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FORCED-CONVECTION HEAT-TRANSFER MEASUREMENTS WITH A MOLTEN FLUORIDE SALT MIXTURE FLOWING IN A SMOOTH TUBE

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OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

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ABSTRACT

Heat-transfer coefficients were determined experimentally for a proposed MSBR fuel salt (LiF-BeF_2-ThF_4-UF_4;67.5-20.0-12.0-0.5 mole %) flowing by forced convection through a 0.18-in.-ID horizontal, circular tube for the following range of variables:

Reynolds modulus	400 – 30,600
Prandtl modulus	4 – 14
Average fluid temperature (°F)	1050 – 1550
Heat flux (Btu/hr·ft^2)	22,000 – 560,000

Within these ranges, the heat-transfer coefficient was found to vary from 320 up to 6900 Btu/hr·ft^2·°F (Nusselt modulus of 6.5 to 138). Correlations of the experimental data resulted in the equations:

$$N_{Nu} = 1.89 \left[N_{Re}\, N_{Pr}\, (D/L)\right]^{0.33} (\mu/\mu_s)^{0.14} \quad ,$$

with an average absolute deviation of 6.6% for $N_{Re} < 1000$;

$$N_{Nu} = 0.107 \, (N_{Re}^{2/3} - 135)\, N_{Pr}^{1/3} \, (\mu/\mu_s)^{0.14} \quad ,$$

with an average absolute deviation of 4.1% for $3500 < N_{Re} < 12{,}000$; and

$$N_{Nu} = 0.0234 \, N_{Re}^{0.8} N_{Pr}^{1/3} \, (\mu/\mu_s)^{0.14} \quad ,$$

with an average absolute deviation of 6.2% for $N_{Re} > 12{,}000$.

Keywords: Heat transfer, fused salts, forced convection, heat exchangers, fluid flow, correlations.

INTRODUCTION

The design of molten salt reactors requires detailed information about the transport properties of the proposed fuel, coolant and blanket mixtures. Although the molten salts generally behave as normal fluids with respect to heat transfer,[1,2] the possibility of unexpected effects, such as nonwetting of metallic surfaces or the formation of low-conductance surface films, indicates that heat-transfer measurements for specific reactor salts are needed.[3] This report describes heat-transfer experiments with a proposed reactor fuel of mixed fluoride salts (LiF-BeF_2ThF_4-UF_4; 67.5-20.0-12.0-0.5 mole %). The technique employs forced convection of the liquid salts through a smooth thin-walled Hastelloy N tube. Resistance heating supplies the tube with a uniform heat flux. This method is particularly well suited to the molten salt system because the electrical resistance of the molten salt is very large compared with that of the metal tube. Furthermore, the resistance of Hastelloy N remains nearly constant over the entire temperature range of the measurements, which simplifies the achievement of an axially uniform heat flux. In addition, a constant heat capacity of the molten salt in the observed temperature range makes possible several convenient assumptions in the calculation of local fluid bulk temperatures.

DESCRIPTION OF THE APPARATUS

The apparatus for studying heat transfer with the molten salt system is shown schematically in Fig. 1 and in the photograph, Fig. 2. Molten salt flows by means of gas pressure through a small diameter, electrically heated test section. The flow of molten salt alternates in direction as pressure from an inert gas supply is added to either of two storage vessels located at each end of the test channel. Each 6-gal salt reservoir is suspended from a weigh cell whose recorded signal indicates the flow rate. The flow of salt reverses automatically by the action of solenoid valves that control the flow of inert gas to the reservoirs. The rate of flow of the salt may be varied from 0.25 to 1.7 gal/min, emptying a reservoir in from 3 to 20 minutes.

The weigh cell circuit shown in Fig. 3 illustrates the electrical and mechanical systems that control the flow of gas and thereby the flow of molten salt. A second suspension system maintains tension on the test section, to prevent it from sagging, by means of counter weights connected by flexible cables. The test section consists of a smooth Hastelloy N tube, 24.5 in. long, 0.25-in. outside diameter, and 0.035-in.-wall

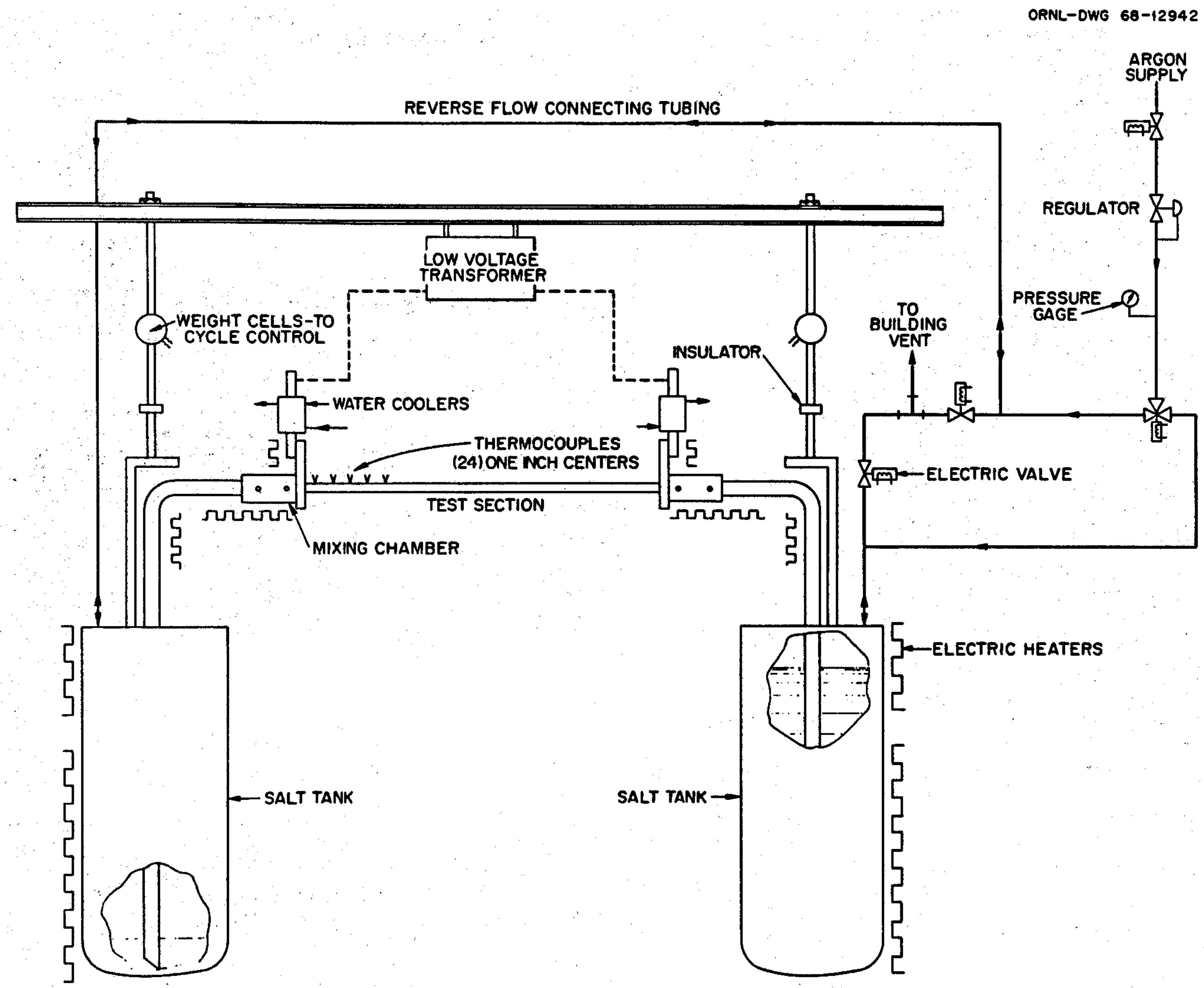

Fig. 1. Schematic diagram for determining the heat-transfer characteristics of molten salt by forced convection.

