P(J)
      IF (ABS(DP(J)) .LE. EPS) GO TO 502
      IF (J .NE. 1) GO TO 403
      G(J+1) = G(J) * (PH(J) / P(J)) ** 0.5555
      GO TO 404
403 IF (DP(J) .LT. 0.0 .AND. DP(J-1) .LT. 0.0) GO TO 402
      IF (DP(J) .GT. 0.0 .AND. DP(J-1) .GT. 0.0) GO TO 402
C
C   G(J+1) = 0.5 * (G(J) + G(J-1))
C
      GO TO 404
402 SLOPE = (DP(J-1) - DP(J)) / (G(J-1) - G(J))
      BB = DP(J-1) - SLOPE * G(J-1)
      G(J+1) = -BB / SLOPE
404 CONTINUE
      IF (J .NE. 1) GO TO 407
      WRITE(7, 406)
406 FORMAT(1X/1X// 'FLOW ITERATION RESULTS'//
12X, 'I', 2X, 'INITIAL FLOW', 3X, 'PRESS DROP', 4X, 'PRESS HEAD', 4X,
2' LI RESISVTY', 4X, 'LI PRESS HD', 4X, 'PRESS DIFF', 5X, 'NEXT FLOW',
34X, 'INLET TEMP'//
3 10X, ' (GPM)', 9X, ' (PSI)', 8X, ' (PSI)', 6X, ' (MICROHMS-CM)', 4X, ' (PSI)'
4, 11X, ' (PSI)', 10X, ' (GPM)', 7X, ' (DEG F)')
407 WRITE(7, 405) J, G(J), P(J), PL(J), RES(J), PH(J), DP(J), G(J+1), TD(IUF)
405 FORMAT(13, 2X, 1PE12.5, 2X, 1PE12.5, 2X, 1PE12.5, 2X, 1PE12.5, 3X, 1PE12.
15, 3X, 1PE12.5, 2X, 1PE12.5, 2X, 1PE12.5)
501 CONTINUE

      IF (J .LT. NMAX) GO TO 503
      WRITE(7, 408)
408 FORMAT(1X/1X/ ' *****FLOW RATE ITERATION FAILED TO CONVERGE*****')
      GO TO 105
502 CONTINUE
      WRITE(7, 405) J, G(J), P(J), PL(J), RES(J), PH(J), DP(J), G(J+1), TD(IUF)
503 CONTINUE
C
C   PRINTOUT INPUT DATA
C
      WRITE(7, 180)
180 FORMAT(1X/1X/54X, '*****INPUT DATA*****', 1X/)
      WRITE(7, 181)
181 FORMAT(1X/1X// 'COEFFICIENTS FOR PUMP HEAD & EXREACTOR PRESSURE D
1ROP'//
12X, 'I', 2X, 'PUMP HEAD (CHD(I))', 2X, 'EXREACTOR (COEF(I))')
      DO 183 I = 1, 4
      WRITE(7, 182) I, CHD(I), COEF(I)
183 CONTINUE
      IF (CHD(5) .EQ. ZERO) THEN
        WRITE(7, 414)

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414 FORMAT(1X//REF. PUMP HEAD CURVE UNCORRECTED AS CHD(5) = ZERO')
      ELSE
        WRITE(7, 413) CHD(5)
413 FORMAT(1X//REF. PUMP HEAD LIQ RESISTIVITY (MICROHMS-CM) = '
1, 1PE12.5)
      END IF
182 FORMAT(13, 4X, 1PE12.5, 9X, 1PE12.5)
      WRITE(7, 82)
82 FORMAT(1X/1X// 'LTIV RADIAL GEOMETRY DIAMETERS (INCHES)'//)
      WRITE(7, 84) DT(1), DT(2), DT(3)
84 FORMAT('CORE & LOWER & INTERMEDIATE & UPPER REGION'//
1'DT(1)=O.D. SAMPLE CAPSULE'//
26X, '-I.D. ARGON CLEARANCE GAP =', 1PE12.5/
3'DT(2)=O.D. ARGON CLEARANCE GAP'//
46X, '-I.D. TEST CONTAINER =', 1PE12.5/
5'DT(3)=O.D. TEST CONTAINER =', 1PE12.5/)
      WRITE(7, 86) DL(1), DL(2), DL(3), DL(4), DL(5), DL(6), DL(7)
86 FORMAT('LOWER & INTERMEDIATE REGION'//
1'DL(1)=I.D. DOWNFLOW ANNULUS'//
26X, '-O.D. TEST CONTAINER =', 1PE12.5/
3'DL(2)=O.D. DOWNFLOW ANNULUS'//
46X, '-I.D. FLOW DIVIDER =', 1PE12.5/
5'DL(3)=O.D. FLOW DIVIDER'//
66X, '-I.D. UPFLOW ANNULUS =', 1PE12.5/
7'DL(4)=O.D. UPFLOW ANNULUS'//
86X, '-I.D. FLOW HOUSING =', 1PE12.5/
9'DL(5)=O.D. FLOW HOUSING'//
16X, '-I.D. AR INSULATION GAP =', 1PE12.5/
2'DL(6)=O.D. AR INSULATION GAP'//
36X, '-I.D. OUTSIDE GUIDE TUBE =', 1PE12.5/
4'DL(7)=O.D. OUTSIDE GUIDE TUBE =', 1PE12.5/)
      WRITE(7, 88) DU(1), DU(2), DU(3), DU(4), DU(5), DU(6), DU(7)
88 FORMAT('UPPER REGION'//
1'DU(1)=I.D. DOWNFLOW ANNULUS'//
26X, '-O.D. TEST CONTAINER =', 1PE12.5/
3'DU(2)=O.D. DOWNFLOW ANNULUS'//
46X, '-I.D. FLOW DIVIDER =', 1PE12.5/
5'DU(3)=O.D. FLOW DIVIDER'//
66X, '-I.D. UPFLOW ANNULUS =', 1PE12.5/
7'DU(4)=O.D. UPFLOW ANNULUS'//
86X, '-I.D. FLOW HOUSING =', 1PE12.5/
9'DU(5)=O.D. FLOW HOUSING'//
16X, '-I.D. AR INSULATION GAP =', 1PE12.5/
2'DU(6)=O.D. AR INSULATION GAP'//
36X, '-I.D. OUTSIDE GUIDE TUBE =', 1PE12.5/
4'DU(7)=O.D. OUTSIDE GUIDE TUBE =', 1PE12.5/)
      WRITE(7, 90) DDL, DDC, DDI, DDU
90 FORMAT(1X/1X// 'AXIAL LTIV REGION LENGTHS (INCHES)'//
1'LOWER REGION (DDL) =', 1PE12.5/
2'CORE REGION (DDC) =', 1PE12.5/
3'INTERMEDIATE REGION (DDI) =', 1PE12.5/
4'UPPER REGION (DDU) =', 1PE12.5/)
      WRITE(7, 92) DBOTC, DTOPC, DBOTP, DTOPP
92 FORMAT(1X/1X// 'AXIAL DISTANCES FROM LOOP BOTTOM (INCHES)'//
1'BOTTOM OF TOP COVER (DBOTC) =', 1PE12.5/
2'TOP OF TOP COVER (DTOPC) =', 1PE12.5/
3'BOTTOM OF SMALL PLUG (DBOTP) =', 1PE12.5/
4'TOP OF SMALL PLUG (DTOPP) =', 1PE12.5/)
      WRITE(7, 94) NL, NC, NI, NU
94 FORMAT(1X// 'NUMBER OF AXIAL NODES IN EACH REGION'//
1'LOWER REGION =', I3/
2'CORE REGION =', I3/
3'INTERMEDIATE REGION =', I3/
4'UPPER REGION =', I3/)

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WRITE(7,96) TEBRL,TEBRU,TI,TTOPC,TTOPP
96 FORMAT(1X/' INPUTTED TEMPERATURES IN DEGREES F'/
1'EBR-II INLET TEMP (TEBRL) = ',1PE12.5/
2'EBR-II OUTLET TEMP (TEBRU) = ',1PE12.5/
3'LTIV LOWER LOOP TEMP (TI) = ',1PE12.5/
4'COVER TOP TEMP (TTOPC) = ',1PE12.5/
5'SMALL PLUG TOP TEMP (TTOPP) = ',1PE12.5/)
WRITE(7,98) QG,VFCAP,E1,E2,VFLO,PRESI
98 FORMAT(1X/' INITIAL CONDITIONS'/
1'GAMMA HEATING IN W/GM (QG) = ',1PE12.5/
2'VOLUME FRACTION SS IN CAPSULES (VFCAP) = ',1PE12.5/
3'EMISSIVITY HOUSING TUBE (E1) = ',1PE12.5/
4'EMISSIVITY GUIDE TUBE (E2) = ',1PE12.5/
5'INITIAL LTIV LITHIUM FLOW RATE IN GPM (VFLO) = ',1PE12.5/
6'PRESSURE AT DOWNCOMER INLET (PRESI) = ',1PE12.5/)
WRITE(7,62)
62 FORMAT(1X/' PHYSICAL PROPERTY DATA'/
IF(MPH.EQ.0) WRITE(7,164)
IF(MPH.NE.0) WRITE(7,64) DENL,TKL,CPL,VISL
64 FORMAT(' LITHIUM AT 500F'/
1'DENSITY IN LB/FT3 (DENL) = ',1PE12.5/
2'THERMAL COND IN BTU/HR/FT/DEG F (TKL) = ',1PE12.5/
3'HEAT CAPACITY IN BTU/LB-DEG F (CPL) = ',1PE12.5/
4'VISCOSITY IN LB/FT-HR (VISL) = ',1PE12.5/)
164 FORMAT(' LITHIUM '/
1'DENSITY IN LB/FT3 (DENL) = VARIABLE'/
2'THERMAL COND IN BTU/HR/FT/DEG F (TKL) = VARIABLE'/
3'HEAT CAPACITY IN BTU/LB-DEG F (CPL) = VARIABLE'/
4'VISCOSITY IN LB/FT-HR (VISL) = VARIABLE'/)
WRITE(7,66) DENA,TKA,CPA,VISA
66 FORMAT(' ARGON AT 600F'/
1'DENSITY IN LB/FT3 (DENA) = ',1PE12.5/
2'THERMAL COND IN BTU/HR/FT/DEG F (TKA) = ',1PE12.5/
3'HEAT CAPACITY IN BTU/LB-DEG F (CPA) = ',1PE12.5/
4'VISCOSITY IN LB/FT-HR (VISA) = ',1PE12.5/)
WRITE(7,68) DENS,TKS,CPS,TKFD
68 FORMAT(' STAINLESS STEEL AT 75F'/
1'DENSITY IN LB/FT3 (DENS) = ',1PE12.5/
2'THERMAL COND IN BTU/HR/FT/DEG F (TKS) = ',1PE12.5/
3'HEAT CAPACITY IN BTU/LB-DEG F (CPS) = ',1PE12.5/
4'THERM COND OF FLOW DIVIDER IN UPPER REG (TKFD) = ',1PE12.5/)
WRITE(7,52)MIT,NIT,MPH,NTYPE,NMAX,EPS
52 FORMAT(1X/' CONTROL OPTIONS & PARAMETERS'/
1' PRINT OPTIONS'/
2'PRINT PLOT DATA (MIT = 0 YES) = ',I3/
3'PRINT AXIAL DATA (NIT = 0 YES) = ',I3/
4' PHYSICAL PROPERTY DATA OPTIONS'/
5'VARIABLE LITHIUM PROP (MPH = 0 YES) = ',I3/
6' FLOW RATE ITERATION OPTION'/
7'FLOW INTERATION CALC (NTYPE = 0 YES) = ',I3/
8'MAXIMUM NUMBER OF ITERATIONS (NMAX) = ',I3/
9'PRESS DIFF CONVERGENCE CRITERIA (EPS) = ',1PE12.5,' PSI'/)
WRITE(7,54)
54 FORMAT(1X/1X/,54X,'*****OUTPUT RESULTS*****',1X/1X/)
WRITE(7,56)
56 FORMAT(' LTIV GEOMETRIC CALCULATIONAL RESULTS'/
11X/' CORE & LOWER & INTERMEDIATE & UPPER REGION'/
25X,' ITEM',13X,' THICKNESS',7X,' SURFACE AREA (FT2/FT)',6X,' VOLUME (F
3T3/FT)'/
422X,' OR GAP (IN.)',6X,' OUTSIDE',6X,' INSIDE')
WRITE(7,58) GTT(1),ADT(1), VDT(1)
58 FORMAT(' SAMPLE CAPSULE',7X,1PE12.5,4X,1PE12.5,17X,1PE12.5)
WRITE(7,59) GTT(2),ADT(2),ADT(1),VDT(2)
59 FORMAT(' ARGON CLEARANCE GAP',2X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,

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```

11PE12.5)
WRITE(7,57) GTT(3),ADT(3),ADT(2),VDT(3)
57 FORMAT(' TEST CONTAINER',7X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
WRITE(7,55)
55 FORMAT(1X/' LOWER & INTERMEDIATE REGION'/
15X,' ITEM',13X,' THICKNESS',7X,' SURFACE AREA (FT2/FT)',6X,' VOLUME (F
2T3/FT)'/
322X,' OR GAP (IN.)',6X,' OUTSIDE',6X,' INSIDE')
WRITE(7,53) GTL(1),ADL(2),ADL(1),VDL(1)
WRITE(7,33) GTL(2),ADL(3),ADL(2),VDL(2)
WRITE(7,37) GTL(3),ADL(4),ADL(3),VDL(3)
WRITE(7,47) GTL(4),ADL(5),ADL(4),VDL(4)
WRITE(7,45) GTL(5),ADL(6),ADL(5),VDL(5)
WRITE(7,43) GTL(6),ADL(7),ADL(6),VDL(6)
53 FORMAT(' LITHIUM DOWNCOMER',4X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
33 FORMAT(' FLOW DIVIDER',9X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
37 FORMAT(' LITHIUM UPCOMER',6X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
47 FORMAT(' FLOW HOUSING',9X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
45 FORMAT(' ARGON INSULATION',5X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
43 FORMAT(' GUIDE TUBE',11X,1PE12.5,4X,1PE12.5,1X,1PE12.5,4X,
11PE12.5)
WRITE(7,35)
35 FORMAT(1X/' UPPER REGION'/
15X,' ITEM',13X,' THICKNESS',7X,' SURFACE AREA (FT2/FT)',6X,' VOLUME (F
2T3/FT)'/
322X,' OR GAP (IN.)',6X,' OUTSIDE',6X,' INSIDE')
WRITE(7,53) GTU(1),ADU(2),ADU(1),VDU(1)
WRITE(7,33) GTU(2),ADU(3),ADU(2),VDU(2)
WRITE(7,37) GTU(3),ADU(4),ADU(3),VDU(3)
WRITE(7,47) GTU(4),ADU(5),ADU(4),VDU(4)
WRITE(7,45) GTU(5),ADU(6),ADU(5),VDU(5)
WRITE(7,43) GTU(6),ADU(7),ADU(6),VDU(6)
WRITE(7,23) IUF, 2(IUF),ADLI,ADUI,ADLO,ADUO,VGUC,VGDC
23 FORMAT(1X/' GENERAL HEAT TRANSFER GEOMETRIC DATA'/
1'TOTAL NUMBER OF AXIAL NODES (MAX OF 100) (IUF) = ',I3,/
2'TOTAL AXIAL LENGTH OF LTIV INREACTOR (Z(IUF)) = ',1PE12.5,' FT'/
3'SURFACE AREA LOWER REGION FOR INNER H.T. (ADLI) = ',1PE12.5,
4' FT2/FT'/
5'SURFACE AREA UPPER REGION FOR INNER H.T. (ADUI) = ',1PE12.5,
6' FT2/FT'/
7'SURFACE AREA LOWER REGION FOR OUTER H.T. (ADLO) = ',1PE12.5,
8' FT2/FT'/
9'SURFACE AREA UPPER REGION FOR OUTER H.T. (ADUO) = ',1PE12.5,
1' FT2/FT'/
2'VOLUME STEEL IN UPCOMER INCORE REG (VGUC) = ',1PE12.5,' FT3/FT'/
3'VOLUME STEEL IN DWNCOMER INCORE REG (VGDC) = ',1PE12.5,' FT3/FT'/)
WRITE(7,11) TI,TD(IUF),TU(IUF),QDT(IUF),QUT(IUF),QOT(IUF),
1PRES(IUF),PRESU(IUF),TOTPRES,PBOTL,DELPEX,TPLOOP
WRITE(7,411) J,PH(J),DP(J)
411 FORMAT(1X/' PUMP HEAD & PRESSURE DIFFERENTIAL'/
1'NUMBER OF PRESSURE DROP ITERATIONS (J) = ',I3,/
2'ALIP PUMP HEAD (PH(J)) = ',1PE12.5,' PSI'/
3'PRESSURE DIFFERENCE (PH-TPLOOP) (DP(J)) = ',1PE12.5,' PSI'/)
WRITE(7,211) G(J),TFR,GFRD(1),GFRU(1),GFRD(IUF),GFRU(IUF)
211 FORMAT(1X/' LITHIUM MASS FLOW RATES'/
1'CONVERGED LOOP FLOW RATE (G(J)) = ',1PE12.5,' GPM'/
1'LOOP MASS FLOW RATE (TFR) = ',1PE12.5,' LBS/HR'/
2'LOWER REG. DOWNCOMER MASS FLUX (GFRD) = ',1PE12.5,' LBS/HR-FT2'/

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3' LOWER REG. UPCOMER MASS FLUX (GFRU) = ',1PE12.5,' LBS/HR-FT2'/
4' UPPER REG. DOWNCOMER MASS FLUX (GFRD) = ',1PE12.5,' LBS/HR-FT2'/
5' UPPER REG. UPCOMER MASS FLUX (GFRU) = ',1PE12.5,' LBS/HR-FT2'/
WRITE(7,5) QGE,QGUC,QGDC,QDG(ICF),QUG(ICF),QGT(ICF)
11 FORMAT(1X,' SUMMARY OF THERMAL AND HYDRAULIC CONDITIONS'/
1' COMBINED LOWER LITHIUM TEMPERATURE (TI) = ',1PE12.5,' DEG F'/
2' DOWNCOMER INLET LITHIUM TEMPERATURE (TD(IUF)) = ',1PE12.5,
3' DEG F'/
4' UPCOMER OUTLET LITHIUM TEMPERATURE (TU(IUF)) = ',1PE12.5,
5' DEG F'/
61X/' HEAT TRANSFERRED TO DOWNCOMER (QDT(IUF)) = ',1PE12.5,
7' BTU/HR'/
8' HEAT TRANSFERRED TO UPCOMER (QUG(IUF)) = ',1PE12.5,' BTU/HR'/
9' TOTAL HEAT TRANSFERRED FROM EBR-II (QOT(IUF)) = ',1PE12.5,
1' BTU/HR'/
2' DOWNCOMER PRESSURE DROP (PRESD(IUF)) = ',1PE12.5,' PSI'/
3' UPCOMER PRESSURE DROP (PRESU(IUF)) = ',1PE12.5,' PSI'/
4' TOTAL INREACTOR PRESS DROP (TOTPRES) = ',1PE12.5,' PSI'/
5' LITHIUM PRESSURE AT LTIV BOTTOM (PBOTL) = ',1PE12.5,' PSI'/
6' EXREACTOR LTIV PRESSURE DROP EST (DELPEX) = ',1PE12.5,' PSI'/
7' TOTAL LTIV PRESS DROP ESTIMATE (TPLOOP) = ',1PE12.5,' PSI'/
5 FORMAT('/',
2' INPUT GAMMA HEATING RATE IN S.S. (QGE) = ',1PE12.5,' BTU/HR/FT3'/
3' LINEAR GAMMA HEAT GEN RATE UPCOMER (QGUC) = ',1PE12.5,' BTU/HR/FT
4' /
5' LINEAR GAMMA HEAT GEN RATE DWNCOMER (QGDC) = ',1PE12.5,
6' BTU/HR/FT'/
7' GAMMA HEAT GENERATION IN DOWNCOMER (QDG(ICF)) = ',1PE12.5,
8' BTU/HR'/
9' GAMMA HEAT GENERATION IN UPCOMER (QUG(ICF)) = ',1PE12.5,
1' BTU/HR'/
2' TOTAL GAMMA HEAT GENERATION (QGT(ICF)) = ',1PE12.5,' BTU/HR'/

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C
C PRINT OUT AXIAL RESULTS
C

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IF(NIT .GT. 0) GO TO 104

WRITE(7,17)
17 FORMAT('1')
WRITE(7,25)
25 FORMAT('//52X,'*****AXIAL OUTPUT RESULTS*****1X/1X//')
WRITE(7,15)
15 FORMAT(25X,'AXIAL THERMAL RESULTS'/)
WRITE(7,114)
114 FORMAT('/', ' TABLE KEY'/
1' 2= AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT'/
2' TEBR2= EBR-II SODIUM LTIV SURFACE TEMPERATURE, DEG. F'/
3' TU= UPCOMER LITHIUM TEMPERATURE (CLOSEST TO EBR-II), DEG. F'/
4' TD= DOWNCOMER LITHIUM TEMPERATURE (CLOSEST TO TEST), DEG. F'/
5' UO= OVERALL OUTSIDE FILM COEFF (EBR TO UPCOM), BTU/HR/FT2/F'/
6' QO=AXIAL INCREMENT OUTSIDE HEAT TRANSFER (EBR TO UPCOM), BTU/HR'/
7' UI= OVERALL INSIDE FILM COEF (UPCOM TO DWNCOM), BTU/HR/FT2/F'/
8' QD=AXIAL INCREMENT INSIDE HEAT TRANSFER (UPCOM TO DWNCOM), BTU/HR
9' /
1' QU=AXIAL INCREMENT HEAT TRANSFERRED TO UPCOMER (QO-QD), BTU/HR'/
2' QDT=INTEGRATED AXIAL (FROM I=1) DWNCOM HEAT TRANSFER, BTU/HR'/
3' QOT=TOTAL INTEGRATED AXIAL (FROM I=1) HEAT TRANSFERRED FROM EBR-I
4I, BTU/HR'/

DO 70 I=1,IUF
IF(I .EQ. 1) THEN
WRITE(7,31)

```

```

WRITE(7,69)
ELSE IF(I .EQ. ICI) THEN
WRITE(7,41)
WRITE(7,69)
ELSE IF(I .EQ. III) THEN
WRITE(7,51)
WRITE(7,69)
ELSE IF(I .EQ. IUI) THEN
WRITE(7,61)
WRITE(7,69)
END IF
70 WRITE(7,28) I,2(I),TEBR2(I),TU(I),TD(I),UO(I),QO(I),UI(I),QD(I)
1,QU(I),QDT(I),QOT(I)
WRITE(7,115)
115 FORMAT('/',25X,'DOWNCOMER FLOW AND PHYSICAL PROPERTY DATA RESULTS')
WRITE(7,214)
214 FORMAT('/', ' TABLE KEY'/
1' 2=AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT'/
2' TFRD=LITHIUM FLOW VELOCITY, FT/SEC'/
3' HFD=LITHIUM HEAT TRANSFER FILM COEFFICIENT, BTU/HR-FT2-F'/
5' REYD=LITHIUM REYNOLDS NUMBER, DIMENSIONLESS'/
6' CPD=LITHIUM HEAT CAPACITY, BTU/LB-F'/
7' TKD=LITHIUM THERMAL CONDUCTIVITY, BTU/HR-FT-F'/
8' VISD=LITHIUM VISCOSITY, LB/FT-HR'/
9' DEND=LITHIUM DENSITY, LB/FT3'/
1' FFD=LITHIUM FRICTION FACTOR, DIMENSIONLESS'/
2' DEPU=DOWNCOMER INCREMENTAL PRESSURE DROP, PSI'/
3' PTOPD=DOWNCOMER LITHIUM PRESSURE, PSI'/
DO 170 I=1,IUF
IF(I .EQ. 1) THEN
WRITE(7,31)
WRITE(7,169)
ELSE IF(I .EQ. ICI) THEN
WRITE(7,41)
WRITE(7,169)
ELSE IF(I .EQ. III) THEN
WRITE(7,51)
WRITE(7,169)
ELSE IF(I .EQ. IUI) THEN
WRITE(7,61)
WRITE(7,169)
END IF
170 WRITE(7,28) I,2(I),TFRD(I),HFD(I),REYD(I),CPD(I),TKD(I),
1VISD(I),DEND(I),FFD(I),DELDP(I),PTOPD(I)
WRITE(7,116)
116 FORMAT('/',25X,'UPCOMER FLOW AND PHYSICAL PROPERTY DATA RESULTS')
WRITE(7,314)
314 FORMAT('/', ' TABLE KEY'/
1' 2=AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT'/
2' TFRU=LITHIUM FLOW VELOCITY, FT/SEC'/
3' HFU=LITHIUM HEAT TRANSFER FILM COEFFICIENT, BTU/HR-FT2-F'/
5' REYU=LITHIUM REYNOLDS NUMBER, DIMENSIONLESS'/
6' CPU=LITHIUM HEAT CAPACITY, BTU/LB-F'/
7' TKU=LITHIUM THERMAL CONDUCTIVITY, BTU/HR-FT-F'/
8' VISU=LITHIUM VISCOSITY, LB/FT-HR'/
9' DENU=LITHIUM DENSITY, LB/FT3'/
1' FFU=LITHIUM FRICTION FACTOR, DIMENSIONLESS'/
2' DELPU=UPCOMER INCREMENTAL PRESSURE DROP, PSI'/
3' PTOPU=UPCOMER LITHIUM PRESSURE, PSI'/
DO 270 I=1,IUF
IF(I .EQ. 1) THEN
WRITE(7,31)
WRITE(7,269)
ELSE IF(I .EQ. ICI) THEN

```

```

WRITE(7,41)
WRITE(7,269)
ELSE IF(1.EQ.111) THEN
WRITE(7,51)
WRITE(7,269)
ELSE IF(1.EQ.101) THEN
WRITE(7,61)
WRITE(7,269)
END IF
270 WRITE(7,28) I,Z(I),TFRU(I),HFU(I),REYU(I),CPU(I),TKU(I),
1VISU(I),DENU(I),FFU(I),DELP(I),PTOPU(I)
WRITE(7,13)
WRITE(7,110)
110 FORMAT(/,' TABLE KEY' /
1'Z = DISTANCE FROM LTIV LOOP BOTTOM, FT' /
2'QGD = GAMMA HEAT GENERATION IN AXIAL DOWNCOMER INCREMENT, BTU/HR
3' /
4'QGU = GAMMA HEAT GENERATION IN AXIAL UPCOMER INCREMENT, BTU/HR' /
5'QDG = INTEGRATED AXIAL GAMMA HEAT GEN IN DWNCOMER FROM INITIAL IC
6I NODE, BTU/HR' /
7'QUG = INTEGRATED AXIAL GAMMA HEAT GEN IN UPCOMER FROM INITIAL ICI
8 NODE, BTU/HR' /
9'QGT = TOTAL INTEGRATED AXIAL GAMMA HEAT GEN FROM INITIAL ICI NODE
1, BTU/HR' /
WRITE(7,49)
DO 71 I=ICI,ICF
71 WRITE(7,28) I,Z(I),QGD(I),QGU(I),QDG(I),QUG(I)
1,QGT(I)
C WRITE(7,27) EDDL,EDDU,EDUL,EDUU,PR,GDL,GDU,GUL,GUU
C WRITE(7,27) REDL,REDU,REUL,REUU,HDL,HDU,HUL,HUU
C WRITE(7,27) RES1,RES2,RES3,RO,RI,RL2,RL3,RL4,REL2,REL3,REL4
C WRITE(7,27) REU1,REU2,REU3,RU,RK,RU2,RU3,RU4,RUL2,RUL3,RUL4
C
C WRITE OUT NODAL DATA FOR OSPPS PLOTTING ON FORT.9 FILE
C
104 IF( MIT .GT. 0) GO TO 105
WRITE(9,226)
226 FORMAT(/,25X,'UPCOMER & DOWNCOMER AXIAL TEMPERATURES'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (TU(IX),IX=1,IUF)
WRITE(9,225)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (TD(IX),IX=1,IUF)
WRITE(9,227)
227 FORMAT(/,25X,'EBR-II AXIAL TEMPERATURES'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (TEBR2(IX),IX=1,IUF)
WRITE(9,228)
228 FORMAT(/,25X,'OUTER FILM HEAT TRANSFER COEF.'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (UO(IX),IX=1,IUF)
WRITE(9,229)
229 FORMAT(/,25X,'INNER FILM HEAT TRANSFER COEF.'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (UI(IX),IX=1,IUF)
WRITE(9,230)
230 FORMAT(/,25X,'TOTAL HEAT TRANSFER FROM EBR-II'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (QOT(IX),IX=1,IUF)
WRITE(9,231)
231 FORMAT(/,25X,'HEAT TRANSFER TO DOWNCOMER'//)
WRITE(9,*) (Z(IX),IX=1,IUF)

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```

WRITE(9,*) (QOT(IX),IX=1,IUF)
WRITE(9,232)
232 FORMAT(/,25X,'HEAT TRANSFER TO UPCOMER'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (QUT(IX),IX=1,IUF)
WRITE(9,233)
233 FORMAT(/,25X,'PRESSURE DROP DOWNCOMER & UPCOMER'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (PRESD(IX),IX=1,IUF)
WRITE(9,225)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (PRESU(IX),IX=1,IUF)
WRITE(9,234)
234 FORMAT(/,25X,'PRESSURE LEVEL DOWNCOMER & UPCOMER'//)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (PTOPD(IX),IX=1,IUF)
WRITE(9,225)
WRITE(9,*) (Z(IX),IX=1,IUF)
WRITE(9,*) (PTOPU(IX),IX=1,IUF)

27 FORMAT (/11(1X,1PE12.5))
28 FORMAT (1X,I3,11(1X,1PE12.5))
31 FORMAT (/20X,'LOWER REGION'//)
41 FORMAT (/20X,'CORE REGION'//)
51 FORMAT (/20X,'INTERMEDIATE REGION'//)
61 FORMAT (/20X,'UPPER REGION'//)
13 FORMAT(/,25X,'CORE REGION GAMMA HEATING RESULTS'//)
38 FORMAT(/)
69 FORMAT(11X,'Z',10X,'TEBR2',9X,'TU',11X,'TD',11X,'UO',11X,'QO',11X,
1'UI',11X,'QD',11X,'QU',11X,'QDT',10X,'QOT')
169 FORMAT(11X,'Z',11X,'TFRD',9X,'HFD',10X,'REYD',9X,'CPD',
19X,'TKD',9X,'VISD',9X,'DEND',10X,'FFD',9X,'DELPD',9X,'PTOPD')
269 FORMAT(11X,'Z',11X,'TFRU',9X,'HFU',10X,'REYU',9X,'CPU',
19X,'TKU',9X,'VISU',9X,'DENU',10X,'FFU',9X,'DELP',9X,'PTOPU')
49 FORMAT(10X,'Z',10X,
1'QGD',10X,'QGU',10X,'QDG',10X,'QUG',10X,'QGT')
225 FORMAT(1X/1X/)

105 CONTINUE
CALL ITIME(IARRAY)
WRITE(7,225)
WRITE(7,212) IARRAY(1),IARRAY(2),IARRAY(3)
212 FORMAT(5X,'END TIME: ',I3,' HRS',I3,' MIN',I3,' SEC')

STOP

END

SUBROUTINE LIPROP(TP,CP,TK,VIS,DEN)
C GIVEN THE TEMPERATURE THIS SUBROUTINE CALCULATES THE LITHIUM
C PHYSICAL PROPERTIES USING THE POLYNOMIAL FITS GIVEN IN ANL MEMO
C RE/EBR0155. TEMPERATURE ARE IN DEG F.
C
IMPLICIT REAL*8 (A-H, O-Z)
DATA A1,A2,A3,A4 /1.1257,-2.8867D-4,2.3D-7,-7.0833D-11/
DATA B1,B2,B3,B4 /31.1,-0.015583,1.875D-5,-1.6667D-8/
DATA C1,C2,C3,C4 /2.39,-0.0041333,4.25D-6,-1.6667D-9/
DATA D1,D2,D3,D4 /34.1,-0.0092917,1.000D-5,-5.2083D-9/

T1=TP**2.0
T2=T1*TP

```

```

C
C CALC HEAT CAPACITY (BTU/LB-F)
C
C CP=A1 + A2*TP + A3*T1 + A4*T2
C
C CALC THERMAL CONDUCTIVITY (BTU/HR-FT-DEG F)
C
C TK=B1 +B2*TP +B3*T1 +B4*T2
C
C CALC VISCOSITY (LB/FT-HR)
C
C VIS=C1 +C2*TP + C3*T1 + C4*T2
C
C CALC DENSITY (LB/FT3)
C
C DEN = D1 +D2*TP + D3*T1 +D4*T2
C
C RETURN
C END
C
C SUBROUTINE LICOEF (MREG,TFR,GFR,RENO,HFF)
C
C SUBROUTINE CALCULATES THE LITHIUM HEAT TRANSFER FILM COEFFICIENT
C GIVEN THE MASS FLOW RATE (TFR),PROPERTIES, AND REGION. TRANSMITS
C MASS FLUX (GFR), REYNOLDS NO (RENO), AND H.T. FILM COEFF IN UNITS
C OF (BTU/HR/FT2/F). CORRELATION IS FOR TURBULENT LIQUID METAL
C FLOW THROUGHOUT CIRCULAR DUCTS GIVEN IN ECKERT & DRAKE PAGE 300.
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
C COMMON EDDL,EDDU,EDUL,EDUU,VDL,VDU,PR,VISL,
C 1TKL,SEV,CH,EX
C DIMENSION VDL(6),VDU(6)
C
C MREG=1 DOWNCOMER LOWER REGION
C
C IF(MREG.EQ. 1) THEN
C VD=VDL(1)
C ED=EDDL
C
C MREG=2 DOWNCOMER UPPER REGION
C
C ELSE IF(MREG.EQ. 2) THEN
C VD=VDU(1)
C ED=EDDU
C
C MREG=3 UPCOMER LOWER REGION
C
C ELSE IF(MREG.EQ. 3) THEN
C VD=VDL(3)
C ED=EDUL
C
C MREG=4 UPCOMER UPPER REGION
C
C ELSE IF(MREG.EQ. 4) THEN
C VD=VDU(3)
C ED=EDUU
C
C END IF
C
C GFR=TFR/VD
C RENO=ED*GFR/VISL
C HFF=(TKL/ED)*(SEV+CH*(RENO*PR)**EX)

```

```

RETURN
END
C
C SUBROUTINE LIFRIC (NREG,D,RE,G,FF,DELP)
C
C THIS SUBROUTINE CALCULATES THE FRICTION FACTOR AND AXIAL NODAL
C FRICTION PRESSURE DROP IN THE DOWNCOMER AND UPCOMER SECTIONS
C
C IMPLICIT REAL*8 (A-H,O-Z)
C
C COMMON EDDL,EDDU,EDUL,EDUU,VDL,VDU,PR,VISL,TKL,SEV,CH,EX
C COMMON DELL,DELC,DELI,DELU,CFRC
C
C DIMENSION VDL(6),VDU(6)
C
C NREG=1 DOWNCOMER LOWER REGION
C
C IF(NREG.EQ. 1) THEN
C C=(DELL/EDDL)*CFRC/D
C
C NREG=2 UPCOMER LOWER REGION
C
C ELSE IF(NREG.EQ. 2) THEN
C C=(DELL/EDUL)*CFRC/D
C
C NREG=3 DOWNCOMER CORE REGION
C
C ELSE IF(NREG.EQ. 3) THEN
C C=(DELC/EDDL)*CFRC/D
C
C NREG=4 UPCOMER CORE REGION
C
C ELSE IF(NREG.EQ. 4) THEN
C C=(DELC/EDUL)*CFRC/D
C
C NREG=5 DOWNCOMER INTERMEDIATE REGION
C
C ELSE IF(NREG.EQ. 5) THEN
C C=(DELI/EDDL)*CFRC/D
C
C NREG=6 UPCOMER INTERMEDIATE REGION
C
C ELSE IF(NREG.EQ. 6) THEN
C C=(DELI/EDUL)*CFRC/D
C
C NREG=7 DOWNCOMER UPPER REGION
C
C ELSE IF(NREG.EQ. 7) THEN
C C=(DELU/EDDU)*CFRC/D
C
C NREG=8 UPCOMER UPPER REGION
C
C ELSE IF(NREG.EQ. 8) THEN
C C=(DELU/EDUU)*CFRC/D
C
C END IF
C
C FF=0.0014 + (0.125)/(RE**0.32)
C DELP=C*FF*(G**2.0)
C
C RETURN
C END

```

```
      SUBROUTINE LIRES(TDD,RIS)
C
C  THIS SUBROUTINE CALCULATES THE LITHIUM ELECTRICAL RESISTIVITY IN
C  UNITS OF MICROHMS-CM. THE CORRELATION REF IS:
C    PRATT & WHITNEY AIRCRAFT. "THE ELECTRICAL RESISTIVITY OF
C    LITHIUM AND SODIUM-POTASSIUM ALLOY", REPORT NO. PWAC-349.
C    MIDDLETOWN, CONN.
C
      IMPLICIT REAL*8 (A-H,O-Z)