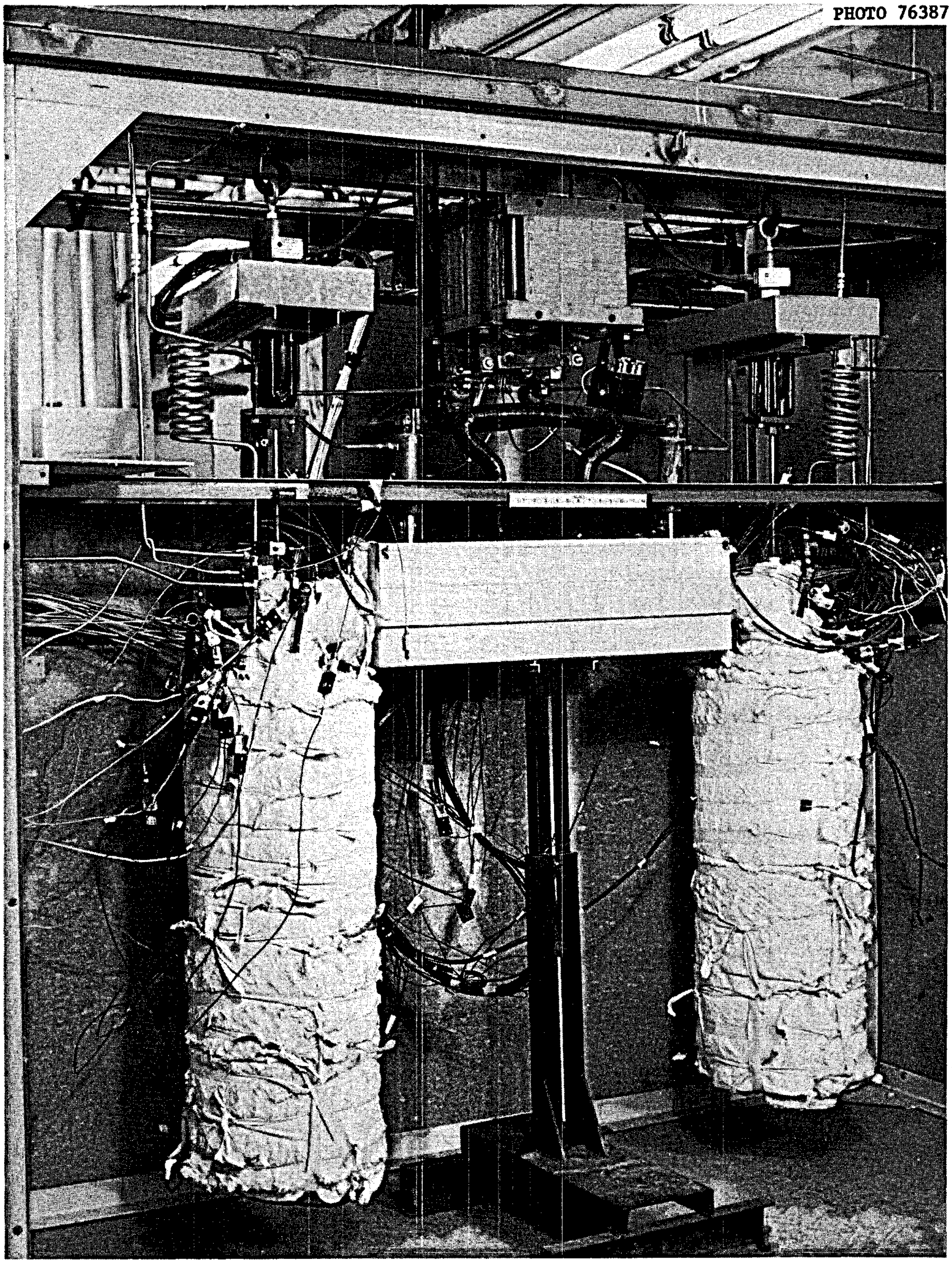

Fig. 2. Photograph of the apparatus viewed from the same aspect as that of Fig. 1.

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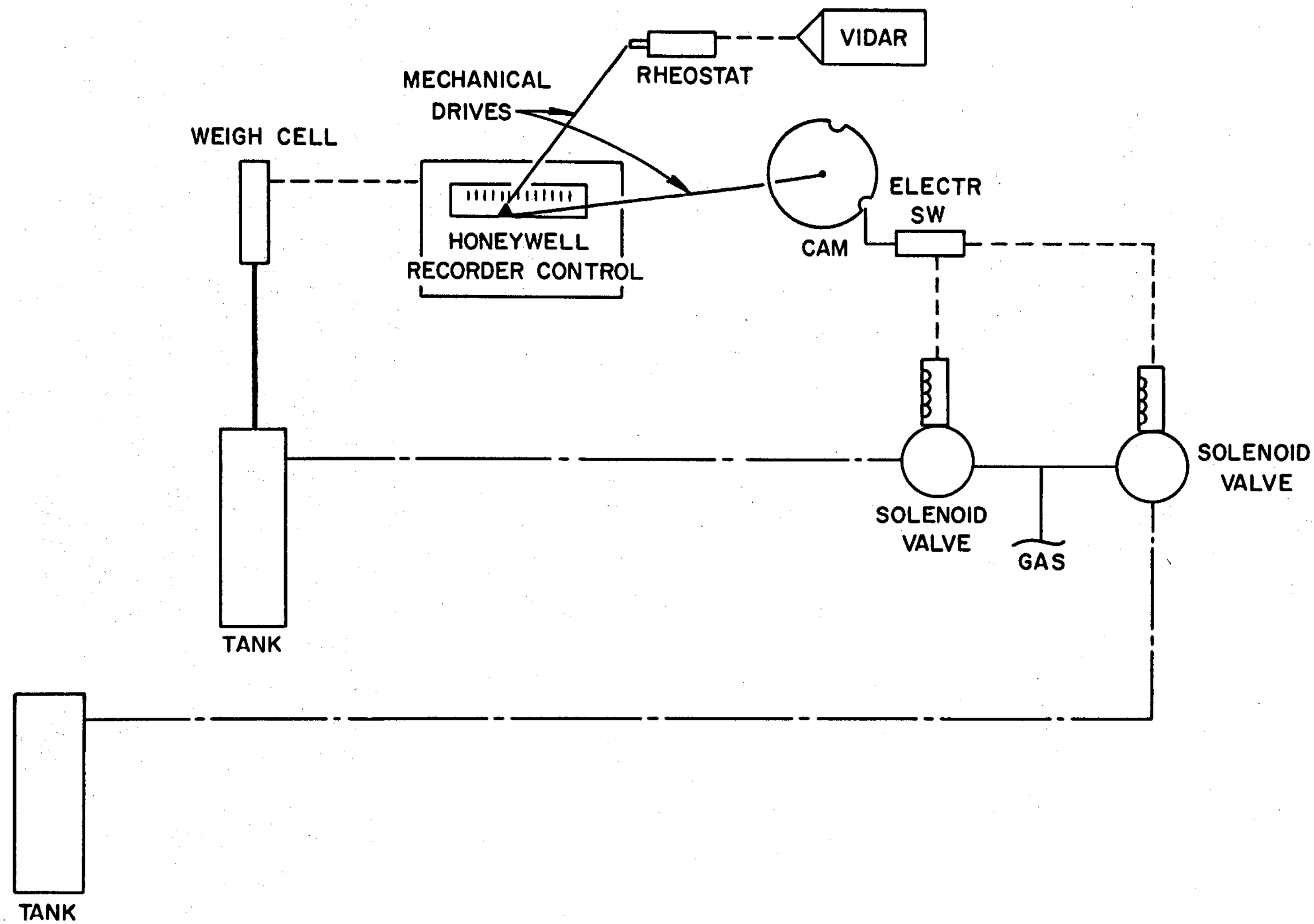

Fig. 3. Weigh cell circuit for molten salt heat-transfer system.

thickness and is resistance heated with a 60 Hz ac power supply. A detail of the mixing chambers located at each end of the test section is shown in Fig. A-1, Appendix A. The electrodes connecting the test section with the power circuit serve also as end plates of the disk-and-donut mixing chambers. The power circuit to the test section is shown in Fig. 4. The electrical power to the test section is supplied by a 440/25 v, 25 kva transformer and is measured with a General Electric watt transducer, also shown in Fig. 4. The test section is insulated with a 3-in.-thick layer of vermiculite powder contained in a sheet metal tray. The salt reservoirs and connecting tubes are heated by auxiliary clamshell and Calrod heaters placed in positions indicated in Fig. 1. A typical heater circuit for an auxiliary heater is depicted in Fig. 5.