      TCC=(TDD-32.0)/1.8
      RIS=17.2+5.24E-02*TCC-4.46E-05*(TCC)**2.0

      RETURN
      END
```

APPENDIX F
TMOLL AXIAL OUTPUT RESULTS

TABLE KEY
 Z= AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT
 TEBR2= EBR-II SODIUM LTIV SURFACE TEMPERATURE, DEG. F
 TU= UPCOMER LITHIUM TEMPERATURE (CLOSEST TO EBR-II), DEG. F
 TD= DOWNCOMER LITHIUM TEMPERATURE (CLOSEST TO TEST), DEG. F
 UO= OVERALL OUTSIDE FILM COEFF (EBR TO UPCOM), BTU/HR/FT²/F
 QO=AXIAL INCREMENT OUTSIDE HEAT TRANSFER (EBR TO UPCOM), BTU/HR
 UI= OVERALL INSIDE FILM COEF (UPCM TO DWNCOM), BTU/HR/FT²/F
 QD=AXIAL INCREMENT INSIDE HEAT TRANSFER (UPCOM TO DWNCOM), BTU/HR
 QU=AXIAL INCREMENT HEAT TRANSFERED TO UPCOMER (QO-QD), BTU/HR
 QDT=INTEGRATED AXIAL (FROM I=1) DWNCOM HEAT TRANSFER, BTU/HR
 QOT=TOTAL INTEGRATED AXIAL (FROM I=1) HEAT TRANSFERED FROM EBR-II, BTU/HR

LOWER REGION

	Z	TEBR2	TU	TD	UO	QO	UI	QD	QU	QDT	QOT
1	4.09367E-01	7.00000E+02	5.50125E+02	5.50000E+02	8.23187E+00	2.81209E+02	1.43297E+03	0.00000E+00	2.81209E+02	0.00000E+00	2.81209E+02
2	8.18733E-01	7.00000E+02	5.50236E+02	5.49986E+02	8.23272E+00	2.81004E+02	1.43296E+03	3.05938E+01	2.50410E+02	3.05938E+01	5.62213E+02
3	1.22810E+00	7.00000E+02	5.50334E+02	5.49959E+02	8.23348E+00	2.80821E+02	1.43296E+03	6.11650E+01	2.19656E+02	9.17588E+01	8.43034E+02
4	1.63747E+00	7.00000E+02	5.50418E+02	5.49918E+02	8.23415E+00	2.80660E+02	1.43295E+03	9.17163E+01	1.88944E+02	1.83475E+02	1.12369E+03
5	2.04683E+00	7.00000E+02	5.50489E+02	5.49864E+02	8.23472E+00	2.80522E+02	1.43295E+03	1.22250E+02	1.58272E+02	3.05725E+02	1.40422E+03

CORE REGION

	Z	TEBR2	TU	TD	UO	QO	UI	QD	QU	QDT	QOT
6	2.15933E+00	7.00000E+02	5.51343E+02	5.48879E+02	8.23520E+00	7.70599E+01	1.43295E+03	4.19831E+01	3.50768E+01	3.47708E+02	1.48128E+03
7	2.27183E+00	7.18300E+02	5.52147E+02	5.47838E+02	8.37958E+00	8.75603E+01	1.43294E+03	1.65635E+02	-7.80749E+01	5.13343E+02	1.56884E+03
8	2.38433E+00	7.36600E+02	5.52901E+02	5.46743E+02	8.52676E+00	9.84351E+01	1.43294E+03	2.89600E+02	-1.91165E+02	8.02944E+02	1.66727E+03
9	2.49683E+00	7.54900E+02	5.53604E+02	5.45592E+02	8.67676E+00	1.09695E+02	1.43294E+03	4.13891E+02	-3.04196E+02	1.21683E+03	1.77697E+03
10	2.60933E+00	7.73200E+02	5.54257E+02	5.44385E+02	8.82959E+00	1.21351E+02	1.43294E+03	5.38519E+02	-4.17168E+02	1.75535E+03	1.89832E+03
11	2.72183E+00	7.91500E+02	5.54860E+02	5.43123E+02	8.98529E+00	1.33415E+02	1.43294E+03	6.63497E+02	-5.30082E+02	2.41885E+03	2.03173E+03
12	2.83433E+00	8.09800E+02	5.55413E+02	5.41806E+02	9.14386E+00	1.45897E+02	1.43295E+03	7.88839E+02	-6.42942E+02	3.20769E+03	2.17763E+03
13	2.94683E+00	8.28100E+02	5.55916E+02	5.40432E+02	9.30534E+00	1.58809E+02	1.43296E+03	9.14557E+02	-7.55748E+02	4.12225E+03	2.33644E+03
14	3.05933E+00	8.46400E+02	5.56368E+02	5.39002E+02	9.46973E+00	1.72163E+02	1.43298E+03	1.04067E+03	-8.68502E+02	5.16291E+03	2.50860E+03
15	3.17183E+00	8.64700E+02	5.56770E+02	5.37516E+02	9.63707E+00	1.85970E+02	1.43299E+03	1.16718E+03	-9.81208E+02	6.33009E+03	2.69457E+03

INTERMEDIATE REGION

	Z	TEBR2	TU	TD	UO	QO	UI	QD	QU	QDT	QOT
16	3.57112E+00	8.83000E+02	5.55043E+02	5.35473E+02	9.80736E+00	7.10700E+02	1.43301E+03	4.59306E+03	-3.88236E+03	1.09232E+04	3.40527E+03
17	3.97040E+00	8.83000E+02	5.53284E+02	5.33396E+02	9.79411E+00	7.13498E+02	1.43313E+03	4.66885E+03	-3.95536E+03	1.55920E+04	4.11877E+03
18	4.36969E+00	8.83000E+02	5.51492E+02	5.31286E+02	9.78065E+00	7.16339E+02	1.43325E+03	4.74496E+03	-4.02862E+03	2.03370E+04	4.83511E+03
19	4.76897E+00	8.83000E+02	5.49667E+02	5.29141E+02	9.76695E+00	7.19225E+02	1.43336E+03	4.82139E+03	-4.10217E+03	2.51584E+04	5.55434E+03
20	5.16826E+00	8.83000E+02	5.47809E+02	5.26962E+02	9.75304E+00	7.22154E+02	1.43349E+03	4.89814E+03	-4.17599E+03	3.00565E+04	6.27649E+03
21	5.56755E+00	8.83000E+02	5.45919E+02	5.24749E+02	9.73891E+00	7.25126E+02	1.43361E+03	4.97523E+03	-4.25010E+03	3.50317E+04	7.00162E+03
22	5.96683E+00	8.83000E+02	5.43995E+02	5.22501E+02	9.72455E+00	7.28141E+02	1.43373E+03	5.05264E+03	-4.32450E+03	4.00844E+04	7.72976E+03
23	6.36612E+00	8.83000E+02	5.42038E+02	5.20219E+02	9.70998E+00	7.31199E+02	1.43386E+03	5.13040E+03	-4.39920E+03	4.52148E+04	8.46096E+03
24	6.76540E+00	8.83000E+02	5.40048E+02	5.17902E+02	9.69519E+00	7.34300E+02	1.43398E+03	5.20850E+03	-4.47420E+03	5.04233E+04	9.19526E+03
25	7.16469E+00	8.83000E+02	5.38024E+02	5.15550E+02	9.68017E+00	7.37442E+02	1.43411E+03	5.28694E+03	-4.54950E+03	5.57102E+04	9.93270E+03
26	7.56397E+00	8.83000E+02	5.35966E+02	5.13163E+02	9.66494E+00	7.40627E+02	1.43424E+03	5.36575E+03	-4.62512E+03	6.10760E+04	1.06733E+04
27	7.96326E+00	8.83000E+02	5.33875E+02	5.10741E+02	9.64950E+00	7.43853E+02	1.43437E+03	5.44491E+03	-4.70105E+03	6.65209E+04	1.14172E+04
28	8.36254E+00	8.57062E+02	5.31718E+02	5.08283E+02	9.40041E+00	6.74856E+02	1.43450E+03	5.52443E+03	-4.84957E+03	7.20453E+04	1.20920E+04
29	8.76183E+00	8.25750E+02	5.29493E+02	5.05794E+02	9.11172E+00	5.95122E+02	1.43464E+03	5.59665E+03	-5.00152E+03	7.76419E+04	1.26872E+04
30	9.16111E+00	7.94438E+02	5.27206E+02	5.03276E+02	8.83252E+00	5.19818E+02	1.43478E+03	5.66042E+03	-5.14060E+03	8.33024E+04	1.32070E+04
31	9.56040E+00	7.63126E+02	5.24863E+02	5.00733E+02	8.56272E+00	4.48732E+02	1.43492E+03	5.71621E+03	-5.26748E+03	8.90186E+04	1.36557E+04
32	9.95969E+00	7.31814E+02	5.22468E+02	4.98169E+02	8.30219E+00	3.81655E+02	1.43506E+03	5.76446E+03	-5.38281E+03	9.47830E+04	1.40374E+04
33	1.03590E+01	7.00502E+02	5.20027E+02	4.95586E+02	8.05084E+00	3.18386E+02	1.43521E+03	5.80560E+03	-5.48722E+03	1.00589E+05	1.43557E+04
34	1.07583E+01	7.00000E+02	5.17572E+02	4.92988E+02	8.03106E+00	3.21063E+02	1.43535E+03	5.84004E+03	-5.51897E+03	1.06429E+05	1.46768E+04
35	1.11575E+01	7.00000E+02	5.15103E+02	4.90375E+02	8.01494E+00	3.24790E+02	1.43550E+03	5.87476E+03	-5.54997E+03	1.12303E+05	1.50016E+04
36	1.15568E+01	7.00000E+02	5.12621E+02	4.87746E+02	7.99877E+00	3.28521E+02	1.43564E+03	5.90989E+03	-5.58137E+03	1.18213E+05	1.53301E+04
37	1.19561E+01	7.00000E+02	5.10124E+02	4.85101E+02	7.98257E+00	3.32258E+02	1.43579E+03	5.94542E+03	-5.61316E+03	1.24159E+05	1.56624E+04

38	1	23554E+01	7	00000E+02	5	07612E+02	4	82440E+02	7	96632E+00	3	36001E+02	1	43594E+03	5	98136E+03	-5	64536E+03	1	30140E+05	1	59984E+04
39	1	27547E+01	7	00000E+02	5	05086E+02	4	79763E+02	7	95003E+00	3	39748E+02	1	43608E+03	6	01771E+03	-5	67796E+03	1	36158E+05	1	63381E+04
40	1	31540E+01	7	00000E+02	5	02546E+02	4	77070E+02	7	93370E+00	3	43502E+02	1	43623E+03	6	05446E+03	-5	71096E+03	1	42212E+05	1	66816E+04
41	1	35533E+01	7	00000E+02	4	99991E+02	4	74360E+02	7	91733E+00	3	47261E+02	1	43638E+03	6	09162E+03	-5	74436E+03	1	48304E+05	1	70289E+04
42	1	39525E+01	7	00000E+02	4	97420E+02	4	71634E+02	7	90091E+00	3	51025E+02	1	43653E+03	6	12919E+03	-5	77816E+03	1	54433E+05	1	73799E+04
43	1	43518E+01	7	00000E+02	4	94835E+02	4	68890E+02	7	88445E+00	3	54796E+02	1	43668E+03	6	16717E+03	-5	81237E+03	1	60600E+05	1	77347E+04
44	1	47511E+01	7	00000E+02	4	92234E+02	4	66130E+02	7	86794E+00	3	58572E+02	1	43683E+03	6	20556E+03	-5	84698E+03	1	66806E+05	1	80933E+04
45	1	51504E+01	7	00000E+02	4	89617E+02	4	63352E+02	7	85139E+00	3	62354E+02	1	43697E+03	6	24436E+03	-5	88200E+03	1	73050E+05	1	84556E+04
46	1	55497E+01	7	00000E+02	4	86985E+02	4	60557E+02	7	83479E+00	3	66142E+02	1	43712E+03	6	28357E+03	-5	91743E+03	1	79334E+05	1	88218E+04
47	1	59490E+01	7	00000E+02	4	84336E+02	4	57744E+02	7	81815E+00	3	69936E+02	1	43727E+03	6	32319E+03	-5	95326E+03	1	85657E+05	1	91917E+04
48	1	63483E+01	7	00000E+02	4	81672E+02	4	54913E+02	7	80147E+00	3	73735E+02	1	43742E+03	6	36323E+03	-5	98950E+03	1	92020E+05	1	95655E+04
49	1	67475E+01	7	00000E+02	4	78991E+02	4	52064E+02	7	78474E+00	3	77541E+02	1	43757E+03	6	40369E+03	-6	02615E+03	1	98424E+05	1	99430E+04
50	1	71468E+01	7	00000E+02	4	76294E+02	4	49198E+02	7	76796E+00	3	81353E+02	1	43773E+03	6	44456E+03	-6	06320E+03	2	04868E+05	2	03243E+04
51	1	75461E+01	7	00000E+02	4	73580E+02	4	46312E+02	7	75114E+00	3	85171E+02	1	43788E+03	6	48584E+03	-6	10067E+03	2	11354E+05	2	07095E+04
52	1	79454E+01	7	00000E+02	4	70850E+02	4	43409E+02	7	73428E+00	3	88996E+02	1	43803E+03	6	52755E+03	-6	13855E+03	2	17882E+05	2	10985E+04
53	1	83447E+01	7	00000E+02	4	68102E+02	4	40486E+02	7	71736E+00	3	92826E+02	1	43818E+03	6	56967E+03	-6	17684E+03	2	24451E+05	2	14913E+04
54	1	87440E+01	7	00000E+02	4	65337E+02	4	37545E+02	7	70040E+00	3	96663E+02	1	43834E+03	6	61221E+03	-6	21554E+03	2	31064E+05	2	18880E+04
55	1	91433E+01	7	00000E+02	4	62555E+02	4	34584E+02	7	68340E+00	4	00506E+02	1	43849E+03	6	65517E+03	-6	25466E+03	2	37719E+05	2	22885E+04

UPPER REGION

	Z	TEBR2	TU	TD	UO	QO	UI	QD	QU	QDT	QOT											
56	1	96300E+01	7	00000E+02	4	62783E+02	4	34573E+02	7	13754E+00	5	39917E+02	3	93569E+00	2	58463E+01	5	14070E+02	2	37745E+05	2	28284E+04
57	2	01168E+01	7	00000E+02	4	63012E+02	4	34561E+02	7	13887E+00	5	39498E+02	3	93569E+00	2	60683E+01	5	13429E+02	2	37771E+05	2	33679E+04
58	2	06035E+01	7	00000E+02	4	63240E+02	4	34550E+02	7	14021E+00	5	39079E+02	3	93569E+00	2	62901E+01	5	12789E+02	2	37797E+05	2	39070E+04
59	2	10903E+01	7	00000E+02	4	63468E+02	4	34538E+02	7	14154E+00	5	38661E+02	3	93569E+00	2	65117E+01	5	12149E+02	2	37824E+05	2	44457E+04
60	2	15770E+01	7	00000E+02	4	63695E+02	4	34526E+02	7	14287E+00	5	38243E+02	3	93569E+00	2	67331E+01	5	11510E+02	2	37850E+05	2	49839E+04
61	2	20638E+01	6	70075E+02	4	63886E+02	4	34514E+02	6	94421E+00	4	56566E+02	3	93569E+00	2	69543E+01	4	29612E+02	2	37877E+05	2	54405E+04
62	2	25505E+01	6	32932E+02	4	64035E+02	4	34502E+02	6	70719E+00	3	61209E+02	3	93569E+00	2	71420E+01	3	34067E+02	2	37904E+05	2	58017E+04
63	2	30373E+01	5	95789E+02	4	64144E+02	4	34490E+02	6	48087E+00	2	72028E+02	3	93569E+00	2	72905E+01	2	44737E+02	2	37932E+05	2	60737E+04
64	2	35240E+01	5	58646E+02	4	64215E+02	4	34477E+02	6	26504E+00	1	88618E+02	3	93569E+00	2	74023E+01	1	62125E+02	2	37959E+05	2	62632E+04
65	2	40108E+01	5	21504E+02	4	64252E+02	4	34465E+02	6	05945E+00	1	10589E+02	3	93569E+00	2	74798E+01	8	31093E+01	2	37987E+05	2	63729E+04
66	2	44975E+01	4	84361E+02	4	64257E+02	4	34453E+02	5	86385E+00	3	75644E+01	3	93569E+00	2	75253E+01	1	00391E+01	2	38014E+05	2	64105E+04
67	2	49843E+01	4	47218E+02	4	64231E+02	4	34441E+02	5	67802E+00	-3	08212E+01	3	93569E+00	2	75407E+01	-5	83620E+01	2	38042E+05	2	63797E+04
68	2	54710E+01	4	10075E+02	4	64176E+02	4	34428E+02	5	50169E+00	-9	49191E+01	3	93569E+00	2	75281E+01	-1	22447E+02	2	38069E+05	2	62847E+04
69	2	59578E+01	3	72933E+02	4	64095E+02	4	34416E+02	5	33460E+00	-1	55067E+02	3	93569E+00	2	74891E+01	-1	82556E+02	2	38097E+05	2	61297E+04
70	2	64445E+01	3	35790E+02	4	63989E+02	4	34404E+02	5	17651E+00	-2	11591E+02	3	93569E+00	2	74253E+01	-2	39016E+02	2	38124E+05	2	59181E+04
71	2	69313E+01	2	98647E+02	4	63859E+02	4	34392E+02	5	02713E+00	-2	64800E+02	3	93569E+00	2	73383E+01	-2	92138E+02	2	38151E+05	2	56533E+04
72	2	74180E+01	2	61504E+02	4	63707E+02	4	34380E+02	4	88622E+00	-3	14993E+02	3	93569E+00	2	72295E+01	-3	42223E+02	2	38179E+05	2	53383E+04
73	2	79048E+01	2	24361E+02	4	63533E+02	4	34368E+02	4	75349E+00	-3	62454E+02	3	93569E+00	2	71000E+01	-3	89554E+02	2	38206E+05	2	49758E+04
74	2	83915E+01	1	87219E+02	4	63340E+02	4	34356E+02	4	62868E+00	-4	07451E+02	3	93569E+00	2	69510E+01	-4	34402E+02	2	38233E+05	2	45684E+04
75	2	88783E+01	1	50076E+02	4	63128E+02	4	34344E+02	4	51150E+00	-4	50242E+02	3	93569E+00	2	67835E+01	-4	77026E+02	2	38259E+05	2	41181E+04
76	2	93650E+01	1	12933E+02	4	62898E+02	4	34332E+02	4	40168E+00	-4	91069E+02	3	93569E+00	2	65984E+01	-5	17667E+02	2	38286E+05	2	36271E+04
77	2	98518E+01	8	00000E+01	4	62652E+02	4	34320E+02	4	31012E+00	-5	25759E+02	3	93569E+00	2	63966E+01	-5	52156E+02	2	38312E+05	2	31013E+04
78	3	03385E+01	8	00000E+01	4	62407E+02	4	34309E+02	4	30920E+00	-5	25309E+02	3	93569E+00	2	61805E+01	-5	51490E+02	2	38339E+05	2	25760E+04
79	3	08253E+01	8	00000E+01	4	62162E+02	4	34297E+02	4	30827E+00	-5	24860E+02	3	93569E+00	2	59645E+01	-5	50824E+02	2	38365E+05	2	20511E+04
80	3	13120E+01	8	00000E+01	4	61917E+02	4	34286E+02	4	30735E+00	-5	24411E+02	3	93569E+00	2	57488E+01	-5	50160E+02	2	38390E+05	2	15267E+04
81	3	17988E+01	8	00000E+01	4	61672E+02	4	34274E+02	4	30643E+00	-5	23963E+02	3	93569E+00	2	55332E+01	-5	49497E+02	2	38416E+05	2	10028E+04
82	3	22855E+01	8	00000E+01	4	61428E+02	4	34263E+02	4	30551E+00	-5	23516E+02	3	93569E+00	2	53178E+01	-5	48883E+02	2	38441E+05	2	04793E+04
83	3	27723E+01	8	00000E+01	4	61184E+02	4	34252E+02	4	30459E+00	-5	23070E+02	3	93569E+00	2	51026E+01	-5	48172E+02	2	38466E+05	1	99562E+04
84	3	32590E+01	8	00000E+01	4	60941E+02	4	34241E+02	4	30368E+00	-5	22624E+02	3	93569E+00	2	48876E+01	-5	47512E+02	2	38491E+05	1	94336E+04
85	3	37458E+01	8	00000E+01	4	60698E+02	4	34230E+02	4	30276E+00	-5	22179E+02	3	93569E+00	2	46728E+01	-5	46852E+02	2	38516E+05	1	89114E+04
86	3	42325E+01	8	00000E+01	4	60455E+02	4	34219E+02	4	30185E+00	-5	21735E+02	3	93569E+00	2	44581E+01	-5	46193E+02	2	38540E+05	1	83896E+04
87	3	47193E+01	8	00000E+01	4	60212E+02	4	34208E+02	4	30094E+00	-5	21291E+02	3	93569E+00	2	42437E+01	-5	45535E+02	2	38565E+05	1	78684E+04
88	3	52060E+01	8	00000E+01	4	59970E+02	4	34197E+02	4	30002E+00	-5	20848E+02	3	93569E+00	2	40294E+01	-5	44878E+02	2	38589E+05	1	73475E+04
89	3	56928E+01	8	00000E+01	4	59728E+02	4	34187E+02	4	29912E+00	-5	20406E+02	3	93569E+00	2	38153E+01	-5	44222E+02	2	38612E+05	1	68271E+04
90	3	61795E+01	8	00000E+01	4	59486E+02	4	34176E+02	4	29821E+00	-											

94	3.81265E+01	8.00000E+01	4.58521E+02	4.34135E+02	4.29459E+00	-5.18207E+02	3.93569E+00	2.27475E+01	-5.40954E+02	2.38728E+05	1.42317E+04
95	3.86133E+01	8.00000E+01	4.58281E+02	4.34125E+02	4.29369E+00	-5.17769E+02	3.93569E+00	2.25345E+01	-5.40303E+02	2.38751E+05	1.37139E+04

DOWNCOMER FLOW AND PHYSICAL PROPERTY DATA RESULTS

TABLE KEY
Z=AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT
TFRD=LITHIUM FLOW VELOCITY, FT/SEC
HFD=LITHIUM HEAT TRANSFER FILM COEFFICIENT, BTU/HR-FT²-F
REYD=LITHIUM REYNOLDS NUMBER, DIMENSIONLESS
CPD=LITHIUM HEAT CAPACITY, BTU/LB-F
TKD=LITHIUM THERMAL CONDUCTIVITY, BTU/HR-FT-F
VIRD=LITHIUM VISCOSITY, LB/FT-HR
DEND=LITHIUM DENSITY, LB/FT³
FFD=LITHIUM FRICTION FACTOR, DIMENSIONLESS
DEPU=DOWNCOMER INCREMENTAL PRESSURE DROP, PSI
PTOPD=DOWNCOMER LITHIUM PRESSURE, PSI

LOWER REGION

Z	TFRD	HFD	REYD	CPD	TKD	VIRD	DEND	FFD	DELPD	PTOPD	
1	4.09367E-01	1.14089E+01	2.71985E+04	1.13715E+04	1.02472E+00	2.54283E+01	1.12501E+00	3.11480E+01	7.69576E-03	5.50923E-01	6.48243E+01
2	8.18733E-01	1.14089E+01	2.71985E+04	1.13715E+04	1.02472E+00	2.54283E+01	1.12501E+00	3.11480E+01	7.69576E-03	5.50923E-01	6.53752E+01
3	1.22810E+00	1.14088E+01	2.71986E+04	1.13714E+04	1.02472E+00	2.54284E+01	1.12503E+00	3.11481E+01	7.69578E-03	5.50924E-01	6.59262E+01
4	1.63747E+00	1.14088E+01	2.71988E+04	1.13711E+04	1.02473E+00	2.54287E+01	1.12505E+00	3.11482E+01	7.69583E-03	5.50926E-01	6.64771E+01
5	2.04683E+00	1.14088E+01	2.71992E+04	1.13707E+04	1.02473E+00	2.54291E+01	1.12509E+00	3.11483E+01	7.69590E-03	5.50929E-01	6.70280E+01

CORE REGION

Z	TFRD	HFD	REYD	CPD	TKD	VIRD	DEND	FFD	DELPD	PTOPD	
6	2.15933E+00	1.14087E+01	2.71997E+04	1.13702E+04	1.02474E+00	2.54296E+01	1.12514E+00	3.11484E+01	7.69600E-03	1.51404E-01	6.71794E+01
7	2.27183E+00	1.14076E+01	2.72081E+04	1.13605E+04	1.02483E+00	2.54395E+01	1.12610E+00	3.11514E+01	7.69771E-03	1.51424E-01	6.73308E+01
8	2.38433E+00	1.14065E+01	2.72169E+04	1.13503E+04	1.02494E+00	2.54500E+01	1.12712E+00	3.11546E+01	7.69953E-03	1.51444E-01	6.74823E+01
9	2.49683E+00	1.14053E+01	2.72262E+04	1.13395E+04	1.02505E+00	2.54610E+01	1.12819E+00	3.11579E+01	7.70145E-03	1.51466E-01	6.76338E+01
10	2.60933E+00	1.14040E+01	2.72360E+04	1.13281E+04	1.02516E+00	2.54725E+01	1.12932E+00	3.11614E+01	7.70347E-03	1.51489E-01	6.77852E+01
11	2.72183E+00	1.14026E+01	2.72462E+04	1.13162E+04	1.02529E+00	2.54846E+01	1.13051E+00	3.11650E+01	7.70559E-03	1.51513E-01	6.79368E+01
12	2.83433E+00	1.14012E+01	2.72569E+04	1.13037E+04	1.02541E+00	2.54972E+01	1.13176E+00	3.11689E+01	7.70782E-03	1.51538E-01	6.80883E+01
13	2.94683E+00	1.13998E+01	2.72681E+04	1.12906E+04	1.02555E+00	2.55103E+01	1.13307E+00	3.11729E+01	7.71015E-03	1.51564E-01	6.82399E+01
14	3.05933E+00	1.13982E+01	2.72796E+04	1.12770E+04	1.02569E+00	2.55239E+01	1.13444E+00	3.11770E+01	7.71260E-03	1.51592E-01	6.83915E+01
15	3.17183E+00	1.13967E+01	2.72917E+04	1.12628E+04	1.02583E+00	2.55381E+01	1.13587E+00	3.11814E+01	7.71515E-03	1.51621E-01	6.85431E+01

INTERMEDIATE REGION

Z	TFRD	HFD	REYD	CPD	TKD	VIRD	DEND	FFD	DELPD	PTOPD	
16	3.57112E+00	1.13950E+01	2.73042E+04	1.12480E+04	1.02599E+00	2.55528E+01	1.13737E+00	3.11859E+01	7.71781E-03	5.38240E-01	6.90813E+01
17	3.97040E+00	1.13927E+01	2.73213E+04	1.12276E+04	1.02620E+00	2.55729E+01	1.13944E+00	3.11922E+01	7.72148E-03	5.38389E-01	6.96197E+01
18	4.36969E+00	1.13904E+01	2.73386E+04	1.12067E+04	1.02641E+00	2.55933E+01	1.14155E+00	3.11986E+01	7.72523E-03	5.38540E-01	7.01582E+01
19	4.76897E+00	1.13880E+01	2.73562E+04	1.11855E+04	1.02663E+00	2.56140E+01	1.14372E+00	3.12050E+01	7.72907E-03	5.38696E-01	7.06969E+01
20	5.16826E+00	1.13856E+01	2.73741E+04	1.11639E+04	1.02686E+00	2.56349E+01	1.14593E+00	3.12117E+01	7.73299E-03	5.38855E-01	7.12358E+01
21	5.56755E+00	1.13832E+01	2.73921E+04	1.11419E+04	1.02709E+00	2.56561E+01	1.14820E+00	3.12184E+01	7.73699E-03	5.39017E-01	7.17748E+01
22	5.96683E+00	1.13807E+01	2.74105E+04	1.11195E+04	1.02732E+00	2.56776E+01	1.15051E+00	3.12252E+01	7.74107E-03	5.39184E-01	7.23140E+01
23	6.36612E+00	1.13781E+01	2.74290E+04	1.10967E+04	1.02756E+00	2.56993E+01	1.15288E+00	3.12322E+01	7.74525E-03	5.39354E-01	7.28533E+01
24	6.76540E+00	1.13755E+01	2.74478E+04	1.10734E+04	1.02780E+00	2.57212E+01	1.15530E+00	3.12393E+01	7.74951E-03	5.39528E-01	7.33929E+01
25	7.16469E+00	1.13729E+01	2.74668E+04	1.10497E+04	1.02805E+00	2.57434E+01	1.15778E+00	3.12465E+01	7.75386E-03	5.39706E-01	7.39326E+01
26	7.56397E+00	1.13702E+01	2.74860E+04	1.10256E+04	1.02830E+00	2.57659E+01	1.16031E+00	3.12539E+01	7.75830E-03	5.39888E-01	7.44725E+01
27	7.96326E+00	1.13675E+01	2.75055E+04	1.10011E+04	1.02856E+00	2.57887E+01	1.16289E+00	3.12614E+01	7.76284E-03	5.40074E-01	7.50125E+01
28	8.36254E+00	1.13647E+01	2.75252E+04	1.09761E+04	1.02882E+00	2.58116E+01	1.16554E+00	3.12690E+01	7.76746E-03	5.40264E-01	7.55528E+01
29	8.76183E+00	1.13619E+01	2.75452E+04	1.09507E+04	1.02909E+00	2.58349E+01	1.16824E+00	3.12768E+01	7.77219E-03	5.40459E-01	7.60933E+01

30	9.16111E+00	1.13590E+01	2.75653E+04	1.09249E+04	1.02937E+00	2.58583E+01	1.17100E+00	3.12847E+01	7.77700E-03	5.40657E-01	7.66339E+01
31	9.56040E+00	1.13561E+01	2.75857E+04	1.08987E+04	1.02965E+00	2.58820E+01	1.17382E+00	3.12927E+01	7.78190E-03	5.40859E-01	7.71748E+01
32	9.95969E+00	1.13532E+01	2.76061E+04	1.08722E+04	1.02993E+00	2.59058E+01	1.17668E+00	3.13008E+01	7.78688E-03	5.41065E-01	7.77158E+01
33	1.03590E+01	1.13502E+01	2.76267E+04	1.08453E+04	1.03022E+00	2.59297E+01	1.17959E+00	3.13090E+01	7.79193E-03	5.41274E-01	7.82571E+01
34	1.07583E+01	1.13472E+01	2.76474E+04	1.08182E+04	1.03051E+00	2.59537E+01	1.18255E+00	3.13173E+01	7.79705E-03	5.41487E-01	7.87986E+01
35	1.11575E+01	1.13442E+01	2.76682E+04	1.07909E+04	1.03080E+00	2.59778E+01	1.18555E+00	3.13256E+01	7.80224E-03	5.41702E-01	7.93403E+01
36	1.15668E+01	1.13411E+01	2.76890E+04	1.07633E+04	1.03110E+00	2.60019E+01	1.18858E+00	3.13341E+01	7.80748E-03	5.41920E-01	7.98822E+01
37	1.19561E+01	1.13380E+01	2.77100E+04	1.07355E+04	1.03140E+00	2.60261E+01	1.19167E+00	3.13426E+01	7.81279E-03	5.42141E-01	8.04244E+01
38	1.23554E+01	1.13349E+01	2.77310E+04	1.07074E+04	1.03170E+00	2.60503E+01	1.19479E+00	3.13513E+01	7.81817E-03	5.42365E-01	8.09667E+01
39	1.27547E+01	1.13318E+01	2.77520E+04	1.06790E+04	1.03201E+00	2.60747E+01	1.19796E+00	3.13600E+01	7.82362E-03	5.42592E-01	8.15093E+01
40	1.31540E+01	1.13286E+01	2.77732E+04	1.06505E+04	1.03232E+00	2.60991E+01	1.20118E+00	3.13688E+01	7.82913E-03	5.42822E-01	8.20521E+01
41	1.35533E+01	1.13254E+01	2.77944E+04	1.06216E+04	1.03264E+00	2.61236E+01	1.20444E+00	3.13777E+01	7.83471E-03	5.43055E-01	8.25952E+01
42	1.39525E+01	1.13221E+01	2.78157E+04	1.05925E+04	1.03296E+00	2.61481E+01	1.20775E+00	3.13866E+01	7.84036E-03	5.43291E-01	8.31385E+01
43	1.43518E+01	1.13189E+01	2.78372E+04	1.05631E+04	1.03328E+00	2.61727E+01	1.21111E+00	3.13957E+01	7.84609E-03	5.43531E-01	8.36820E+01
44	1.47511E+01	1.13156E+01	2.78587E+04	1.05335E+04	1.03361E+00	2.61974E+01	1.21451E+00	3.14049E+01	7.85189E-03	5.43774E-01	8.42258E+01
45	1.51504E+01	1.13122E+01	2.78803E+04	1.05036E+04	1.03394E+00	2.62222E+01	1.21797E+00	3.14141E+01	7.85776E-03	5.44020E-01	8.47698E+01
46	1.55497E+01	1.13088E+01	2.79019E+04	1.04734E+04	1.03428E+00	2.62471E+01	1.22148E+00	3.14235E+01	7.86370E-03	5.44269E-01	8.53141E+01
47	1.59490E+01	1.13054E+01	2.79237E+04	1.04430E+04	1.03462E+00	2.62721E+01	1.22504E+00	3.14330E+01	7.86973E-03	5.44522E-01	8.58586E+01
48	1.63483E+01	1.13020E+01	2.79456E+04	1.04123E+04	1.03496E+00	2.62971E+01	1.22865E+00	3.14425E+01	7.87583E-03	5.44778E-01	8.64034E+01
49	1.67475E+01	1.12985E+01	2.79676E+04	1.03813E+04	1.03531E+00	2.63223E+01	1.23232E+00	3.14522E+01	7.88201E-03	5.45038E-01	8.69484E+01
50	1.71468E+01	1.12950E+01	2.79897E+04	1.03500E+04	1.03566E+00	2.63475E+01	1.23604E+00	3.14620E+01	7.88827E-03	5.45301E-01	8.74937E+01
51	1.75461E+01	1.12915E+01	2.80119E+04	1.03185E+04	1.03602E+00	2.63728E+01	1.23982E+00	3.14719E+01	7.89461E-03	5.45568E-01	8.80393E+01
52	1.79454E+01	1.12879E+01	2.80342E+04	1.02866E+04	1.03638E+00	2.63983E+01	1.24366E+00	3.14819E+01	7.90103E-03	5.45838E-01	8.85851E+01
53	1.83447E+01	1.12842E+01	2.80567E+04	1.02545E+04	1.03675E+00	2.64238E+01	1.24756E+00	3.14920E+01	7.90754E-03	5.46112E-01	8.91312E+01
54	1.87440E+01	1.12806E+01	2.80792E+04	1.02221E+04	1.03712E+00	2.64495E+01	1.25151E+00	3.15023E+01	7.91414E-03	5.46390E-01	8.96776E+01
55	1.91433E+01	1.12769E+01	2.81019E+04	1.01894E+04	1.03749E+00	2.64752E+01	1.25553E+00	3.15126E+01	7.92082E-03	5.46671E-01	9.02243E+01

UPPER REGION

	Z	TFRD	HFD	REYD	CPD	TKD	VISD	DEND	FFD	DELFD	PTOPD
56	1.96300E+01	8.00863E+00	2.02354E+04	9.98119E+03	1.03787E+00	2.65011E+01	1.25960E+00	3.15231E+01	7.96405E-03	2.44382E-01	9.04687E+01
57	2.01168E+01	8.00862E+00	2.02354E+04	9.98107E+03	1.03787E+00	2.65012E+01	1.25962E+00	3.15232E+01	7.96407E-03	2.44383E-01	9.07131E+01
58	2.06035E+01	8.00861E+00	2.02355E+04	9.98094E+03	1.03788E+00	2.65013E+01	1.25964E+00	3.15232E+01	7.96410E-03	2.44383E-01	9.09575E+01
59	2.10903E+01	8.00860E+00	2.02356E+04	9.98081E+03	1.03788E+00	2.65014E+01	1.25965E+00	3.15232E+01	7.96413E-03	2.44384E-01	9.12018E+01
60	2.15770E+01	8.00858E+00	2.02356E+04	9.98068E+03	1.03788E+00	2.65015E+01	1.25967E+00	3.15233E+01	7.96415E-03	2.44384E-01	9.14462E+01
61	2.20638E+01	8.00857E+00	2.02357E+04	9.98055E+03	1.03788E+00	2.65016E+01	1.25969E+00	3.15233E+01	7.96418E-03	2.44385E-01	9.16906E+01
62	2.25505E+01	8.00856E+00	2.02358E+04	9.98042E+03	1.03788E+00	2.65017E+01	1.25970E+00	3.15234E+01	7.96421E-03	2.44385E-01	9.19350E+01
63	2.30373E+01	8.00855E+00	2.02358E+04	9.98029E+03	1.03788E+00	2.65018E+01	1.25972E+00	3.15234E+01	7.96424E-03	2.44386E-01	9.21794E+01
64	2.35240E+01	8.00854E+00	2.02359E+04	9.98015E+03	1.03789E+00	2.65019E+01	1.25974E+00	3.15235E+01	7.96426E-03	2.44386E-01	9.24238E+01
65	2.40108E+01	8.00853E+00	2.02360E+04	9.98002E+03	1.03789E+00	2.65020E+01	1.25975E+00	3.15235E+01	7.96429E-03	2.44387E-01	9.26682E+01
66	2.44975E+01	8.00852E+00	2.02360E+04	9.97989E+03	1.03789E+00	2.65021E+01	1.25977E+00	3.15235E+01	7.96432E-03	2.44388E-01	9.29125E+01
67	2.49843E+01	8.00851E+00	2.02361E+04	9.97975E+03	1.03789E+00	2.65022E+01	1.25979E+00	3.15236E+01	7.96435E-03	2.44388E-01	9.31569E+01
68	2.54710E+01	8.00850E+00	2.02362E+04	9.97962E+03	1.03789E+00	2.65023E+01	1.25980E+00	3.15236E+01	7.96438E-03	2.44389E-01	9.34013E+01
69	2.59578E+01	8.00849E+00	2.02362E+04	9.97948E+03	1.03789E+00	2.65024E+01	1.25982E+00	3.15237E+01	7.96441E-03	2.44389E-01	9.36457E+01
70	2.64445E+01	8.00848E+00	2.02363E+04	9.97935E+03	1.03790E+00	2.65026E+01	1.25984E+00	3.15237E+01	7.96443E-03	2.44390E-01	9.38901E+01
71	2.69313E+01	8.00846E+00	2.02364E+04	9.97922E+03	1.03790E+00	2.65027E+01	1.25985E+00	3.15238E+01	7.96446E-03	2.44390E-01	9.41345E+01
72	2.74180E+01	8.00845E+00	2.02364E+04	9.97908E+03	1.03790E+00	2.65028E+01	1.25987E+00	3.15238E+01	7.96449E-03	2.44391E-01	9.43789E+01
73	2.79048E+01	8.00844E+00	2.02365E+04	9.97895E+03	1.03790E+00	2.65029E+01	1.25989E+00	3.15239E+01	7.96452E-03	2.44391E-01	9.46233E+01
74	2.83915E+01	8.00843E+00	2.02366E+04	9.97882E+03	1.03790E+00	2.65030E+01	1.25990E+00	3.15239E+01	7.96455E-03	2.44392E-01	9.48677E+01
75	2.88783E+01	8.00842E+00	2.02366E+04	9.97869E+03	1.03790E+00	2.65031E+01	1.25992E+00	3.15239E+01	7.96457E-03	2.44392E-01	9.51121E+01
76	2.93650E+01	8.00841E+00	2.02367E+04	9.97855E+03	1.03790E+00	2.65032E+01	1.25994E+00	3.15240E+01	7.96460E-03	2.44393E-01	9.53564E+01
77	2.98518E+01	8.00840E+00	2.02368E+04	9.97842E+03	1.03791E+00	2.65033E+01	1.25995E+00	3.15240E+01	7.96463E-03	2.44393E-01	9.56008E+01
78	3.03385E+01	8.00839E+00	2.02368E+04	9.97830E+03	1.03791E+00	2.65034E+01	1.25997E+00	3.15241E+01	7.96466E-03	2.44394E-01	9.58452E+01
79	3.08253E+01	8.00838E+00	2.02369E+04	9.97817E+03	1.03791E+00	2.65035E+01	1.25999E+00	3.15241E+01	7.96468E-03	2.44394E-01	9.60896E+01
80	3.13120E+01	8.00837E+00	2.02370E+04	9.97804E+03	1.03791E+00	2.65036E+01	1.26000E+00	3.15241E+01	7.96471E-03	2.44395E-01	9.63340E+01
81	3.17988E+01	8.00836E+00	2.02370E+04	9.97792E+03	1.03791E+00	2.65037E+01	1.26002E+00	3.15242E+01	7.96474E-03	2.44395E-01	9.65784E+01
82	3.22855E+01	8.00835E+00	2.02371E+04	9.97779E+03	1.03791E+00	2.65038E+01	1.26003E+00	3.15242E+01	7.96476E-03	2.44396E-01	9.68228E+01
83	3.27723E+01	8.00834E+00	2.02372E+04	9.97767E+03	1.03791E+00	2.65039E+01	1.26005E+00	3.15243E+01	7.96479E-03	2.44396E-01	9.70672E+01
84	3.32590E+01	8.00833E+00	2.02372E+04	9.97755E+03	1.03792E+00	2.65040E+01	1.26007E+00	3.15243E+01	7.96481E-03	2.44397E-01	9.73116E+01
85	3.37458E+01	8.00832E+00	2.02373E+04	9.97742E+03	1.03792E+00	2.65041E+01	1.26008E+00	3.15243E+01	7.96484E-03	2.44397E-01	9.75560E+01

86	3.42325E+01	8.00831E+00	2.02373E+04	9.97730E+03	1.03792E+00	2.65042E+01	1.26010E+00	3.15244E+01	7.96486E-03	2.44398E-01	9.78004E+01
87	3.47193E+01	8.00830E+00	2.02374E+04	9.97718E+03	1.03792E+00	2.65043E+01	1.26011E+00	3.15244E+01	7.96489E-03	2.44398E-01	9.80448E+01
88	3.52060E+01	8.00829E+00	2.02375E+04	9.97707E+03	1.03792E+00	2.65044E+01	1.26013E+00	3.15245E+01	7.96491E-03	2.44399E-01	9.82892E+01
89	3.56928E+01	8.00828E+00	2.02375E+04	9.97695E+03	1.03792E+00	2.65045E+01	1.26014E+00	3.15245E+01	7.96494E-03	2.44399E-01	9.85336E+01
90	3.61795E+01	8.00827E+00	2.02376E+04	9.97683E+03	1.03792E+00	2.65046E+01	1.26016E+00	3.15245E+01	7.96496E-03	2.44400E-01	9.87780E+01
91	3.66663E+01	8.00826E+00	2.02376E+04	9.97672E+03	1.03793E+00	2.65046E+01	1.26017E+00	3.15246E+01	7.96499E-03	2.44400E-01	9.90224E+01
92	3.71530E+01	8.00825E+00	2.02377E+04	9.97660E+03	1.03793E+00	2.65047E+01	1.26018E+00	3.15246E+01	7.96501E-03	2.44401E-01	9.92668E+01
93	3.76398E+01	8.00824E+00	2.02378E+04	9.97649E+03	1.03793E+00	2.65048E+01	1.26020E+00	3.15246E+01	7.96504E-03	2.44401E-01	9.95112E+01
94	3.81265E+01	8.00823E+00	2.02378E+04	9.97638E+03	1.03793E+00	2.65049E+01	1.26021E+00	3.15247E+01	7.96506E-03	2.44401E-01	9.97556E+01
95	3.86133E+01	8.00822E+00	2.02379E+04	9.97627E+03	1.03793E+00	2.65050E+01	1.26023E+00	3.15247E+01	7.96508E-03	2.44402E-01	1.00000E+02

UPCOMER FLOW AND PHYSICAL PROPERTY DATA RESULTS

TABLE KEY

Z=AXIAL DISTANCE FROM LTIV LOOP BOTTOM, FT
TFRU=LITHIUM FLOW VELOCITY, FT/SEC
HFU=LITHIUM HEAT TRANSFER FILM COEFFICIENT, BTU/HR-FT²-F
REYU=LITHIUM REYNOLDS NUMBER, DIMENSIONLESS
CPU=LITHIUM HEAT CAPACITY, BTU/LB-F
TKU=LITHIUM THERMAL CONDUCTIVITY, BTU/HR-FT-F
VISU=LITHIUM VISCOSITY, LB/FT-HR
DENU=LITHIUM DENSITY, LB/FT³
FFU=LITHIUM FRICTION FACTOR, DIMENSIONLESS
DELFU=UPCOMER INCREMENTAL PRESSURE DROP, PSI
PTOPU=UPCOMER LITHIUM PRESSURE, PSI

LOWER REGION

	Z	TFRU	HFU	REYU	CPU	TKU	VISU	DENU	FFU	DELFU	PTOPU
1	4.09367E-01	6.08757E+00	1.67605E+04	9.35427E+03	1.02472E+00	2.54283E+01	1.12501E+00	3.11480E+01	8.10173E-03	1.07110E-01	6.41663E+01
2	8.18733E-01	6.08764E+00	1.67599E+04	9.35528E+03	1.02471E+00	2.54270E+01	1.12489E+00	3.11477E+01	8.10150E-03	1.07108E-01	6.40592E+01
3	1.22810E+00	6.08771E+00	1.67593E+04	9.35618E+03	1.02470E+00	2.54259E+01	1.12478E+00	3.11473E+01	8.10129E-03	1.07107E-01	6.39521E+01
4	1.63747E+00	6.08776E+00	1.67587E+04	9.35697E+03	1.02469E+00	2.54249E+01	1.12469E+00	3.11470E+01	8.10111E-03	1.07105E-01	6.38450E+01
5	2.04683E+00	6.08781E+00	1.67583E+04	9.35765E+03	1.02468E+00	2.54240E+01	1.12461E+00	3.11468E+01	8.10095E-03	1.07104E-01	6.37379E+01

CORE REGION

	Z	TFRU	HFU	REYU	CPU	TKU	VISU	DENU	FFU	DELFU	PTOPU
6	2.15933E+00	6.08786E+00	1.67579E+04	9.35821E+03	1.02467E+00	2.54233E+01	1.12454E+00	3.11466E+01	8.10082E-03	2.94335E-02	6.37084E+01
7	2.27183E+00	6.08836E+00	1.67533E+04	9.36510E+03	1.02459E+00	2.54147E+01	1.12371E+00	3.11440E+01	8.09925E-03	2.94302E-02	6.36790E+01
8	2.38433E+00	6.08883E+00	1.67489E+04	9.37158E+03	1.02451E+00	2.54066E+01	1.12294E+00	3.11416E+01	8.09777E-03	2.94271E-02	6.36496E+01
9	2.49683E+00	6.08928E+00	1.67448E+04	9.37764E+03	1.02443E+00	2.53989E+01	1.12221E+00	3.11393E+01	8.09638E-03	2.94242E-02	6.36201E+01
10	2.60933E+00	6.08969E+00	1.67410E+04	9.38329E+03	1.02436E+00	2.53918E+01	1.12153E+00	3.11372E+01	8.09509E-03	2.94215E-02	6.35907E+01
11	2.72183E+00	6.09007E+00	1.67375E+04	9.38854E+03	1.02430E+00	2.53852E+01	1.12091E+00	3.11352E+01	8.09389E-03	2.94190E-02	6.35613E+01