The inlet and outlet salt temperatures are measured by four, 40-mil-diam, Chromel-Alumel sheathed thermocouples inserted into two wells in each mixing chamber (Fig. A-1). The temperature distribution along the test section is measured by a series of 24 Chromel-Alumel thermocouples (0.005-in.-diam wire) spot welded at 1-in. intervals to the outside tube wall. The scheme for attaching these thermocouples is shown in Fig. A-2.

Details of a salt reservoir can be seen in Fig. A-3. The interior of these tanks as well as the test section and the mixing chambers are stress relieved and hydrogen fired before they are assembled.

A data acquisition system provides for the automatic monitoring of the temperatures; record is made by a paper printout and a paper tape punch. In this system a multichannel Vidar data recorder reads emf signals from each thermocouple, from the weigh cells, and from the power circuit in a sequential switching arrangement known as a "crossbar scanner." The manufacturer claims an accuracy of better than ±0.5°F for the Vidar system. The data recording equipment is shown schematically in Fig. 6 and in a photograph in Fig. 7.

The weigh cell and wattmeter calibration curves and a list of pertinent experimental equipment may be found in Appendix A as Fig. A-4, Fig. A-5, and Table A-1, respectively.

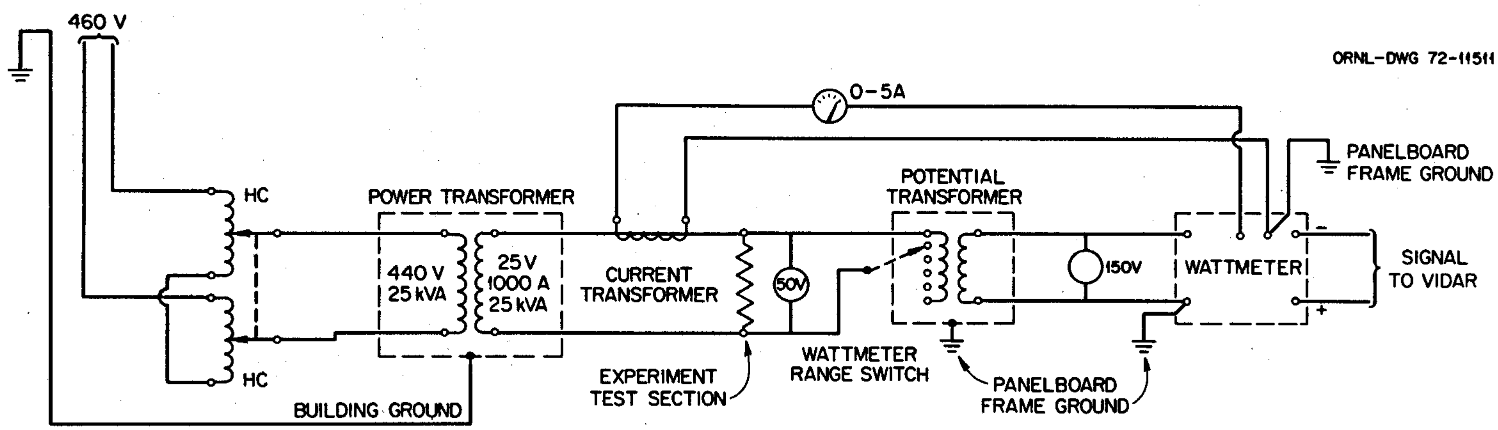

Fig. 4. Test-section power circuit for molten salt heat-transfer experiment.

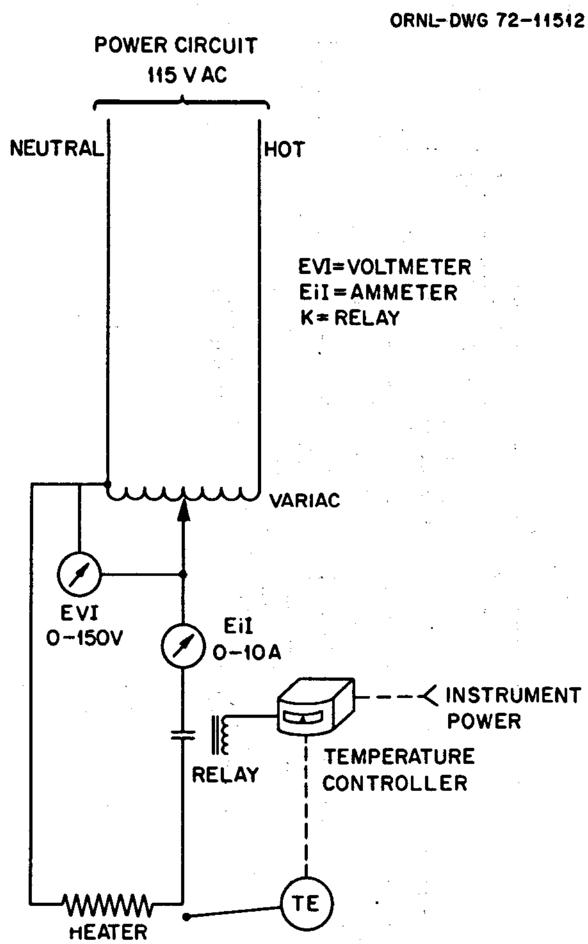

Fig. 5. Typical heater circuit for molten salt heat-transfer experiments.

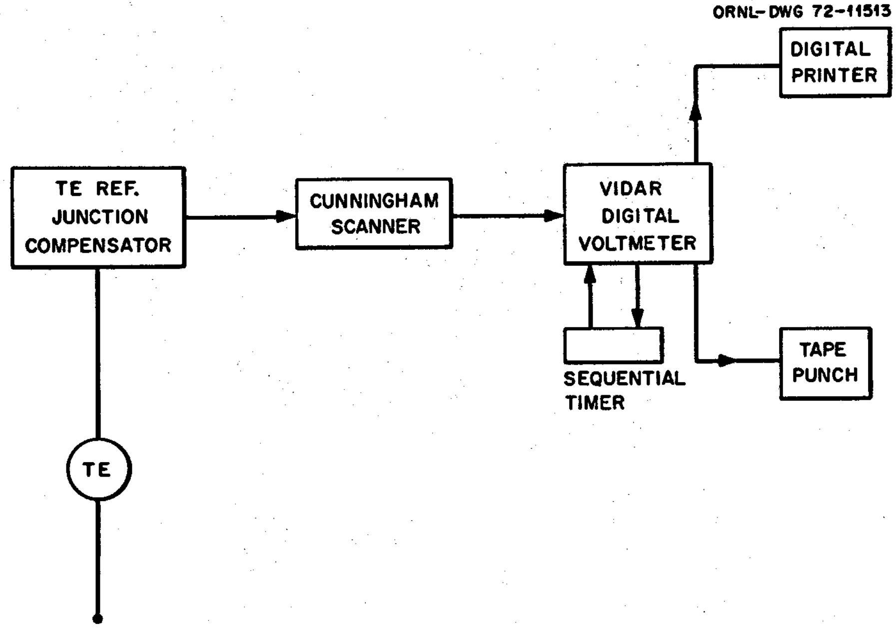

Fig. 6. Thermocouple circuit for molten salt heat-transfer system.