12	2.83433E+00	6.09043E+00	1.67342E+04	9.39337E+03	1.02424E+00	2.53790E+01	1.12033E+00	3.11334E+01	8.09279E-03	2.94167E-02	6.35319E+01
13	2.94683E+00	6.09075E+00	1.67312E+04	9.39781E+03	1.02418E+00	2.53734E+01	1.11980E+00	3.11317E+01	8.09178E-03	2.94146E-02	6.35025E+01
14	3.05933E+00	6.09105E+00	1.67285E+04	9.40183E+03	1.02413E+00	2.53683E+01	1.11932E+00	3.11302E+01	8.09086E-03	2.94127E-02	6.34731E+01
15	3.17183E+00	6.09131E+00	1.67260E+04	9.40545E+03	1.02409E+00	2.53637E+01	1.11889E+00	3.11289E+01	8.09004E-03	2.94110E-02	6.34436E+01

INTERMEDIATE REGION

	Z	TFRU	HFU	REYU	CPU	TKU	VISU	DENU	FFU	DELFU	PTOPU
16	3.57112E+00	6.09155E+00	1.67238E+04	9.40867E+03	1.02405E+00	2.53596E+01	1.11851E+00	3.11277E+01	8.08930E-03	1.04380E-01	6.33393E+01
17	3.97040E+00	6.09054E+00	1.67332E+04	9.39484E+03	1.02422E+00	2.53772E+01	1.12015E+00	3.11328E+01	8.09245E-03	1.04403E-01	6.32349E+01
18	4.36969E+00	6.08950E+00	1.67428E+04	9.38072E+03	1.02439E+00	2.53950E+01	1.12184E+00	3.11381E+01	8.09568E-03	1.04427E-01	6.31304E+01
19	4.76897E+00	6.08845E+00	1.67525E+04	9.36630E+03	1.02457E+00	2.54132E+01	1.12357E+00	3.11435E+01	8.09897E-03	1.04452E-01	6.30260E+01
20	5.16826E+00	6.08737E+00	1.67623E+04	9.35158E+03	1.02475E+00	2.54316E+01	1.12534E+00	3.11490E+01	8.10235E-03	1.04477E-01	6.29215E+01
21	5.56755E+00	6.08627E+00	1.67723E+04	9.33656E+03	1.02494E+00	2.54503E+01	1.12715E+00	3.11547E+01	8.10579E-03	1.04502E-01	6.28170E+01

22	5.96683E+00	6.08516E+00	1.67825E+04	9.32123E+03	1.02513E+00	2.54693E+01	1.12900E+00	3.11604E+01	8.10932E-03	1.04529E-01	6.27125E+01
23	6.36612E+00	6.08402E+00	1.67928E+04	9.30560E+03	1.02533E+00	2.54885E+01	1.13090E+00	3.11662E+01	8.11293E-03	1.04556E-01	6.26079E+01
24	6.76540E+00	6.08286E+00	1.68033E+04	9.28965E+03	1.02552E+00	2.55080E+01	1.13284E+00	3.11722E+01	8.11661E-03	1.04583E-01	6.25033E+01
25	7.16469E+00	6.08167E+00	1.68139E+04	9.27339E+03	1.02573E+00	2.55278E+01	1.13483E+00	3.11782E+01	8.12038E-03	1.04611E-01	6.23987E+01
26	7.56397E+00	6.08047E+00	1.68246E+04	9.25681E+03	1.02594E+00	2.55478E+01	1.13686E+00	3.11844E+01	8.12423E-03	1.04640E-01	6.22941E+01
27	7.96326E+00	6.07924E+00	1.68355E+04	9.23991E+03	1.02615E+00	2.55681E+01	1.13894E+00	3.11907E+01	8.12816E-03	1.04670E-01	6.21894E+01
28	8.36254E+00	6.07799E+00	1.68466E+04	9.22268E+03	1.02636E+00	2.55886E+01	1.14106E+00	3.11971E+01	8.13218E-03	1.04700E-01	6.20847E+01
29	8.76183E+00	6.07670E+00	1.68580E+04	9.20486E+03	1.02659E+00	2.56098E+01	1.14327E+00	3.12037E+01	8.13635E-03	1.04731E-01	6.19800E+01
30	9.16111E+00	6.07537E+00	1.68697E+04	9.18643E+03	1.02682E+00	2.56315E+01	1.14557E+00	3.12106E+01	8.14067E-03	1.04764E-01	6.18752E+01
31	9.56040E+00	6.07400E+00	1.68817E+04	9.16744E+03	1.02706E+00	2.56537E+01	1.14794E+00	3.12176E+01	8.14514E-03	1.04798E-01	6.17704E+01
32	9.95969E+00	6.07259E+00	1.68939E+04	9.14791E+03	1.02731E+00	2.56765E+01	1.15039E+00	3.12249E+01	8.14974E-03	1.04833E-01	6.16656E+01
33	1.03590E+01	6.07114E+00	1.69064E+04	9.12790E+03	1.02756E+00	2.56996E+01	1.15291E+00	3.12323E+01	8.15447E-03	1.04869E-01	6.15607E+01
34	1.07583E+01	6.06967E+00	1.69191E+04	9.10744E+03	1.02782E+00	2.57231E+01	1.15550E+00	3.12399E+01	8.15932E-03	1.04905E-01	6.14558E+01
35	1.11575E+01	6.06818E+00	1.69318E+04	9.08679E+03	1.02808E+00	2.57466E+01	1.15813E+00	3.12476E+01	8.16423E-03	1.04943E-01	6.13509E+01
36	1.15568E+01	6.06668E+00	1.69445E+04	9.06597E+03	1.02835E+00	2.57702E+01	1.16079E+00	3.12553E+01	8.16920E-03	1.04981E-01	6.12459E+01
37	1.19561E+01	6.06516E+00	1.69573E+04	9.04496E+03	1.02862E+00	2.57938E+01	1.16348E+00	3.12631E+01	8.17423E-03	1.05019E-01	6.11409E+01
38	1.23554E+01	6.06364E+00	1.69701E+04	9.02377E+03	1.02889E+00	2.58175E+01	1.16622E+00	3.12710E+01	8.17932E-03	1.05058E-01	6.10358E+01
39	1.27547E+01	6.06210E+00	1.69830E+04	9.00240E+03	1.02917E+00	2.58412E+01	1.16899E+00	3.12789E+01	8.18446E-03	1.05097E-01	6.09307E+01
40	1.31540E+01	6.06055E+00	1.69959E+04	8.98083E+03	1.02945E+00	2.58650E+01	1.17179E+00	3.12869E+01	8.18967E-03	1.05137E-01	6.08256E+01
41	1.35533E+01	6.05898E+00	1.70088E+04	8.95908E+03	1.02973E+00	2.58888E+01	1.17464E+00	3.12950E+01	8.19494E-03	1.05178E-01	6.07204E+01
42	1.39525E+01	6.05740E+00	1.70218E+04	8.93713E+03	1.03001E+00	2.59127E+01	1.17752E+00	3.13031E+01	8.20028E-03	1.05219E-01	6.06152E+01
43	1.43518E+01	6.05581E+00	1.70348E+04	8.91498E+03	1.03030E+00	2.59367E+01	1.18045E+00	3.13114E+01	8.20568E-03	1.05261E-01	6.05099E+01
44	1.47511E+01	6.05420E+00	1.70479E+04	8.89264E+03	1.03059E+00	2.59607E+01	1.18341E+00	3.13197E+01	8.21115E-03	1.05303E-01	6.04046E+01
45	1.51504E+01	6.05258E+00	1.70610E+04	8.87010E+03	1.03089E+00	2.59847E+01	1.18642E+00	3.13281E+01	8.21668E-03	1.05345E-01	6.02993E+01
46	1.55497E+01	6.05094E+00	1.70742E+04	8.84736E+03	1.03119E+00	2.60089E+01	1.18947E+00	3.13366E+01	8.22228E-03	1.05389E-01	6.01939E+01
47	1.59490E+01	6.04929E+00	1.70874E+04	8.82442E+03	1.03149E+00	2.60331E+01	1.19256E+00	3.13451E+01	8.22795E-03	1.05433E-01	6.00885E+01
48	1.63483E+01	6.04762E+00	1.71006E+04	8.80126E+03	1.03179E+00	2.60573E+01	1.19570E+00	3.13538E+01	8.23369E-03	1.05477E-01	5.99830E+01
49	1.67475E+01	6.04594E+00	1.71139E+04	8.77791E+03	1.03210E+00	2.60817E+01	1.19888E+00	3.13625E+01	8.23951E-03	1.05522E-01	5.98775E+01
50	1.71468E+01	6.04424E+00	1.71273E+04	8.75434E+03	1.03241E+00	2.61061E+01	1.20211E+00	3.13713E+01	8.24540E-03	1.05568E-01	5.97719E+01
51	1.75461E+01	6.04252E+00	1.71407E+04	8.73055E+03	1.03273E+00	2.61306E+01	1.20538E+00	3.13802E+01	8.25136E-03	1.05614E-01	5.96663E+01
52	1.79454E+01	6.04079E+00	1.71541E+04	8.70656E+03	1.03305E+00	2.61552E+01	1.20871E+00	3.13892E+01	8.25739E-03	1.05661E-01	5.95606E+01
53	1.83447E+01	6.03904E+00	1.71676E+04	8.68234E+03	1.03338E+00	2.61798E+01	1.21208E+00	3.13983E+01	8.26351E-03	1.05709E-01	5.94549E+01
54	1.87440E+01	6.03727E+00	1.71812E+04	8.65791E+03	1.03371E+00	2.62045E+01	1.21550E+00	3.14075E+01	8.26970E-03	1.05757E-01	5.93491E+01
55	1.91433E+01	6.03549E+00	1.71948E+04	8.63326E+03	1.03404E+00	2.62293E+01	1.21897E+00	3.14168E+01	8.27597E-03	1.05806E-01	5.92433E+01

UPPER REGION

	Z	TFRU	HFU	REYU	CPU	TKU	VISU	DENU	FFU	DELPU	PTOPU
56	1.96300E+01	5.21500E+00	1.66263E+04	7.44035E+03	1.03437E+00	2.62542E+01	1.22249E+00	3.14262E+01	8.61108E-03	1.00227E-01	5.91431E+01
57	2.01168E+01	5.21513E+00	1.66252E+04	7.44212E+03	1.03435E+00	2.62522E+01	1.22220E+00	3.14254E+01	8.61053E-03	1.00223E-01	5.90429E+01
58	2.06035E+01	5.21526E+00	1.66241E+04	7.44389E+03	1.03432E+00	2.62501E+01	1.22191E+00	3.14247E+01	8.60998E-03	1.00219E-01	5.89427E+01
59	2.10903E+01	5.21539E+00	1.66230E+04	7.44565E+03	1.03429E+00	2.62481E+01	1.22162E+00	3.14239E+01	8.60943E-03	1.00215E-01	5.88425E+01
60	2.15770E+01	5.21551E+00	1.66219E+04	7.44741E+03	1.03426E+00	2.62461E+01	1.22133E+00	3.14231E+01	8.60889E-03	1.00212E-01	5.87422E+01
61	2.20638E+01	5.21564E+00	1.66208E+04	7.44917E+03	1.03424E+00	2.62440E+01	1.22104E+00	3.14223E+01	8.60834E-03	1.00208E-01	5.86420E+01
62	2.25505E+01	5.21575E+00	1.66199E+04	7.45065E+03	1.03421E+00	2.62423E+01	1.22080E+00	3.14217E+01	8.60789E-03	1.00204E-01	5.85418E+01
63	2.30373E+01	5.21583E+00	1.66192E+04	7.45180E+03	1.03419E+00	2.62410E+01	1.22061E+00	3.14212E+01	8.60753E-03	1.00202E-01	5.84416E+01
64	2.35240E+01	5.21589E+00	1.66186E+04	7.45264E+03	1.03418E+00	2.62400E+01	1.22048E+00	3.14208E+01	8.60727E-03	1.00200E-01	5.83414E+01
65	2.40108E+01	5.21593E+00	1.66183E+04	7.45319E+03	1.03417E+00	2.62394E+01	1.22039E+00	3.14206E+01	8.60710E-03	1.00199E-01	5.82412E+01
66	2.44975E+01	5.21595E+00	1.66181E+04	7.45348E+03	1.03417E+00	2.62390E+01	1.22034E+00	3.14205E+01	8.60701E-03	1.00198E-01	5.81410E+01
67	2.49843E+01	5.21596E+00	1.66181E+04	7.45351E+03	1.03417E+00	2.62390E+01	1.22033E+00	3.14204E+01	8.60700E-03	1.00198E-01	5.80408E+01
68	2.54710E+01	5.21594E+00	1.66182E+04	7.45331E+03	1.03417E+00	2.62392E+01	1.22037E+00	3.14205E+01	8.60706E-03	1.00198E-01	5.79406E+01
69	2.59578E+01	5.21591E+00	1.66185E+04	7.45289E+03	1.03418E+00	2.62397E+01	1.22043E+00	3.14207E+01	8.60719E-03	1.00199E-01	5.78404E+01
70	2.64445E+01	5.21587E+00	1.66189E+04	7.45226E+03	1.03419E+00	2.62404E+01	1.22054E+00	3.14210E+01	8.60739E-03	1.00201E-01	5.77402E+01
71	2.69313E+01	5.21581E+00	1.66194E+04	7.45144E+03	1.03420E+00	2.62414E+01	1.22067E+00	3.14214E+01	8.60764E-03	1.00203E-01	5.76400E+01
72	2.74180E+01	5.21573E+00	1.66200E+04	7.45044E+03	1.03422E+00	2.62426E+01	1.22084E+00	3.14218E+01	8.60795E-03	1.00205E-01	5.75398E+01
73	2.79048E+01	5.21565E+00	1.66208E+04	7.44926E+03	1.03423E+00	2.62439E+01	1.22103E+00	3.14223E+01	8.60832E-03	1.00207E-01	5.74396E+01
74	2.83915E+01	5.21555E+00	1.66216E+04	7.44792E+03	1.03426E+00	2.62455E+01	1.22125E+00	3.14229E+01	8.60873E-03	1.00210E-01	5.73394E+01
75	2.88783E+01	5.21544E+00	1.66225E+04	7.44643E+03	1.03428E+00	2.62472E+01	1.22149E+00	3.14235E+01	8.60919E-03	1.00214E-01	5.72392E+01
76	2.93650E+01	5.21532E+00	1.66235E+04	7.44479E+03	1.03430E+00	2.62491E+01	1.22176E+00	3.14243E+01	8.60970E-03	1.00217E-01	5.71390E+01
77	2.98518E+01	5.21519E+00	1.66247E+04	7.44301E+03	1.03433E+00	2.62512E+01	1.22206E+00	3.14250E+01	8.61025E-03	1.00221E-01	5.70388E+01

78	3.03385E+01	5.21506E+00	1.66258E+04	7.44111E+03	1.03436E+00	2.62534E+01	1.22237E+00	3.14259E+01	8.61084E-03	1.00225E-01	5.69385E+01
79	3.08253E+01	5.21492E+00	1.66270E+04	7.43921E+03	1.03439E+00	2.62555E+01	1.22268E+00	3.14267E+01	8.61143E-03	1.00230E-01	5.68383E+01
80	3.13120E+01	5.21478E+00	1.66282E+04	7.43731E+03	1.03442E+00	2.62577E+01	1.22299E+00	3.14275E+01	8.61202E-03	1.00234E-01	5.67381E+01
81	3.17988E+01	5.21464E+00	1.66294E+04	7.43542E+03	1.03445E+00	2.62599E+01	1.22330E+00	3.14284E+01	8.61261E-03	1.00238E-01	5.66378E+01
82	3.22855E+01	5.21451E+00	1.66306E+04	7.43352E+03	1.03448E+00	2.62621E+01	1.22361E+00	3.14292E+01	8.61320E-03	1.00242E-01	5.65376E+01
83	3.27723E+01	5.21437E+00	1.66317E+04	7.43163E+03	1.03451E+00	2.62643E+01	1.22393E+00	3.14300E+01	8.61378E-03	1.00246E-01	5.64373E+01
84	3.32590E+01	5.21423E+00	1.66329E+04	7.42974E+03	1.03454E+00	2.62665E+01	1.22424E+00	3.14308E+01	8.61437E-03	1.00251E-01	5.63371E+01
85	3.37458E+01	5.21409E+00	1.66341E+04	7.42786E+03	1.03457E+00	2.62686E+01	1.22455E+00	3.14317E+01	8.61496E-03	1.00255E-01	5.62368E+01
86	3.42325E+01	5.21396E+00	1.66352E+04	7.42597E+03	1.03460E+00	2.62708E+01	1.22486E+00	3.14325E+01	8.61554E-03	1.00259E-01	5.61366E+01
87	3.47193E+01	5.21382E+00	1.66364E+04	7.42409E+03	1.03463E+00	2.62730E+01	1.22517E+00	3.14333E+01	8.61613E-03	1.00263E-01	5.60363E+01
88	3.52060E+01	5.21368E+00	1.66376E+04	7.42220E+03	1.03466E+00	2.62751E+01	1.22548E+00	3.14341E+01	8.61671E-03	1.00267E-01	5.59360E+01
89	3.56928E+01	5.21355E+00	1.66388E+04	7.42032E+03	1.03469E+00	2.62773E+01	1.22579E+00	3.14350E+01	8.61730E-03	1.00272E-01	5.58358E+01
90	3.61795E+01	5.21341E+00	1.66399E+04	7.41845E+03	1.03472E+00	2.62794E+01	1.22610E+00	3.14358E+01	8.61788E-03	1.00276E-01	5.57355E+01
91	3.66663E+01	5.21327E+00	1.66411E+04	7.41657E+03	1.03475E+00	2.62816E+01	1.22641E+00	3.14366E+01	8.61847E-03	1.00280E-01	5.56352E+01
92	3.71530E+01	5.21314E+00	1.66422E+04	7.41470E+03	1.03478E+00	2.62838E+01	1.22672E+00	3.14374E+01	8.61905E-03	1.00284E-01	5.55349E+01
93	3.76398E+01	5.21300E+00	1.66434E+04	7.41282E+03	1.03481E+00	2.62859E+01	1.22703E+00	3.14383E+01	8.61964E-03	1.00288E-01	5.54346E+01
94	3.81265E+01	5.21287E+00	1.66446E+04	7.41095E+03	1.03484E+00	2.62880E+01	1.22734E+00	3.14391E+01	8.62022E-03	1.00292E-01	5.53344E+01
95	3.86133E+01	5.21273E+00	1.66457E+04	7.40908E+03	1.03487E+00	2.62902E+01	1.22765E+00	3.14399E+01	8.62080E-03	1.00297E-01	5.52341E+01

CORE REGION GAMMA HEATING RESULTS

TABLE KEY

Z = DISTANCE FROM LTIV LOOP BOTTOM, FT
 QGD = GAMMA HEAT GENERATION IN AXIAL DOWNCOMER INCREMENT, BTU/HR
 QGU = GAMMA HEAT GENERATION IN AXIAL UPCOMER INCREMENT, BTU/HR
 QDG = INTEGRATED AXIAL GAMMA HEAT GEN IN DWNCOMER FROM INITIAL ICI NODE, BTU/HR
 QUG = INTEGRATED AXIAL GAMMA HEAT GEN IN UPCOMER FROM INITIAL ICI NODE, BTU/HR
 QGT = TOTAL INTEGRATED AXIAL GAMMA HEAT GEN FROM INITIAL ICI NODE, BTU/HR

	Z	QGD	QGU	QDG	QUG	QGT
6	2.15933E+00	2.17327E+03	1.88551E+03	2.17327E+03	1.88551E+03	4.05879E+03
7	2.27183E+00	2.17327E+03	1.88551E+03	4.34655E+03	3.77103E+03	8.11757E+03
8	2.38433E+00	2.17327E+03	1.88551E+03	6.51982E+03	5.65654E+03	1.21764E+04
9	2.49683E+00	2.17327E+03	1.88551E+03	8.69309E+03	7.54205E+03	1.62351E+04
10	2.60933E+00	2.17327E+03	1.88551E+03	1.08664E+04	9.42757E+03	2.02939E+04
11	2.72183E+00	2.17327E+03	1.88551E+03	1.30396E+04	1.13131E+04	2.43527E+04
12	2.83433E+00	2.17327E+03	1.88551E+03	1.52129E+04	1.31986E+04	2.84115E+04
13	2.94683E+00	2.17327E+03	1.88551E+03	1.73862E+04	1.50841E+04	3.24703E+04
14	3.05933E+00	2.17327E+03	1.88551E+03	1.95595E+04	1.69696E+04	3.65291E+04
15	3.17183E+00	2.17327E+03	1.88551E+03	2.17327E+04	1.88551E+04	4.05879E+04

END TIME: 14 HRS 9 MIN 29 SEC

Fig. 1. Concept of Low Temperature Test Vehicle

Fig. 2. Concept of Low Temperature Test Vehicle, Plan View

Fig. 3. Arrangement of INCOT in EBR-II (ANL Neg. No. 104-1094, Rev. 1)

Fig. 4. LTIV Capsule Holder

Fig. 5. Schematic of Upper LTIV In-reactor Loop Region

112-8624

Fig. 6. Annular Linear Induction (ALIP) Pump for
Mark-II Integral Sodium TREAT Loop

G10835

Fig. 7. Lithium-to-Air LTIV Heat Exchanger

Fig. 8. Isothermal Irradiation Facility (IIF) Operating Configuration

Fig. 9. Isothermal Irradiation Facility (IIF) Temperature Control Cart Disconnected for Fuel Handling

Fig. 10. Dimensional Data, Low Temperature Test Vehicle

Fig. 11. Loop Thermal Performance

Fig. 12. Loop Lithium Velocity in No. 16 BWG Gage Loop Tubing

Fig. 13. Loop Lithium Velocity in No. 13 BWG Gage Loop Tubing

Fig. 14. Loop Hydraulic Performance

Fig. 15. Loop Flow Divider Tangential Stress

a. ALIP No. 1 Performance: 315°C Sodium
(ANL Neg. No. 900-79-31)

b. Dual ALIP Performance: 315°C Sodium
(ANL Neg. No. 900-79-9)

Fig. 16. TREAT ALIP Performance With 315°C Sodium

Fig. 17. Loop Hydraulic Performance With Lithium ALIPs

Fig. 18. Lithium Temperature for Insulated Upper Flow Divider (Single Pump Operation)

Fig. 19. Lithium Pressures for Insulated Upper Flow Divider (Single Pump Operation)

Fig. 20. Lithium Temperatures for Insulated Upper Flow Divider (Dual Pump Operation)

Fig. 21. Lithium Pressures for Insulated Upper Flow Divider (Dual Pump Operation)

Fig. 22. Schedule for Development of a Fusion Materials Irradiation Test Vehicle

Fig. C1. Lithium Liquid Heat Capacity

Fig. C2. Lithium Liquid Thermal Conductivity

Fig. C3. Lithium Liquid Viscosity

Fig. C4. Lithium Liquid Density

Fig. C5. Liquid Metal Resistivity

Fig. D1. EBR-II Temperature Profile

Fig. D2. Lithium Temperature Profiles

Fig. D3. Lithium Temperature Profiles Near Core

Fig. D4. Overall Inside Heat Transfer Film Coefficient

Fig. D5. Overall Outside Heat Transfer Film Coefficient

Fig. D6. Integrated EBR-II Heat Transfer to Upcomer

Fig. D7. Integrated Lithium Pressure Drop

TABLE I. Design and Performance Characteristics of LTIV Packaged Loop

Coolant	Lithium
Design Temperature	
Loop and Components	450°F (233°C)
Test Section	550°F (288°C)
Design Pressure	
Test Section	100 psi
Ex-reactor	~ 50 psi
Heat Rejection Capability	~ 15 kW
Design Loop Flow Rate	~ 10 gpm
Pump Requirements	~ 10 gpm at ~ 50 psi
Experimental Test Volume (13.5 in. active length)	0.006136 ft ³ (174 cc)

TABLE II. Experimental Requirements (MITA Fusion Tests)

1.0 Test Assembly and Test Section Design

- 1.1 Minimum of one test assembly needed (two or more probable).
- 1.2 Minimum of one canister per test assembly (2 to 4 long term).
- 1.3 Maximize test volume.
- 1.4 Reusable thimble for multiple irradiations.
- 1.5 Capacity to irradiate pressurized gas and lithium-filled tubes.
- 1.6 Make above and below core space available for specimens (long term).

2.0 Experimental Conditions

- 2.1 Desired fluence range of $0.5\text{-}10.0 \times 10^{22}$ n/cm².
- 2.2 Long-range fluence goal of 15.0×10^{22} n/cm².
- 2.3 Test temperature range [200°C (391°F)-500°C (931°F)].
- 2.4 Long-term maximum temperature of 1200°C (2191°F).

TABLE III. Fluence Range Irradiation Times

	Fast Fluence (10^{22} n/cm ²)					
	0.5	1	2	5	10	15
Effective Full Power Days, days	31	61	122	306	612	918
Calendar Time (70% avail.), days	44	87	175	437	875	1312

REQUIREMENTS

- Test fluence range from 0.5×10^{22} - 10.0×10^{22} n/cm²
- Long term-fluence goal is 15.0×10^{22} n/cm²
- Single irradiation without intermediate reconstitution

ASSUMPTIONS

- Fast flux is 1.89×10^{15} for EBR-II row 5 (position 5A3 in run 162A)
- Lifetime limit for cold-worked stainless steel in EBR-II is 10.0×10^{22} n/cm²

CONCLUSIONS

- Requires low swelling advanced alloys (HT9) to meet 15×10^{22} n/cm²
- Intermediate reconstitution may be required

TABLE IV. Operational Requirements

1.0 Operating Conditions

- 1.1 Rapid reconstitution of irradiated specimens.
- 1.2 Minimize operating time at less than design conditions.
- 1.3 Do not intentionally exceed design flux or temperature.

2.0 Thermal Control

- 2.1 Control test temperature [within $\sim 5^{\circ}\text{C}$ (9°F)].
 - 2.2 Minimize axial and radial temperature gradients.
 - 2.3 Measure axial and radial temperature gradients (TCs).
 - 2.4 Control temperature by use of resistance heaters (long term).
 - 2.5 Provide capability to include electrical leads (long term).
 - 2.6 Use an I&C system similar to that of MOTA to control temperature.
-

TABLE V. Safety Requirements

1.0 General Criteria

- 1.1 Design, fabricate, and install to standards of quality.
- 1.2 Utilize accepted design codes and standards commensurate with safety function.
- 1.3 Minimize probability of coolant leaks and fires and their effect on EBR-II.
- 1.4 Provide double containment to insure low probability of failure.
- 1.5 Packaged loop system shall have provisions for inspection, testing, and surveillance.

2.0 Instrumentation

- 2.1 Control, monitor, and maintain loop variables within prescribed operating limits.
- 2.2 Means shall be provided for monitoring loop system to detect coolant leakage.
- 2.3 A loop protective system shall be provided and designed for high functional reliability and testability.
- 2.4 Redundancy and backup shall be provided to the protective system where feasible.
- 2.5 Emergency sources of power shall be provided for the protective systems.
- 2.6 Means shall be provided for testing the protective systems to insure operability with no performance degradation has occurred.

3.0 Safety Features

- 3.1 Provide means necessary to maintain control over radioactive releases (gaseous or liquid).
 - 3.2 Engineered safety features shall be provided to back up the safety provided by loop design, auxiliary systems and protective systems.
 - 3.3 Safeguards protection shall be provided to guard loop equipment from dynamic effects and missiles from plant-equipment failures.
 - 3.4 The loop containment shall be designed so the structure can accommodate the effects of the design basis accident conditions.
-

TABLE VI. Loop In-reactor Physical Characteristics (Ref. Design-insulated Upper Flow Divider)

Item	Description	Dimensions (in.)				Volume (ft ³ /ft)	Surface Area (ft ² /ft)	
		O.D	I.D	BWG Gage	Thickness (or Gap)		O.D.	I.D.
1	Sample Capsule	1.000	---	---	---	5.4542E-03	0.2618	---
2	Gap A-Argon Fill Gas	1.120	1.000	---	0.0600	1.3875E-03	0.2932	0.2618
3	Test Container	1.250	1.120	16	0.0650	1.6804E-03	0.3272	0.2932
Lower Section (Length = 19.14 ft)								
4	Gap B-Li In Downflow	1.370	1.250	---	0.0600	1.7148E-03	0.3587	0.3272
5	Flow Divider	1.500	1.370	16	0.0650	2.0349E-03	0.3927	0.3587
6	Gap C-Li Out Upflow	1.685	1.500	---	0.0925	3.2137E-03	0.4411	0.3927
7	Flow Housing	1.875	1.685	13	0.0950	3.6892E-03	0.4909	0.4411
8	Gap D-Argon Insulation	2.000	1.875	---	0.1925	2.6419E-03	0.5236	0.4909
9	Guide Tube	2.125	2.000	16	0.0625	2.8123E-03	0.5563	0.5236
Upper Section (Length = 19.47 ft)								
10	Gap E-Li In Downflow	1.416	1.250	---	0.0830	2.4138E-03	0.3707	0.3272
11	Flow Divider *	1.750	1.416	13	0.0950	5.7675E-03	0.4582	0.3707
12	Gap F-Li Out Upflow	1.935	1.750	---	0.0925	3.7182E-03	0.5066	0.4582
13	Flow Housing	2.125	1.935	13	0.0950	4.2073E-03	0.5563	0.5066
14	Gap E-Argon Insulation	2.260	2.125	---	0.1300	3.2287E-03	0.5917	0.5563
15	Guide Tube	2.500	2.260	11	0.1200	6.2308E-03	0.6545	0.5917

* Insulated Dual Tube: Outer--1.75 in. O.D. by No. 16 gage (65 mils thick)
Inner--1.50 in. O.D. by No. 19 gage (42 mils thick)
Argon Insulation Gap (60 mils thick)

TABLE VII. Pump Size and Performance Characteristics

RATING

Sodium to 500°C
Electrical Voltage of 230 V, Three Phase, 60 Cycle
Flow Rate Rating of 10 gpm

SIZE

Length: 26 in.
Diameter: 3.75 in. O.D.
Bore: 1.050 in.
Core: 0.625 in. to 0.875 in.

PERFORMANCE (~ 10 gpm Na at 315°C)

<u>ALIP</u>	<u>Max Pressure Head* (MPa/psi)</u>
1	0.54/78.3
2	0.44/63.8
Dual	0.87/126.1

* At 40 amps 'B' Phase Current

TABLE VIII. Comparison of Liquid Metal Properties

Properties	Na	K	NaK	PbBi	Lithium
General					
Composition, wt %	100% Na23	93.4% K39 6.6% K41	22% Na 78% K	44.5% Pb 55.5% Bi	92.5% Li7 7.5% Li6
Atomic Weight	22.997	39.096	33.9	208.	6.94
Melting Point, °F/°C	208/97.8	147/63.7	12/-11	257/125	354/179
Boiling Point, °F/°C	1621/883	1400/760	1443/784	3038/1670	2403/1317
Heat of Fusion, cal/g	27.1	14.6	17.3	9.3	158.0
Heat of Vaporization, cal/g	1005.0	496.0	608.0	204.4	4680.0
Thermal					
Evaluation Temperature, °F/°C	800/427	800/427	751/400	751/400	800/427
Heat Capacity, Btu/lb-°F	0.305	0.183	0.210	0.035	1.0057
Density, lb/ft ³	53.0	46.1	48.36	635.9	30.4
Thermal Condition, Btu/h-ft-°F	40.1	22.8	15.4	7.0	22.1
Viscosity, lb/ft-h	0.61	0.51	0.50	3.7	0.95
Prandtl Number	0.0046	0.0041	0.0068	0.189	0.0432

TABLE IX. In-reactor Physical Characteristics (NaK Coolant)

Item	Description	Dimensions (in.)			Volume (ft ³ / ft)	Surfaces Area (ft ² /ft)	
		O.D	I.D	Thickness		O.D.	I.D.
1	Test Canister	0.875	---	---	4.1758E-03	0.2291	---
2	Gap A-Argon Fill Gas	0.938	0.875	0.0315	6.2297E-04	0.2456	0.2291
3	Test Holder	1.063	0.938	0.0625	1.3642E-03	0.2783	0.2456
4	Gap B-Argon Fill Gas	1.188	1.063	0.0625	1.5347E-03	0.3110	0.2783
5	Test Container	1.313	1.188	0.0625	1.7051E-03	0.3437	0.3110
6	Gap C-NaK In Downflow	1.438	1.313	0.0625	1.8754E-03	0.3765	0.3437
7	Flow Divider	1.563	1.438	0.0625	2.0429E-03	0.4092	0.3765
8	Gap D-NaK Out Upflow	1.688	1.563	0.0625	2.2164E-03	0.4419	0.4092
9	Flow Housing	1.875	1.688	0.0935	3.6340E-03	0.4909	0.4419
10	Gap E-Argon Upper Insulation	2.250	1.875	0.1875	8.4369E-03	0.5890	0.4909
11	Upper Guide Tube	2.500	2.250	0.1250	6.4768E-03	0.6545	0.5890
12	Gap F-Argon In-core Insulation	2.000	1.875	0.0625	2.6419E-03	0.5236	0.4909
13	In-core Guide Tube	2.125	2.000	0.0625	2.8123E-03	0.5563	0.5236

TABLE X. Isothermal Irradiation Facility (IIF) Feasibility Data

General

NaK Cooled	22% Na-78% K
NaK Melting Temperature	12°F
Heat Removal Rating	16 kW
Total NaK Inventory	1.5 to 2.0 gal
Equilibrium Radioactivity Level	0.96 Ci/g
Size of Mobile Cart	4 ft x 4 ft x 4 ft
Shielding Weight	~ 10 tons

In-core Facility

Core Locations	Incot/Insat Modified Control Rod Position
Design Configuration	Annular Flow Channels
Total Length	~ 30 ft
Test Region Size	0.8 in. dia x ~ 13 in. long
Test Temperature Range	200°C to 700°C
NaK In-core Inventory	~ 1.0 gal
Gamma Heat Generation	14 kW
NaK Test Section Velocity	4 ft/s
NaK Flow Rate	5 gpm
Loop Thermal Insulation	Argon Gas

Heat Exchanger

Heat Removal System	NaK to Air
Approximate Size	3 ft x 3 ft x 1 ft
Design	Finned Tube in Shell
Flow Configuration	Transverse Flow
Heat Transfer Surface Area	~ 20 ft ²

Air Side (Rated Conditions--Shell)

Flow Area	~ 0.42 ft ²
Air Flow Rate	1330 cfm
Air Velocity	~ 50 ft/s
Inlet Air Temperature	70°F
Outlet Air Temperature	120°F

TABLE X. (Contd.)

<u>NaK Side (Rated Conditions--Tube)</u>	
Number of Tubes	5
Number of Tube Passes	14
Tube Diameter	0.50 in. I.D.
NaK Flow Rate Per Tube	1 gpm
NaK Velocity	1.6 ft/s
Inlet NaK Temperature	450°F
Outlet NaK Temperature	350°F
<u>Pump</u>	
Type (High Temp)	Mech Canned Rotor
Flow Capacity	5 to 20 gpm
Pressure Head	TBD psia
<u>Expansion Tank</u>	
Type	Sealed Bladder
Size	TBD
Expansion Volume	TBD
Heater Capacity	TBD
NaK Volume	TBD
<u>Instrumentation</u>	
Temperature Sensors	Thermocouples
Pressure Measurement	Diaphragm
Liquid Level Sensor	Impedance Type
NaK Valves	Leak tight
<u>Special Features</u>	
New Shipping Cask Not Required	Use Existing Incot/Insat Cask
Refueling Procedure	Disconnect and Raise In-core Loop
Can Tolerate Core Transient Experiments	Program and Control Test Temp
Test Vehicle Removal	Drain NaK, Disconnect, and Move Cart
Removal Time (With Drained Tubes)	Several Hours after Shutdown
Reasonable Shielding Requirements	~2-3 in. of Lead

TABLE XI. Helium Loop Scoping Feasibility Results

Assumptions

- 1) Same NaK Loop In-reactor Dimensions
- 2) Total Heat Removal of 11.7 kW (γ heat of 9.2 kW)
- 3) Average Test Temp of 500°F (260°C)
- 4) Test Section Helium Velocity of 200 ft/s

Results

In-reactor Condition	Helium System Pressure (psia)			
	14.7	147.0	294.0	588.0
He Temperature Rise (°F)	4044.0	404.0	202.0	101.0
Helium Density (lb/ft ³)	0.00585	0.0585	0.117	0.234
Heat Capacity (Btu/lb-°F)	1.242	1.242	1.242	1.242
Thermal Conductivity (Btu/ft-h-°F)	0.122	0.122	0.122	0.122
Helium Viscosity (lb/h-ft)	0.0715	0.0715	0.0715	0.0715
Prandtl Number	0.72	0.72	0.72	0.72
Friction Pressure Drop (psi)	Not Calc.	45.0	76.0	128.0

TABLE XII. Selection of Lithium for Coolant

Lithium Advantages

- Excellent Thermal Properties
(Best of alkaline metals)
- Compatible With Liquid Sodium
(Immiscible with no chemical reactions)
- Low Corrosion Rate With Stainless Steel
(But more aggressive than sodium)
- Melting Point Above Room Temperature
(Leaks into reactor building will freeze)
- Used as Blanket Material in Fusion Reactors
(Valuable lithium loop experience may be obtained)
- No Long-lived Gamma or Neutron Activation Products
(Impurities and corrosion products maybe present)

Lithium Disadvantages

- Neutron Activation Product is Tritium
(May require removal and collection system)
 - Reactive with Moisture and Oxidizes in Air
(But least reactive of alkaline metals)
 - High Melting Point (180°C)
(Requires loop draining and trace heaters)
 - Very High Thermal Cross Section (940 barns Li-6)
(Potential reactivity insertion implications)
 - Limited Experience With Lithium T and H Loops
(Not nearly as widespread use as Na and NaK)
-

TABLE XIII. Tritium Generation from Lithium Activation

-
- Tritium (Hydrogen 3) is generated by (n,α) activation of Li-6 isotope:

<u>Isotope</u>	<u>Abundance</u>	<u>Cross Section</u>	<u>Reaction</u>
Li-6	7.52%	940 barns	n,α
Li-7	92.48%	0.037 barns	n,β

- Tritium has a half-life of 12.3 y and emits a 0.018 MeV beta particle:

- Tritium is in Class 4 (relatively low) radiotoxicity but nuclide is very mobile with maximum permissible concentrations (MPC):

Air ----- $2 \cdot 10^{-7} \mu\text{C/ml}$

Water---- $3 \cdot 10^{-3} \mu\text{C/ml}$

- ORIGEN computer run yielded for the infinite-cycle activation, a value of ~ 19 Ci/g of lithium attributed entirely to tritium. Results for finite number of cycles should be evaluated accounting for detritiation.
-

TABLE XIV. Experimental Lithium System

-
- Was largest lithium loop in the world ($\sim 3.8 \text{ m}^3/1000 \text{ gal}$) at HEDL in support of FMIT facility.
 - Operated safely and reliably for four years (16,000 h) was shut down January 1984.
 - Development of equipment and procedures for operation at $\sim 270^\circ\text{C}$ (518°F) under argon and vacuum.
 - Confirmed performance of large EM pump $0.038 \text{ m}^3/\text{s}$ (600 gpm) at 221 kPa (33 psi) head. Chemistry loop had small (10 to 50 gpm) MSA Style V AC electromagnetic pump.
 - Developed lithium sampling and analytical chemistry techniques to monitor impurity levels in the liquid lithium.
 - Developed impurity control methods, i.e., cold trap (oxygen, hydrogen) and hot trap (nitrogen). More work needed on hot trap (e.g., reconsider titanium getter).
 - Assessed and confirmed suitability of loop materials (304 SS) and components (valves) to low temperature, low impurity lithium.
 - Corrosion investigations confirmed low rates at FMIT conditions. For 304 SS corrosion allowance of $\sim 0.2 \mu\text{m}/\text{y}$ based on 270°C temp and low impurity concentrations ($\leq 400 \text{ wppm}$ of N_2). For hot trap at 540°C (1000°F), the corrosion rate was estimated at $\sim 25 \mu\text{m}/\text{y}$.
-

TABLE XV. In-reactor Thermal and Hydraulic Loop Design Conditions

Design Conditions

Overall Heat Load	15 kW
Average Temperature	500°F (260°C)
Lithium Density	31.325 lb/ft ³
Lithium Viscosity	1.195 lb/ft-h
Lithium Heat Capacity	1.0313 Btu/lb-°F

Design Dimensions

Upper In-reactor Length	19.27 ft
Lower In-reactor Length	19.14 ft
Total In-reactor Length	38.41 ft
Upper In-reactor Guide Tube O. D.	2.500 in.
Lower In-reactor Guide Tube O. D.	2.125 in.
Radial In-reactor Dimensions	See Tables XVI, XVII, and XVIII

Friction Factor Correlation*

$$f = 0.0014 + 0.125/(\text{Re})^{0.32}$$
$$\text{Re} = (\text{De} \cdot G)/\mu$$

*Reference: Smooth tube turbulent flow correlation, Eq. (47a), on page 53 of D. Q. Kern, Process Heat Transfer, McGraw Hill Book Co., Inc., New York, NY (1950).

TABLE XVI. Loop In-reactor Physical Characteristics for Case 1--Original Nonstandard Tubing

Item	Description	Dimensions (in.)			Volume (ft ³ /ft)	Surface Area (ft ² /ft)	
		O.D	I.D.	Thickness		O.D.	I.D.
1	Sample Capsule	1.000	---	---	5.4542E-03	0.2618	---