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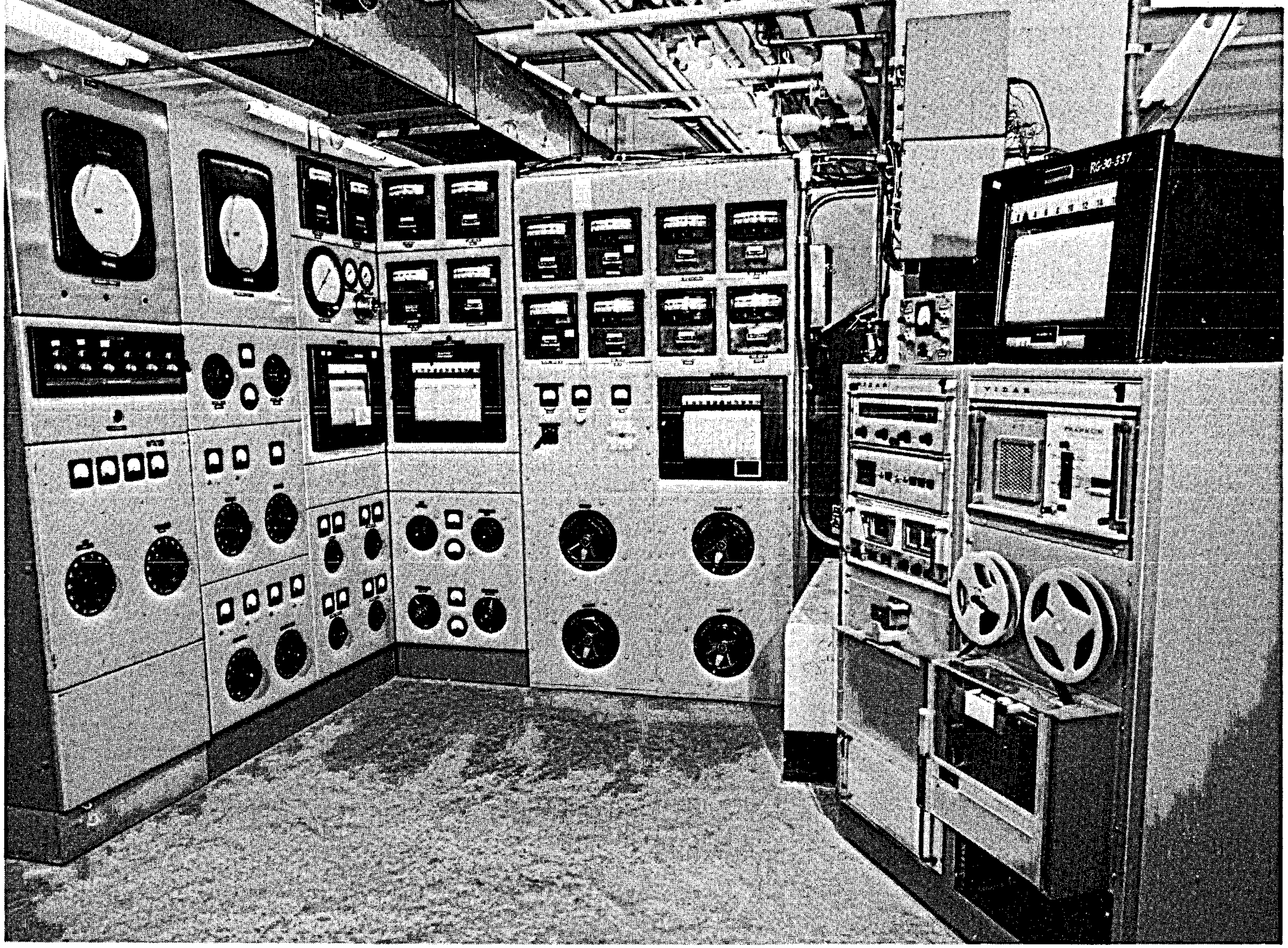

Fig. 7. Photograph of data recording equipment.

OPERATING PROCEDURES

In preparation for the addition of the molten salt mixtures, the system including the test section is heated to the desired temperature level above the melting point of the salt mixture. Approximately 165 lb of the molten salt is then introduced into one of the reservoirs by the force of argon gas pressure. Salt is forced back and forth through the test section as the operation of the apparatus is tested — for leaks, blockages, thermocouple and data recording functioning, etc. After the initial checkout procedure, the system is put on a standby mode by venting the gas pressure to the atmosphere and allowing the salt to siphon to equal levels in both reservoirs.* The standby mode is used to protect the test-section thermocouples by minimizing the heating of the test section.

Before each run, temperatures in the test section are raised to about 1000°F over a period of 45 minutes and the salt flow is reestablished. A fixed flow rate is established and power to the test-section heater is increased to the desired heat flux. When the temperatures indicate steady-state conditions, all parameters — power input, flow rate, and temperatures — are continuously recorded. The flow of salt is reversed when one reservoir is nearly empty, and the heat flux is momentarily reduced to about half the operating value to prevent a temperature excursion in the test section at the time of zero flow. The upper range of flow rates is limited by the time required to empty one of the reservoirs. Whenever the temperature exceeds the desired level, the system is allowed to cool by reducing the power to the test section and other appropriate heaters.

Periodic calibrations of radial heat losses were made by measuring the power required to maintain an empty test section in an isothermal condition as a function of temperature level. The information furnished by this calibration is used in each run, when an isothermal check of the test-section thermocouples is obtained at the desired temperature level

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*This procedure resulted in several salt leaks when a number of power failures occurred during the standby condition. Melting of the confined salt was invariably accompanied by rupture of the thin-walled tubing due to the expansion of the salt upon partial melting. A better standby procedure would be to drain the salt into one reservoir, allowing unrestrained expansion of the salt during melting if an unexpected freeze should occur.

with the hot salt flowing and only enough heat added to the test section to equal the radial heat loss. In Fig. 8, typical test-section thermocouple readings from an isothermal run show a scatter band of ±4°F about the average outside wall temperature. The sheathed thermocouples in the mixing chambers read slightly higher during isothermal runs and are believed to be more accurate. Their readings, therefore, provide the basis for standardization and the tube wall readings are corrected to this standard.

Extensive tests were conducted to insure the reliability of the apparatus and experimental procedures. The first test-section tube produced erratic axial temperature patterns which did not improve with more thermal insulation of the test section. Subsequently, the anomalous axial temperature profiles were traced to the test section, in which a hole had burned through the wall and had been repaired by welding. Excessive weld material protruding into the tube was thought to have disturbed the temperature and velocity profiles. Replacement of the test section eliminated the difficulty.

Other possible sources of error were investigated during the search for the cause of the temperature irregularities. Electrical conduction through the molten salt would result in additional heating of the salt, but the ratio of the resistivity of the salt to that of the test section is greater than 2500, indicating very little heat generated in the salt in this manner. Additional calculations of the radial temperature distribution[4] confirmed that not more than 0.2% of the power was expended by electrical conduction in the salt.

Temperature variations due to free convection are believed to be larger than those attributable to internal heating; but according to the criterion of Shannon and DePew,[5] free convection in the horizontal test-section position is insignificant compared with forced convection in the range of Reynolds numbers described in this work.

As an additional check of natural-convection effects, the reactor fuel salt experiments were repeated with the test section anchored in a vertical position while other equipment arrangements and operational procedures remained unchanged. The object of the change was to compare the effects of free convection in the vertical and horizontal positions. A

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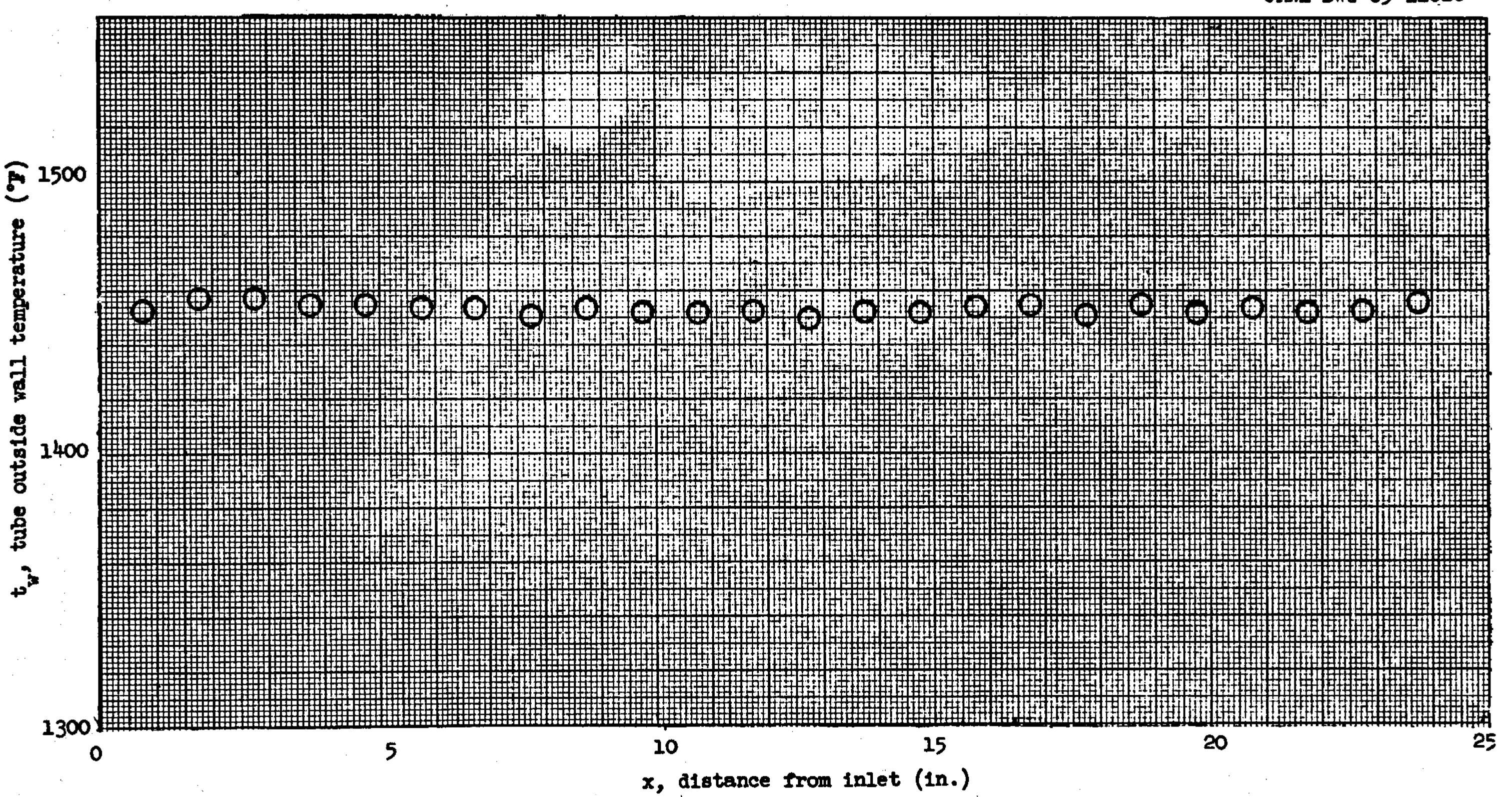

Fig. 8. Tube wall thermocouple readings during isothermal salt flow.

crack developed in one of the piping connections to the test section after 8 runs and repairs were not attempted. However, the results of the vertical runs did not show any difference in the effect of free convection as related to the orientation of the test section. The data are presented later in the report and in Appendix B.

The possibility of heat conduction losses to the electrodes at the ends of the test section prompted calculations to be made based on the conservative assumptions of maximum heat flux and a minimum Reynolds number. The results of these calculations show that the net heat conduction in the axial direction is less than 0.1% of the total heat generated in the test section at a distance of 0.25 in. from the entrance.

The electrical resistivity of the Hastelloy N test-section tube varies less than 1% in the temperature range of 1000 to 1500°F and the heat capacity of the salt varies less than 5% over the same temperature range. The variation of the radial heat loss along length of tube is less than 10% and the heat loss itself is less than 5%. A constant axial voltage drop measured along the test section verified the uniformity of the heat flux generated in the test-section wall and provided a check of the wall thickness and tube radius variation as a function of its length.

Experiments conducted with a well-known heat-transfer salt (HTS)* provided a final test in the new test section of the experimental procedure. Earlier experiments[2] showed that HTS data are well correlated by standard heat-transfer equations. The experiments with HTS in the present system demonstrated that the outside wall temperatures remained parallel to the mean salt temperature over half of the test-section length, indicating fully developed flow and a constant heat-transfer coefficient.

In 11 runs with HTS, the experimentally determined values of the heat-transfer coefficient were compared with those predicted by standard correlations. Ten of the values of the heat-transfer coefficient were within 13% of that predicted by the Sieder-Tate correlation[6] and the other value was within 25%. Before the system was charged with reactor salts, the HTS was removed by extensively flushing with water and drying in heated vacuum for 10 days.

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*HTS: KNO_3-$NaNO_2$-$NaNO_3$ (44-49-7 mole %).

CALCULATIONS

The local coefficient of forced-convective heat transfer is defined by the equation

$$h_x \equiv \frac{(q/A)_x}{(t_s - t_m)_x} \quad , \tag{1}$$

where

h = coefficient of heat transfer, Btu/hr·ft²·°F; h_x, at position x along tube;

q = heat-transfer rate to fluid, Btu/hr;

A = heat-transfer (inner) surface area, ft²;

t = temperature, °F; t_m, fluid mixed mean at any position; t_s, inner surface of the tube at any position x; t_w, outer surface of the tube at any position x.

Beyond the thermal and hydrodynamic entrance regions, h_x reaches an asymptotic value. For a constant heat flux, $(q/A)_x$, this limiting value will occur when $(t_s - t_m)_x$ reaches a constant value.

The inside tube wall temperature is related to the measured outside tube wall temperature by the equation

$$t_w - t_s = \frac{q + q_L}{2\,\pi L k_m}\left[\frac{(r_w)^2}{(r_w)^2 - (r_s)^2}\,\ln\left(\frac{r_w}{r_s}\right) - \frac{1}{2}\right] - \frac{q_L}{2\,\pi L k_m}\left(\ln\frac{r_w}{r_s}\right), \tag{2}$$

where

k = thermal conductivity of fluid, Btu/hr·ft·°F; k_m, thermal conductivity of tube;

L = test-section length, ft;

r = test-section tube radius, ft; r_s, inner surface; r_w, outer surface;

this is the solution to the one-dimensional steady-state heat conduction equation with a source term and a heat loss, q_L, at the outside wall.[7] The only variable on the right-hand side of Eq. (2) is the thermal conductivity of the metal wall, k_m, which remains nearly constant over small temperature rises along the tube. Thus, when the temperature profiles t_w and t_m are parallel, the fluid flow in the tube is essentially fully developed.

For most of the measurements, the heat gained by the fluid in traversing the test section was calculated by the equation

$$q = wC_p(t_{m,o} - t_{m,i}) \quad . \tag{3}$$

in which

C_p = specific heat of fluid at constant pressure, Btu/lb·°F,

w = mass flow rate, lb/hr,

and subscripts

o = outlet

i = inlet.

For the later measurements (Runs 210 through 220), the heat gained by the fluid was determined from the electrical heat generation in the test section corrected for the calibrated heat loss. By calculating the heat input in this manner, the influence of the uncertainties in measuring the fluid mixed-mean inlet and outlet temperatures can be reduced.

The computer program used for reducing the experimental data is given in Appendix C.

RESULTS

Heat-transfer coefficients were determined experimentally in 70 runs covering the laminar, transition, and turbulent flow regimes. Ten runs with HTS to test the equipment are included with data shown in Appendix B. The physical properties and chemical analyses of the molten salt are listed in Appendix D, Tables D-1 and D-2, respectively.