2	Gap A-Argon Fill Gas	1.125	1.000	0.0625	1.4489E-03	0.2945	0.2618
3	Test Container	1.250	1.125	0.0625	1.6192E-03	0.3272	0.2945
4	Gap B-Li In Downflow	1.438	1.250	0.0940	2.7562E-03	0.3765	0.3272
5	Flow Divider	1.563	1.438	0.0625	2.0429E-03	0.4092	0.3765
6	Gap C-Li Out Upflow	1.688	1.563	0.0625	2.2164E-03	0.4419	0.4092
7	Flow Housing	1.875	1.688	0.0935	3.6340E-03	0.4909	0.4419
Upper Section							
8	Gap D-Argon Insulation	2.250	1.875	0.1875	8.4369E-03	0.5890	0.4909
9	Upper Guide Tube	2.500	2.250	0.1250	6.4768E-03	0.6545	0.5890
Lower Section							
10	Gap E-Argon Insulation	2.000	1.875	0.0625	2.6419E-03	0.5236	0.4909
11	In-core Guide Tube	2.125	2.000	0.0625	2.8123E-03	0.5563	0.5236

TABLE XVII. Loop In-reactor Physical Characteristics for Case 2--Straight Standard Tubing

Item	Description	Dimensions (in.)				Volume (ft ³ /ft)	Surface Area (ft ² /ft)	
		O.D	I.D	BWG Gage	Thickness (or Gap)		O.D.	I.D.
1	Sample Capsule	1.000	---	---	---	5.4542E-03	0.2618	---
2	Gap A-Argon Fill Gas	1.120	1.000	---	0.0600	1.3875E-03	0.2932	0.2618
3	Test Container	1.250	1.120	16	0.0650	1.6804E-03	0.3272	0.2932
4	Gap B-Li In Downflow	1.370	1.250	---	0.0600	1.7148E-03	0.3587	0.3272
5	Flow Divider	1.500	1.370	16	0.0650	2.0349E-03	0.3927	0.3587
6	Gap C-Li Out Upflow	1.685	1.500	---	0.0925	3.2137E-03	0.4411	0.3927
7	Flow Housing	1.875	1.685	13	0.0950	3.6892E-03	0.4909	0.4411
Upper Section								
8	Gap D-Argon Insulation	2.260	1.875	---	0.1925	8.6829E-03	0.5917	0.4909
9	Upper Guide Tube	2.500	2.260	11	0.1200	6.2308E-03	0.6545	0.5917
Lower Section								
10	Gap E-Argon Insulation	2.000	1.875	---	0.0625	2.6419E-03	0.5236	0.4909
11	In-core Guide Tube	2.125	2.000	16	0.0625	2.8123E-03	0.5563	0.5236

TABLE XVIII. Loop In-reactor Physical Characteristics for Case 3--Stepped Standard Tubing

Item	Description	Dimensions (in.)				Volume (ft ³ /ft)	Surface Area (ft ² /ft)	
		O.D.	I.D.	BWG Gage	Thickness (or Gap)		O.D.	I.D.
1	Sample Capsule	1.000	---	---	---	5.4542E-03	0.2618	---
2	Gap A-Argon Fill Gas	1.120	1.000	---	0.0600	1.3875E-03	0.2932	0.2618
3	Test Container	1.250	1.120	16	0.0650	1.6804E-03	0.3272	0.2932
Lower Section (Length = 19.14 ft)								
4	Gap B-Li In Downflow	1.370	1.250	---	0.0600	1.7148E-03	0.3587	0.3272
5	Flow Divider	1.500	1.370	16	0.0650	2.0349E-03	0.3927	0.3587
6	Gap C-Li Out Upflow	1.685	1.500	---	0.0925	3.2137E-03	0.4411	0.3927
7	Flow Housing	1.875	1.685	13	0.0950	3.6892E-03	0.4909	0.4411
8	Gap D-Argon Insulation	2.000	1.875	---	0.0625	2.6419E-03	0.5236	0.4909
9	Guide Tube	2.125	2.000	16	0.0625	2.8123E-03	0.5563	0.5236
Upper Section (Length = 19.47 ft)								
10	Gap E-Li In Downflow	1.435	1.250	---	0.0925	2.7092E-03	0.3757	0.3272
11	Flow Divider	1.625	1.435	13	0.0950	3.1710E-03	0.4254	0.3757
12	Gap F-Li Out Upflow	1.810	1.625	---	0.0925	3.4660E-03	0.4739	0.4254
13	Flow Housing	2.000	1.810	13	0.0950	3.9483E-03	0.5236	0.4739
14	Gap E-Argon Insulation	2.260	2.000	---	0.1300	6.0410E-03	0.5917	0.5236
15	Guide Tube	2.500	2.260	11	0.1200	6.2308E-03	0.6545	0.5917

TABLE XIX. Summary of In-reactor Loop Pressure Drop

Lithium Flow Rate (gpm)	Pressure Drop (psi)								
	Downcomer			Upcomer			Total In-reactor		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
20	55.26	221.6	139.5	134.4	42.92	40.28	189.6	265.5	180.0
15	33.42	134.0	84.37	81.33	25.97	24.39	114.8	160.0	108.8
10	16.49	66.10	41.63	40.18	12.83	12.05	56.67	78.93	53.68
7.5	10.57	42.36	26.67	24.40	8.23	7.73	34.97	50.59	34.40
5.0	4.96	19.87	12.51	12.10	3.87	3.63	17.06	23.74	16.14
3.0	2.05	8.23	5.13	4.60	1.52	1.44	6.65	9.73	6.57
2.0	1.22	4.10	2.58	2.29	0.79	0.75	3.51	4.89	3.33

Note:

Case 1 = Original Nonstandard Loop Tubing Design

Case 2 = Continuous Straight Standard Tubing Design

Case 3 = Stepped Standard Tubing Design

TABLE XX. Summary of Ex-reactor Loop Pressure Drop

Lithium Flow Rate (gpm)	Pressure Drop (psi)		
	Flexible Tubing ^a	Components ^b	Total Ex-reactor ^c
20	17.82	20.10	37.92
15	10.70	12.25	22.95
10	5.23	6.10	11.33
7.5	3.16	3.83	6.99
5	1.62	1.79	3.41
3	0.64	0.69	1.33
2	0.32	0.38	0.70

^aBased on assumed 40 ft of 1 in. (No.13 BWG gage) flexible metal tubing and by applying a factor of 3 to smooth tube friction drop.

^bDetermined as the pressure drop difference between the total (Column 4) and flexible tubing (Column 2) and provides for pump, heat exchanger, entrance and exit, and turning pressure losses.

^cEstimated by multiplying Case 1 total in-reactor pressure drop in Table XIX by 0.20.

TABLE XXI. Summary of Total Loop Pressure Drop

Lithium Flow Rate (gpm)	Pressure Drop (psi)								
	In-reactor			Ex-reactor*			Total Loop		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
20	189.6	265.5	180.0	37.92	37.92	37.92	227.5	303.4	217.7
15	114.8	160.0	108.8	22.95	22.95	22.95	137.7	182.9	131.7
10	56.67	78.93	53.68	11.33	11.33	11.33	68.00	90.26	65.01
7.5	34.97	50.59	34.40	6.99	6.99	6.99	41.96	57.58	41.39
5.0	17.06	23.74	16.14	3.41	3.41	3.41	20.42	27.15	19.55
3.0	6.65	9.75	6.57	1.33	1.33	1.33	7.98	11.08	7.90
2.0	3.51	4.89	3.33	0.70	0.70	0.70	4.21	5.59	4.03

*Estimated by multiplying Case 1 in-reactor pressure drop by 0.20.

Note:

Case 1 = Original Nonstandard Tubing Design

Case 2 = Continuous Straight Standard Tubing Design

Case 3 = Stepped Standard Tubing Design

TABLE XXII. Physical Properties for Coolant Pump Performance Assessment

Physical Property	Sodium at 1200°F	Lithium at 500°F
Electrical Resistivity, $\mu\Omega$ -in.	13.75	19.29
Liquid Density, lb/ft ³	49.72	31.33
Viscosity, lb/(ft-h)	0.4717	1.195

TABLE XXIII. Comparison of Pump Performance Parameters

ALIP Model Parameter	Sodium at 1200°F	Lithium at 500°F
Liquid Resistance	1.31 Ω	1.84 Ω
Air-gap Impedance	0.718 + 0.810j	0.673 + 0.986j
Total Impedance Per Phase	0.963 + 1.016j	0.918 + 1.192j
Phase Current	49.49 amps	46.05 amps
Input Power Factor	0.6884	0.6101
Total Input Power	7076 W	5840 W
Developed Pressure (P_1)	99.7 psi	74.7 psi
Pressure Drop Due to Harmonics (P_2)	9.0 psi	5.6 psi
Net Pressure Developed ($P_{dev} = P_1 - P_2$)	90.7 psi	69.2 psi
Pump Hydraulic Pressure Drop (P_{hyd})	19.0 psi	15.9 psi
Output Pressure ($P_0 = P_{dev} - P_{hyd}$)	71.7 psi	53.3 psi
Output Power	1091 W	821.3 W
Pumping Efficiency	15.4%	14.1%

TABLE XXIV. Lithium Electrical Resistivity Correlations

Temperature (°C/°F)	Electrical Resistivity-(μohms-cm)		
	Correlation 1	Correlation 2	Correlation 3
200/391	24.736	25.896	27.219
300/571	27.735	28.906	29.911
400/751	30.599	31.024	32.623
500/931	33.326	32.250	35.342
600/1111	35.918	32.584	38.058

Correlation 1 (T=200°C to 1000°C)

$$\rho(\mu\text{ohms-cm}) = 18.33 + 3.339\text{e-}02 \cdot T + 6.795\text{e-}06 \cdot T^2$$

Ref. E. E. Shpil'rain and V. A. Savchenko, "High Temperature," 6:247 (1968).

Correlation 2 (T=°C)

$$\rho(\mu\text{ohms-cm}) = 17.2 + 5.24\text{e-}02 \cdot T - 4.46\text{e-}05 \cdot T^2$$

Ref. "The Electrical Resistivity of Lithium and Sodium-Potassium Alloy," Pratt & Whitney Aircraft, PWAC-349 (1961).

Correlation 3 (T=200°C to 1430°C)

$$\rho(\mu\text{ohms-cm}) = 21.934 + 2.598\text{e-}02 \cdot T + 2.581\text{e-}06 \cdot T^2 - 1.819\text{e-}09 \cdot T^3$$

Ref. D. V. Rigney, S. M. Kapelner, and R. E. Cleary, "The Electrical Resistivity of Lithium and Columbium-1 Zirconium Alloy to 1430°C," CANEL Report, TIM-854 (September 1965).

TABLE XXV. Reference LTIV Conditions

Input Parameters	Single ALIP	Dual ALIP
Gamma Heating Rate	4.62 W/g-SS	4.62 W/g-SS
Test Section Temperature	550°F	550°F
Test Section SS Volume Fraction	0.50	0.50
LTIV Physical Characteristics	Table VI	Table VI
<u>Output Predictions</u>		
Lithium Flow Rate (at 550°F)	9.0934	11.8073
Inlet Downcomer Temperature	448.0°F	487.6°F
Outlet Upcomer Temperature	471.0°F	504.4°F
In-reactor Pressure Drop	47.5 psi	74.6 psi
Ex-reactor Pressure Drop	9.6 psi	15.1 psi
Total LTIV Pressure Drop	57.1 psi	89.7 psi
Total Gamma Heat Generation	11.89 kW	11.89 kW
Total Heat Transferred from EBR-II	3.736 kW	3.093 kW
Total LTIV Heat Load	15.63 kW	14.98 kW

TABLE XXVI. Test Section Stainless-steel Volume Fraction Effect on LTIV Performance

Case	Test Section Stainless-steel Volume Fraction	Single TREAT ALIP			Dual TREAT ALIP			Gamma Heat Generation (kW)		
		Flow Rate (gpm)	Temp In (°F)	Temp Out (°F)	Flow Rate (gpm)	Temp In (°F)	Temp Out (°F)	Down- comer Region	Up- comer Region	Total
1A	0.25	9.0979	460.6	480.9	11.8107	495.4	510.4	4.77	5.52	10.29
2A	0.50 (Ref)	9.0934	448.0	471.0	11.8073	487.6	504.4	6.37	5.52	11.89
3A	0.75	9.0878	435.4	461.0	11.8038	479.7	498.6	7.97	5.52	13.49
4A	1.00	9.0825	422.8	451.0	11.8002	471.8	492.6	9.57	5.52	15.09

TABLE XXVII. Gamma Heating Rate Effect on LTIV Performance

Case	Gamma Heating Rate (W/g)	Single TREAT ALIP			Dual TREAT ALIP			Gamma Heat Generation (kW)		
		Flow Rate (gpm)	Temp In (°F)	Temp Out (°F)	Flow Rate (gpm)	Temp In (°F)	Temp Out (°F)	Down- comer Region	Up- comer Region	Total
1B	3.0	9.1041	477.7	493.9	11.8148	505.8	517.7	4.14	3.59	7.73
2B	4.62 (Ref)	9.0934	448.0	471.0	11.8073	487.6	504.4	6.37	5.52	11.89
3B	6.0	9.0828	422.6	451.3	11.8007	472.0	493.2	8.27	7.17	15.44
4B	8.0	9.0672	385.5	422.5	11.7906	449.4	476.8	11.03	9.56	20.59

TABLE XXVIII. Test Temperature Effect on LTIV Performance

Case	Test Temp (°F/°C)	Single TREAT ALIP					Dual TREAT ALIP				
		Flow Rate (gpm)	Temperature (°F)		Press Drop (psi)		Flow Rate (gpm)	Temperature (°F)		Press Drop (psi)	
			Inlet	Outlet	Inpile	Total		Inlet	Outlet	Inpile	Total
1C	481/250	8.99	376.4	401.7	47.8	57.2	11.69	417.1	436.0	75.0	89.9
2C	500/260	9.02	396.0	420.7	47.7	57.2	11.72	436.4	454.8	74.9	89.9
3C	520/271	9.05	416.8	440.8	47.6	57.2	11.76	456.9	474.7	74.8	89.8
4C	550/288	9.09	448.0	471.0	47.5	57.1	11.80	487.6	504.4	74.6	89.7
5C	600/316	9.15	500.6	521.2	47.3	57.0	11.88	538.9	554.1	74.3	89.6

TABLE XXIX. Ex-reactor Pressure Drop Effects on LTIV Performance

Case	ExReac Press Drop	Single TREAT ALIP						Dual TREAT ALIP					
		Flow Rate (gpm)	Temperature (°F)		Pressure Drop (psi)			Flow Rate (gpm)	Temperature (°F)		Pressure Drop (psi)		
			Inlet	Outlet	Inpile	Expile	Total		Inlet	Outlet	Inpile	Expile	Total
1D	-25%	9.30	452.4	474.7	49.4	7.5	56.9	12.06	490.0	506.5	77.4	11.8	89.2
2D	Ref	9.09	448.0	471.0	47.5	9.6	57.1	11.80	487.6	504.4	74.6	15.1	89.7
3D	+25%	8.89	443.7	467.2	45.7	11.6	57.3	11.56	485.1	502.4	71.9	18.2	90.2

TABLE XXX. Original and Revised LTIV Reference Conditions

Parameter	Original Reference		Revised Reference	
	Single ALIP	Dual ALIP	Single ALIP	Dual ALIP
Input Parameters				
Gamma Heating Rate (W/g)	4.62	4.62	4.62	4.62
Test Section Temperature (°F)	550.0	550.0	550.0	550.0
Test Section Volume Fraction	0.50	0.50	0.50	0.50
Outer Gap Insulation Model	Radiation	Radiation	Rad and Cond	Rad and Cond
LTIV Physical Characteristics	Table VI	Table VI	Table VI	Table VI
Output Predictions				
Lithium Flow Rate (at 550°F)	9.0934	11.8073	9.0909	11.8061
Inlet Downcomer Temperature (°F)	448.0	487.6	441.6	483.8
Outlet Upcomer Temperature (°F)	471.0	504.4	464.6	500.4
In-reactor Pressure Drop (psi)	47.5	74.6	47.5	74.6
Ex-reactor Pressure Drop (psi)	9.6	15.1	9.6	15.1
Total LTIV Pressure Drop (psi)	57.1	89.7	57.1	89.7
Total Gamma Heat Generation (kW)	11.89	11.89	11.89	11.89
Total Heat Trans from EBR-II (kW)	3.736	3.093	3.834	2.774
Total LTIV Heat Load (kW)	15.63	14.98	15.72	14.66

TABLE XXXI. Insulation Gap Thermal Radiation Emissivity Effect on LTIV Performance

Case	Emissivity Value (ϵ_1 and ϵ_2)	Single TREAT ALIP						Dual TREAT ALIP					
		Flow Rate (gpm)	Temperature (°F)			Heat Load (kW)		Flow Rate (gpm)	Temperature (°F)			Heat Load (kW)	
			Inlet	Outlet	Delta T	EBR-II	Total		Inlet	Outlet	Delta T	EBR-II	Total
1E	0.00	9.09	458.3	476.1	17.8	0.24	12.13	11.80	493.6	506.9	13.3	-0.164	11.72
2E	0.07	9.09	457.4	475.4	18.0	0.44	12.33	11.80	493.1	506.5	13.4	~0.000	11.89
3E	0.55	9.09	448.5	469.4	20.8	2.32	14.21	11.80	487.9	503.0	15.1	1.550	13.44
4E	Ref*	9.09	441.6	464.6	23.0	3.83	15.72	11.80	483.8	500.4	16.6	2.774	14.66
5E	1.00	9.08	433.0	458.9	25.9	5.75	17.64	11.80	478.8	497.1	18.3	4.312	16.20

* Reference emissivity value of 0.79.

TABLE XXXII. Insulation Gap Argon Thermal Conductivity Effect on LTIV Performance

Case	Argon Thermal Conduct Value	Single TREAT ALIP						Dual TREAT ALIP					
		Flow Rate (gpm)	Temperature (°F)			Heat Load (kW)		Flow Rate (gpm)	Temperature (°F)			Heat Load (kW)	
			Inlet	Outlet	Delta T	EBR-II	Total		Inlet	Outlet	Delta T	EBR-II	Total
1F	0*Ref	9.0937	449.7	472.1	22.4	3.431	15.323	11.8076	488.5	505.2	16.7	2.867	14.759
2F	Ref*	9.0909	441.6	464.6	23.0	3.834	15.726	11.8061	483.8	500.4	16.6	2.774	14.666
3F	2*Ref	9.0883	433.5	457.4	23.9	4.352	16.244	11.8045	479.2	495.7	16.5	2.746	14.638
4F	5*Ref	9.0805	409.8	436.8	27.0	6.534	18.426	11.7998	465.5	482.4	16.9	3.015	14.907
5F	10*Ref	9.0673	371.4	406.5	35.1	11.977	23.869	11.7921	443.7	462.2	18.5	4.490	16.382

* Reference argon thermal conductivity value of 0.0172 Btu/h/ft/°F.

TABLE XXXIII. Total Emittance Data*

Surface	Temp. (°F)	ϵ
Stainless Steel, Polished	100.0	0.07 to 0.17
Stainless Steel, After Repeated Heating and Cooling	400 to 1650	0.50 to 0.70
Sheet Steel, Ground	1700	0.55
Sheet Steel, Rolled	100	0.66
Steel, Oxidized at 1100°F	500	0.79
Sheet Steel, Strong Rough Oxide	100	0.80

* Reference: E. M. Sparrow and R. D. Cess, Radiation Heat Transfer, 45, Brooks/Cole Publishing Co., Belmont, CA (1967).

TABLE XXXIV. Thermohydraulic LTIV Performance Comparisons

Parameter	TREAT ALIP at 25 amps		TREAT ALIP at 40 amps	
	Single ALIP	Dual ALIP	Single ALIP	Dual ALIP
Input Parameters				
Gamma Heating Rate (W/g)	4.62	4.62	4.62	4.62
Test Section Temperature (°F)	550.	550.	550.	550.
Test Section Volume Fraction	0.50	0.50	0.50	0.50
Outer Gap Insulation Model	Rad and Cond	Rad and Cond	Rad and Cond	Rad and Cond
LTIV Physical Characteristics	Table VI	Table VI	Table VI	Table VI
Output Predictions				
Lithium Flow Rate (at 550°F)	6.6699	8.7808	9.0909	11.8061
Inlet Downcomer Temperature (°F)	352.8	434.1	441.6	483.8
Outlet Upcomer Temperature (°F)	388.4	458.1	464.6	500.4
In-reactor Pressure Drop (psi)	28.0	44.8	47.5	74.6
Ex-reactor Pressure Drop (psi)	5.7	9.1	9.6	15.1
Total LTIV Pressure Drop (psi)	33.7	53.9	57.1	89.7
Total Gamma Heat Generation (kW)	11.89	11.89	11.89	11.89
Total Heat Trans from EBR-II (kW)	5.948	4.018	3.834	2.774
Total LTIV Heat Load (kW)	17.84	15.91	15.72	14.66

TABLE XXXV. Projected Costs for Development of the Low Temperature Test Vehicle

Cost Breakdown

Activities	Effort (Man-Months)	Estimated Cost (K\$)
Development, Engineering and Design Effort	48 Staff 18 Designer	800 108
Procurement, Fabrication and Assembly Effort	36 Staff 24 Technician	600 240
Materials and Fabrication Costs	—	900

Cost Summary

Effort related costs	\$1748K
Materials and fabrication costs	<u>900K</u>
Total cost	\$2648K

TABLE C1. Speakeasy Program Listings for Curve Fit Results

LISTING OF PROGRAM LICP