The duration of a run usually permitted time for three thermocouple scans to demonstrate thermal steady state. Figure 9 shows typical outside wall temperatures and mean fluid temperatures. A straight line is drawn between the mean inlet and mean outlet fluid temperatures by assuming constant physical properties of the molten salt and uniform heat transfer over the inner surface of the test-section wall. These assumptions are supported by the constant heat capacity of the molten salt in the observed temperature range and the constant resistance of the Hastelloy N test section mentioned earlier.

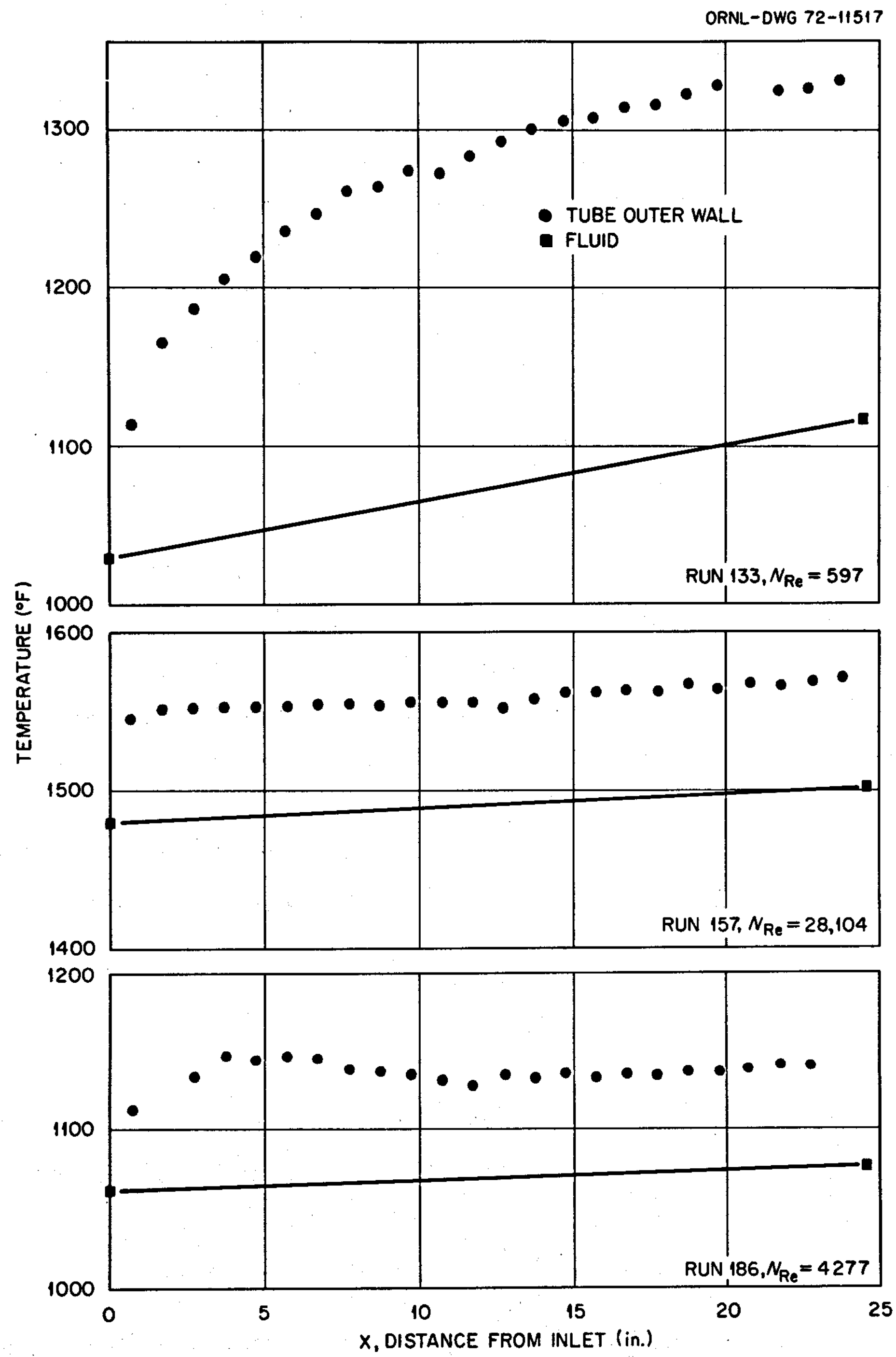

Fig. 9. Axial temperature profiles for molten salt flowing in a smooth tube at laminar (N_{Re} = 597), turbulent (N_{Re} = 28,104), and transition (N_{Re} = 4277) flow.

Three regions of N_{Re} are shown in Fig. 9 — the laminar, transition, and turbulent at N_{Re} = 597, 4277, and 28,104, respectively. The coefficient of heat transfer h_x assumes its limiting value rapidly for turbulent flow; but in laminar and transition flows, a significant entrance region is evident. This entrance region is seen more clearly when h_x is plotted versus the distance along the test section x as in Fig. 10 for the transition flow run. After the thermal and hydrodynamic boundary layers become fully developed, h_x decreases to a limiting value. The test section is not long enough for h_x to reach the limiting value in laminar flow. Therefore, integrated values of h_x over the entire tube length, coupled with the parameter D/L, are used in developing the laminar flow correlations; whereas, the limiting constant h values are used for the transition and turbulent heat-transfer correlations.

Standard heat-transfer correlations for the three flow regimes are given in the following discussion of Eqs. (4) through (8). Heat-transfer data from the 70 runs are then presented in the dimensionless forms of standard correlations for comparison using the data listed in Appendix B and the physical properties in Table D-1.

1. For laminar, forced flow in the absence of natural convection, the equations of Sieder and Tate[6] and Martinelli and Boelter[8] are, respectively:

$$N_{Nu} = 1.86\,[N_{Re}\,N_{Pr}\,(D/L)]^{1/3}\,(\mu/\mu_s)^{0.14} \qquad (4)$$

and

$$N_{Nu} = 1.62\,[N_{Re}\,N_{Pr}\,(D/L)]^{1/3}\quad . \qquad (5)$$

2. For transition region flow beyond the entrance region, a modified form of Hausen equation[2] is:

$$N_{Nu} = 0.116\,(N_{Re}^{2/3} - 125)\,N_{Pr}^{1/3}\,(\mu/\mu_s)^{0.14}\quad . \qquad (6)$$

3. For turbulent flow, the equations recommended in Ref. 9 and attributed to McAdams and to Sieder and Tate are respectively:

$$N_{Nu} = 0.023\,N_{Re}^{0.8}\,N_{Pr}^{0.4}\quad , \qquad (7)$$

$$N_{Nu} = 0.027\,N_{Re}^{0.8}\,N_{Pr}^{1/3}\,(\mu/\mu_s)^{0.14}$$

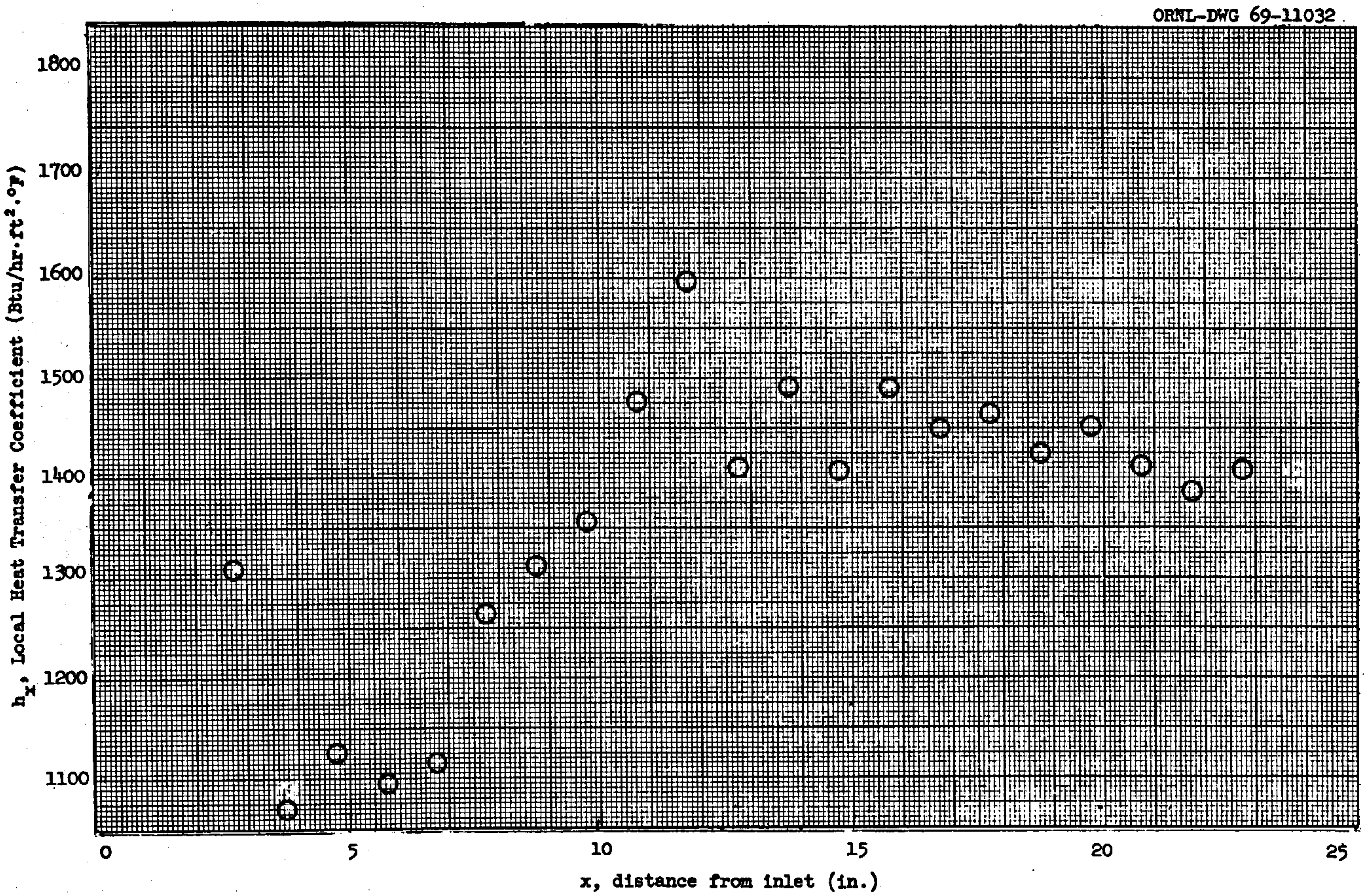

Fig. 10. Axial variation of the heat-transfer coefficient (N_{Re} = 4277).

where

N_{Nu} = Nusselt modulus, hD/k, dimensionless,
N_{Pr} = Prandtl modulus, $C_p\mu/k$, dimensionless,
N_{Re} = Reynolds modulus, $\rho VD/\mu$, dimensionless,

and

V = mean velocity of fluid, ft/hr,

D = inside diameter of tube, ft,

ρ = fluid density evaluated at fluid mixed-mean temperature, lb/ft^3,

μ = fluid viscosity evaluated at fluid mixed-mean temperature, lb/hr·ft; μ_s, evaluated at temperature of the inner surface of the tube.

Equations (4), (6), and (8) are compared with the experimental data in Fig. 11. The experimental results are in good agreement in the laminar region but are slightly below the equations representing the transition and turbulent regions. For example, in the range $3500 < N_{Re} < 30,000$, the data lie about 13% below Eqs. (6) and (8). The heat-transfer data could not be correlated in the transition range $2000 < N_{Re} < 4000$ because of entrance effects that persisted over the length of the test section. The laminar data do not fit Eq. (5) as well as Eq. (4), as shown by comparing Figs. 12 and 11. Similarly, Eq. (7) provides no significant improvement in the correlation of the data for $N_{Re} > 10,000$ over that of Eq. (8) [compare Figs. 13 and 11].

The data plotted in Figs. 11 through 13 suggest that the experimental data for laminar and turbulent flow can be fitted to functions of the form:

$$\text{Ordinate} = K\, N_{Re}^{n} , \tag{9}$$

where K and n are dimensionless constants having different values for laminar and turbulent flows and the "ordinate" is the ordinate used in Fig. 11. Least-squares fits of the data to the form of Eq. (9) were carried out assuming a constant value (1/3) for the Prandtl modulus exponent. These fits were tried with and without a viscosity ratio correction term. We found that when the viscosity ratio correction term was included, the values for the Reynolds modulus exponent, n, came closer to the commonly accepted values of 1/3 for laminar flow and 0.8 for turbulent flow. The resulting equations fitting the experimental

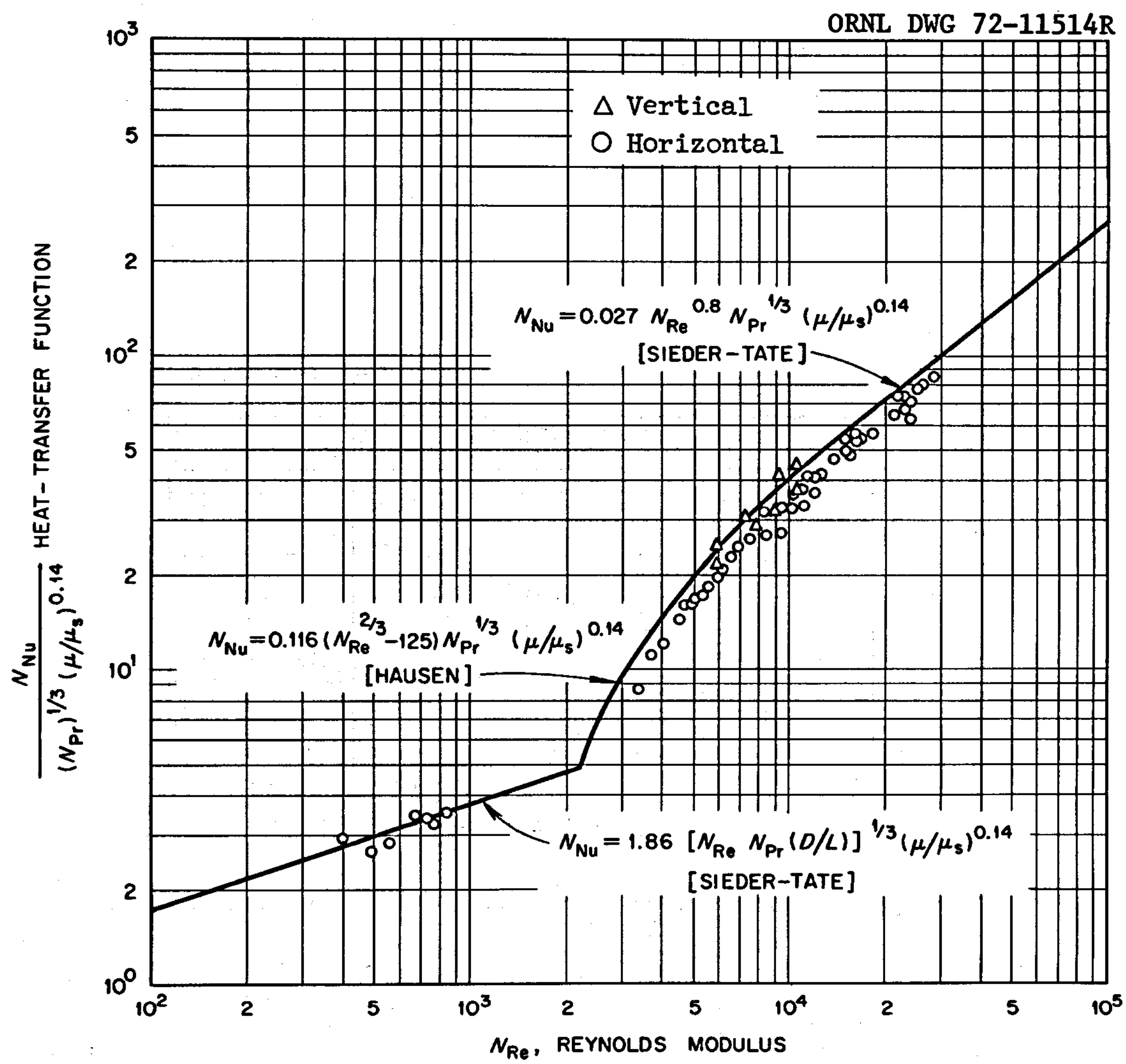

Fig. 11. Comparisons of the molten salt data for Eqs. (4), (6), and (8).