```

1 PROGRAM
2 CP=1.0425,1.02,1.0057,0.9962
3 T=400.,600.,800.,1000.
4 COEF=MULTIREG(T,T**2,T**3,CP:RES,COR)
5 COEF
6 COR
7 CPFIT=COEF(1)+COEF(2)*T+COEF(3)*T**2+COEF(4)*T**3
8 TABULATE T,CP,CPFIT,RES
9 END
:_execute licp
EXECUTION STARTED
0 COEF (A 4 COMPONENT ARRAY)
  1.1257    -2.8867E-4    2.3E-7    -7.0833E-11
OCOR = 1
0  T      CP      CPFIT      RES
  ****      ****      ****      ****
  400  1.0425  1.0425  2.0402E-10
  600  1.02   1.02   2.7414E-10
  800  1.0057  1.0057  1.5904E-10
 1000  .9962   .9962  -2.5077E-10

```

LISTING OF PROGRAM LIDEN

```

1 PROGRAM
2 DEN=31.65,31.0,30.4,29.6
3 T=400.,600.,800.,1000.
4 COEF=MULTIREG(T,T**2,T**3,DEN:RES,COR)
5 COEF
6 COR
7 DENFIT=COEF(1)+COEF(2)*T+COEF(3)*T**2+COEF(4)*T**3
8 TABULATE T,DEN,DENFIT,RES
9 END
:_execute liden
EXECUTION STARTED
0 COEF (A 4 COMPONENT ARRAY)
  34.1    -.0092917    1E-5    -5.2083E-9
OCOR = 1
0  T      DEN      DENFIT      RES
  ****      ****      ****      ****
  400  31.65  31.65  6.1709E-9
  600  31     31     8.2729E-9
  800  30.4   30.4   4.7442E-9
 1000  29.6   29.6   -7.7126E-9

```

LISTING OF PROGRAM LIVIS

```

1 PROGRAM
2 VIS=1.31,1.08,0.95,0.84
3 T=400.,600.,800.,1000.
4 COEF=MULTIREG(T,T**2,T**3,VIS:RES,COR)
5 COEF
6 COR
7 VISFIT=COEF(1)+COEF(2)*T+COEF(3)*T**2+COEF(4)*T**3
8 TABULATE T,VIS,VISFIT,RES
9 END
:_execute livis
EXECUTION STARTED
0 COEF (A 4 COMPONENT ARRAY)
  2.39    -.0041333    4.25E-6    -1.6667E-9
OCOR = 1
0  T      VIS      VISFIT      RES
  ****      ****      ****      ****
  400  1.31  1.31  3.7414E-10
  600  1.08  1.08  3.8063E-10
  800  .95   .95   -1.3428E-10
 1000  .84   .84   -1.2788E-9

```

LISTING OF PROGRAM LITK

```

1 PROGRAM
2 TK=26.8,24.9,22.1,17.6
3 T=400.,600.,800.,1000.
4 COEF=MULTIREG(T,T**2,T**3,TK:RES,COR)
5 COEF
6 COR
7 TKFIT=COEF(1)+COEF(2)*T+COEF(3)*T**2+COEF(4)*T**3
8 TABULATE T,TK,TKFIT,RES
9 END
:_execute litk
EXECUTION STARTED
0 COEF (A 4 COMPONENT ARRAY)
  31.1    -.015583    1.875E-5    -1.6667E-8
OCOR = 1
0  T      TK      TKFIT      RES
  ****      ****      ****      ****
  400  26.8  26.8  5.5089E-9
  600  24.9  24.9  7.1384E-9
  800  22.1  22.1  3.3738E-9
 1000  17.6  17.6  -8.5412E-9

```

TABLE D1. TMOLL Standard Input Results Summary

COEFFICIENTS FOR PUMP HEAD & EXREACTOR PRESSURE DROP

I	PUMP HEAD (CHD(I))	EXREACTOR (COEF(I))
1	8.62900E+01	-3.81930E-01
2	-2.79490E-01	3.33850E-01
3	-7.53300E-02	8.88230E-02
4	9.47910E-04	-4.88580E-04

REF. PUMP HEAD LIQ RESISTIVITY (MICROHMS-CM) = 1.82573E+01

LTIV RADIAL GEOMETRY DIAMETERS (INCHES)

CORE & LOWER & INTERMEDIATE & UPPER REGION

DT(1)=O.D. SAMPLE CAPSULE
=I.D. ARGON CLEARANCE GAP = 1.00000E+00
DT(2)=O.D. ARGON CLEARANCE GAP
=I.D. TEST CONTAINER = 1.12000E+00
DT(3)=O.D. TEST CONTAINER= 1.25000E+00

LOWER & INTERMEDIATE REGION

DL(1)=I.D. DOWNFLOW ANNULUS
=O.D. TEST CONTAINER = 1.25000E+00
DL(2)=O.D. DOWNFLOW ANNULUS
=I.D. FLOW DIVIDER = 1.37000E+00
DL(3)=O.D. FLOW DIVIDER
=I.D. UPFLOW ANNULUS = 1.50000E+00
DL(4)=O.D. UPFLOW ANNULUS
=I.D. FLOW HOUSING = 1.68500E+00
DL(5)=O.D. FLOW HOUSING
=I.D. AR INSULATION GAP = 1.87500E+00
DL(6)=O.D. AR INSULATION GAP
=I.D. OUTSIDE GUIDE TUBE = 2.00000E+00
DL(7)=O.D. OUTSIDE GUIDE TUBE = 2.12500E+00

UPPER REGION

DU(1)=I.D. DOWNFLOW ANNULUS
=O.D. TEST CONTAINER = 1.25000E+00
DU(2)=O.D. DOWNFLOW ANNULUS
=I.D. FLOW DIVIDER = 1.41600E+00
DU(3)=O.D. FLOW DIVIDER
=I.D. UPFLOW ANNULUS = 1.75000E+00
DU(4)=O.D. UPFLOW ANNULUS
=I.D. FLOW HOUSING = 1.93500E+00
DU(5)=O.D. FLOW HOUSING
=I.D. AR INSULATION GAP = 2.12500E+00
DU(6)=O.D. AR INSULATION GAP
=I.D. OUTSIDE GUIDE TUBE = 2.26000E+00
DU(7)=O.D. OUTSIDE GUIDE TUBE = 2.50000E+00

AXIAL LTIV REGION LENGTHS (INCHES)

LOWER REGION (DDL) = 2.45620E+01
CORE REGION (DDC) = 1.35000E+01
INTERMEDIATE REGION (DDI) = 1.91657E+02
UPPER REGION (DDU) = 2.33640E+02

AXIAL DISTANCES FROM LOOP BOTTOM (INCHES)

BOTTOM OF TOP COVER (DBOTC) = 9.15900E+01
TOP OF TOP COVER (DTOPC) = 1.19593E+02
BOTTOM OF SMALL PLUG (DBOTP) = 2.54218E+02
TOP OF SMALL PLUG (DTOPP) = 3.51718E+02

NUMBER OF AXIAL NODES IN EACH REGION

LOWER REGION = 5
CORE REGION = 10
INTERMEDIATE REGION = 40
UPPER REGION = 40

TABLE D1. (Contd.)

INPUTTED TEMPERATURES IN DEGREES F
EBR-II INLET TEMP (TEBRL) = 7.00000E+02
EBR-II OUTLET TEMP (TEBRU) = 8.83000E+02
LTIV LOWER LOOP TEMP (TI) = 5.50000E+02
COVER TOP TEMP (TTOPC) = 7.00000E+02
SMALL PLUG TOP TEMP (TTOPP) = 8.00000E+01

INITIAL CONDITIONS

GAMMA HEATING IN W/GM (QG) = 4.62000E+00
VOLUME FRACTION SS IN CAPSULES (VFCAP) = 5.00000E-01
EMMISSIVITY HOUSING TUBE (E1) = 7.90000E-01
EMMISSIVITY GUIDE TUBE (E2) = 7.90000E-01
INITIAL LTIV LITHIUM FLOW RATE IN GPM (VFLO) = 1.50000E+01
PRESSURE AT DOWNCOMER INLET (PRESI) = 1.00000E+02

PHYSICAL PROPERTY DATA

LITHIUM

DENSITY IN LB/FT3 (DENL) = VARIABLE
THERMAL COND IN BTU/HR/FT/DEG F (TKL) = VARIABLE

HEAT CAPACITY IN BTU/LB-DEG F (CPL) = VARIABLE
VISCOSITY IN LB/FT-HR (VISL) = VARIABLE

ARGON AT 600F

DENSITY IN LB/FT3 (DENA) = 4.92000E-02
THERMAL COND IN BTU/HR/FT/DEG F (TKA) = 1.72000E-02
HEAT CAPACITY IN BTU/LB-DEG F (CPA) = 1.24000E-01
VISCOSITY IN LB/FT-HR (VISA) = 9.05000E-02

STAINLESS STEEL AT 75F

DENSITY IN LB/FT3 (DENS) = 4.98000E+02
THERMAL COND IN BTU/HR/FT/DEG F (TKS) = 9.00000E+00
HEAT CAPACITY IN BTU/LB-DEG F (CPS) = 1.20000E-01
THERM COND OF FLOW DIVIDER IN UPPER REG (TKFD) = 5.50000E-02

CONTROL OPTIONS & PARAMETERS

PRINT OPTIONS

PRINT PLOT DATA (MIT = 0 YES) = 0
PRINT AXIAL DATA (NIT = 0 YES) = 0

PHYSICAL PROPERTY DATA OPTIONS

VARIABLE LITHIUM PROP (MPH = 0 YES) = 0

FLOW RATE ITERATION OPTION

FLOW INTERATION CALC (NTYPE = 0 YES) = 0
MAXIMUM NUMBER OF ITERATIONS (NMAX) = 20
PRESS DIFF CONVERGENCE CRITERIA (EPS) = 1.00000E-02 PSI

TABLE D2. TMOLL Standard Output Results Summary

FLOW ITERATION RESULTS

I	INITIAL FLOW (GPM)	PRESS DROP (PSI)	PRESS HEAD (PSI)	LI RESISVTY (MICROHMS-CM)	LI PRESS HD (PSI)	PRESS DIFF (PSI)	NEXT FLOW (GPM)	INLET TEMP (DEG F)
1	1.50000E+01	1.35955E+02	6.83476E+01	2.79309E+01	4.46760E+01	-9.12786E+01	8.08364E+00	5.07561E+02
2	8.08364E+00	4.67165E+01	7.96090E+01	2.63153E+01	5.52320E+01	8.51547E+00	8.67382E+00	4.14190E+02
3	8.67382E+00	5.27121E+01	7.88169E+01	2.66306E+01	5.40349E+01	1.32273E+00	8.78235E+00	4.31374E+02
4	8.78235E+00	5.38493E+01	7.86673E+01	2.66811E+01	5.38304E+01	-1.88795E-02	8.78082E+00	4.34164E+02
5	8.78082E+00	5.38332E+01	7.86694E+01	2.66804E+01	5.38333E+01	4.53039E-05	0.00000E+00	4.34125E+02

LTIV GEOMETRIC CALCULATIONAL RESULTS

CORE & LOWER & INTERMEDIATE & UPPER REGION

ITEM	THICKNESS	SURFACE AREA (FT2/FT)		VOLUME (FT3/FT)
	OR GAP (IN.)	OUTSIDE	INSIDE	
SAMPLE CAPSULE	5.00000E-01	2.61799E-01		5.45415E-03
ARGON CLEARANCE GAP	6.00000E-02	2.93215E-01	2.61799E-01	1.38754E-03
TEST CONTAINER	6.50000E-02	3.27249E-01	2.93215E-01	1.68042E-03

LOWER & INTERMEDIATE REGION

ITEM	THICKNESS	SURFACE AREA (FT2/FT)		VOLUME (FT3/FT)
	OR GAP (IN.)	OUTSIDE	INSIDE	
LITHIUM DOWNCOMER	6.00000E-02	3.58665E-01	3.27249E-01	1.71479E-03
FLOW DIVIDER	6.50000E-02	3.92699E-01	3.58665E-01	2.03494E-03
LITHIUM UPCOMER	9.25000E-02	4.41132E-01	3.92699E-01	3.21372E-03
FLOW HOUSING	9.50000E-02	4.90874E-01	4.41132E-01	3.68919E-03
ARGON INSULATION	6.25000E-02	5.23599E-01	4.90874E-01	2.64186E-03
GUIDE TUBE	6.25000E-02	5.56324E-01	5.23599E-01	2.81230E-03

UPPER REGION

ITEM	THICKNESS	SURFACE AREA (FT2/FT)		VOLUME (FT3/FT)
	OR GAP (IN.)	OUTSIDE	INSIDE	
LITHIUM DOWNCOMER	8.30000E-02	3.70708E-01	3.27249E-01	2.41377E-03
FLOW DIVIDER	1.67000E-01	4.58149E-01	3.70708E-01	5.76746E-03
LITHIUM UPCOMER	9.25000E-02	5.06582E-01	4.58149E-01	3.71823E-03
FLOW HOUSING	9.50000E-02	5.56324E-01	5.06582E-01	4.20733E-03
ARGON INSULATION	6.75000E-02	5.91667E-01	5.56324E-01	3.22872E-03
GUIDE TUBE	1.20000E-01	6.54498E-01	5.91667E-01	6.23083E-03

TABLE D2. (Contd.)

GENERAL HEAT TRANSFER GEOMETRIC DATA

TOTAL NUMBER OF AXIAL NODES (MAX OF 100) (IUF) = 95
TOTAL AXIAL LENGTH OF LTIV INREACTOR (Z(IUF)) = 3.86133E+01 FT
SURFACE AREA LOWER REGION FOR INNER H.T. (ADLI) = 4.16916E-01 FT2/FT
SURFACE AREA UPPER REGION FOR INNER H.T. (ADUI) = 4.82365E-01 FT2/FT
SURFACE AREA LOWER REGION FOR OUTER H.T. (ADLO) = 5.56324E-01 FT2/FT
SURFACE AREA UPPER REGION FOR OUTER H.T. (ADUO) = 6.54498E-01 FT2/FT

VOLUME STEEL IN UPCOMER INCORE REG (VGUC) = 4.70666E-03 FT3/FT
VOLUME STEEL IN DWNCOMER INCORE REG (VGDC) = 5.42497E-03 FT3/FT

SUMMARY OF THERMAL AND HYDRAULIC CONDITIONS

COMBINED LOWER LITHIUM TEMPERATURE (TI) = 5.50000E+02 DEG F
DOWNCOMER INLET LITHIUM TEMPERATURE (TD(IUF)) = 4.34125E+02 DEG F
UPCOMER OUTLET LITHIUM TEMPERATURE (TU(IUF)) = 4.58281E+02 DEG F

HEAT TRANSFERRED TO DOWNCOMER (QDT(IUF)) = 2.38751E+05 BTU/HR
HEAT TRANSFERRED TO UPCOMER (QUG(IUF)) = -2.25037E+05 BTU/HR
TOTAL HEAT TRANSFERRED FROM EBR-II (QOT(IUF)) = 1.37139E+04 BTU/HR

DOWNCOMER PRESSURE DROP (PRESD(IUF)) = 3.57266E+01 PSI
UPCOMER PRESSURE DROP (PRESU(IUF)) = 9.03933E+00 PSI
TOTAL INREACTOR PRESS DROP (TOTPRES) = 4.47659E+01 PSI
LITHIUM PRESSURE AT LTIV BOTTOM (PBOTL) = 6.42734E+01 PSI
EXREACTOR LTIV PRESSURE DROP EST (DELPEX) = 9.06728E+00 PSI
TOTAL LTIV PRESS DROP ESTIMATE (TPLOOP) = 5.38332E+01 PSI

PUMP HEAD & PRESSURE DIFFERENTIAL

NUMBER OF PRESSURE DROP ITERATIONS (J) = 5
ALIP PUMP HEAD (PH(J)) = 5.38333E+01 PSI
PRESSURE DIFFERENCE (PH-TPLOOP) (DP(J)) = 4.53039E-05 PSI

LITHIUM MASS FLOW RATES

CONVERGED LOOP FLOW RATE (G(J)) = 8.78082E+00 GPM
LOOP MASS FLOW RATE (TFR) = 2.19374E+03 LBS/HR
LOWER REG. DOWNCOMER MASS FLUX (GFRD) = 1.27931E+06 LBS/HR-FT2
LOWER REG. UPCOMER MASS FLUX (GFRU) = 6.82617E+05 LBS/HR-FT2
UPPER REG. DOWNCOMER MASS FLUX (GFRD) = 9.08845E+05 LBS/HR-FT2
UPPER REG. UPCOMER MASS FLUX (GFRU) = 5.89996E+05 LBS/HR-FT2

INPUT GAMMA HEATING RATE IN S.S. (QGE) = 3.56093E+06 BTU/HR/FT3
LINEAR GAMMA HEAT GEN RATE UPCOMER (QGUC) = 1.67601E+04 BTU/HR/FT
LINEAR GAMMA HEAT GEN RATE DWNCOMER (QGDC) = 1.93180E+04 BTU/HR/FT
GAMMA HEAT GENERATION IN DOWNCOMER (QDG(ICF)) = 2.17327E+04 BTU/HR
GAMMA HEAT GENERATION IN UPCOMER (QUG(ICF)) = 1.88551E+04 BTU/HR
TOTAL GAMMA HEAT GENERATION (QGT(ICF)) = 4.05879E+04 BTU/HR

END TIME: 8 HRS 18 MIN 43 SEC