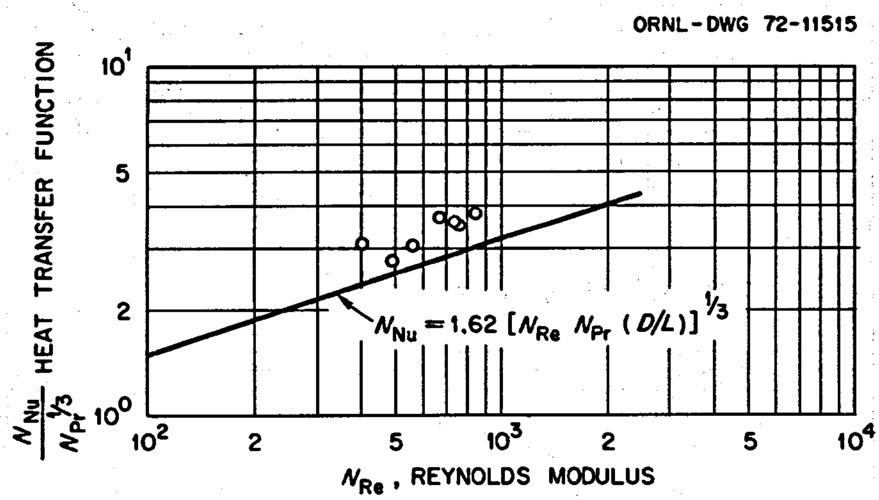

Fig. 12. Comparison of laminar flow data of molten salt with Eq. (5).

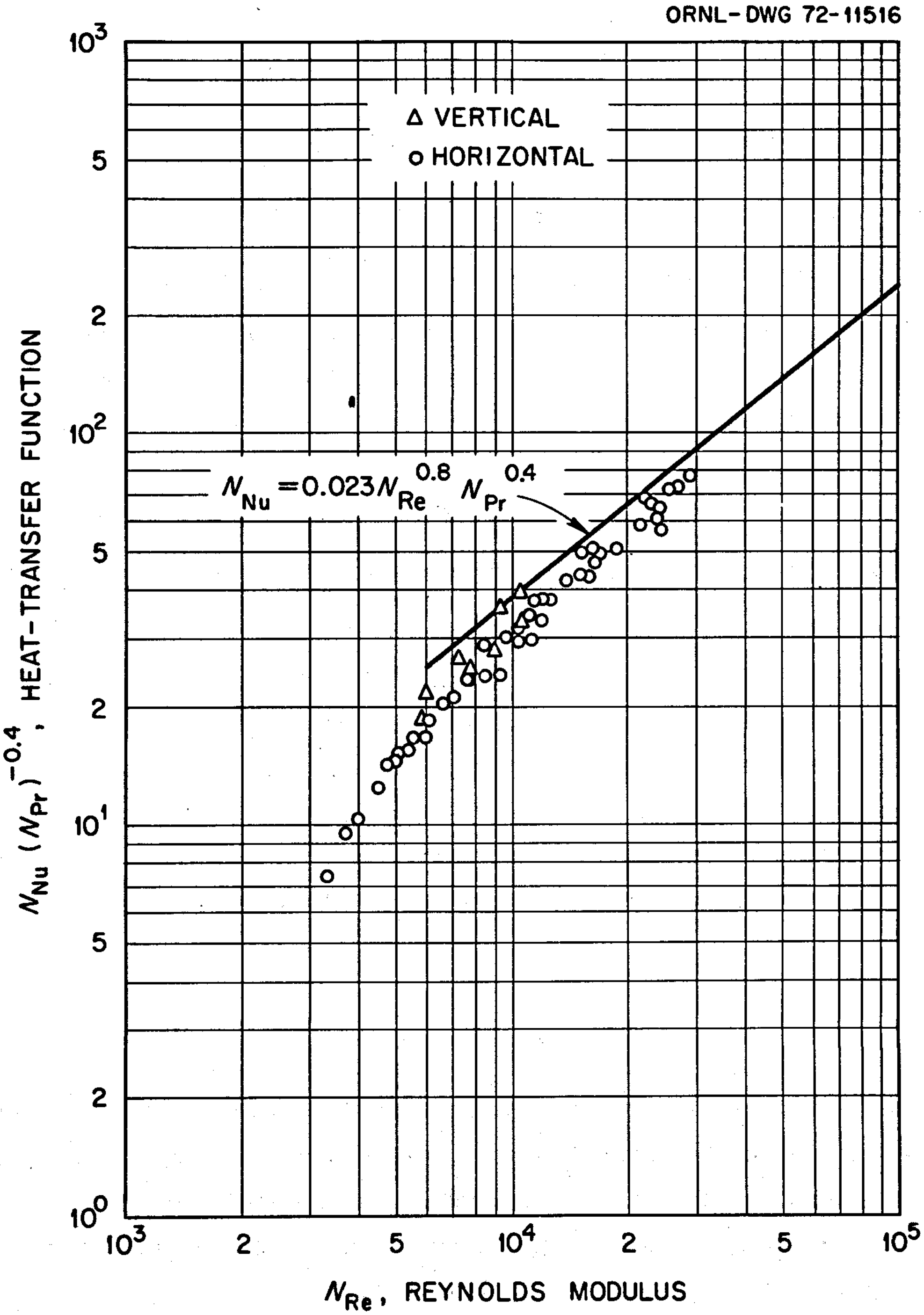

Fig. 13. Comparison of transition and turbulent data of molten salt with Eq. (7).

data are

$$N_{Nu} = 1.89 \, [N_{Re} \, N_{Pr} \, (D/L)]^{0.33} \, (\mu/\mu_s)^{0.14} \quad , \tag{10}$$

with an average absolute deviation of 6.6% for $N_{Re} < 1000$; and

$$N_{Nu} = 0.0234 \, N_{Re}^{2/3} \, N_{Pr}^{1/3} \, (\mu/\mu_s)^{0.14} \quad , \tag{11}$$

with an average absolute deviation of 6.2% for $N_{Re} > 12{,}000$.

Because the data in the transition region did not follow the form of Eq. (9), the equation for the experimental data in this range of N_{Re} was obtained by adjusting the coefficient in Eq. (6), giving the following relation:

$$N_{Nu} = 0.107 \, (N_{Re}^{2/3} - 135) \, N_{Pr} \quad (\mu/\mu_s)^{0.14} \quad , \tag{12}$$

with an average absolute deviation of 4.1% for $3500 < N_{Re} < 12{,}000$.

The heat-transfer measurements made with the test section oriented in a vertical position to test for the possible effects of free convection are in good agreement with the standard correlations, except for four higher points (see Figs. 11 and 13). These higher points were obtained with downflow in contradiction to the predicted enhancement of heat transfer with upflow. Thus, a systematic thermocouple error in one of the mixing chambers is the most probable cause of the higher results with downflow.

DISCUSSION

The results indicate that the proposed reactor fuel salt behaves as a normal fluid in the range $0.5 < N_{Pr} < 100$ with regard to heat transfer. It should be noted that uncertainties in the physical properties of the salts reflect as great an effect on the correlations as does the uncertainty in the heat-transfer coefficient.

Our data lie below the standard correlations in the turbulent and transition regions but not in the laminar region. If the deviations in our data were caused by low-conductance surface films or entrained gas, one would expect the effect to be apparent in all three regions. An uncertainty in the viscosity of the salt might explain the discrepancies in the turbulent and the transition regions since the heat-transfer function in the laminar region is almost independent of the viscosity. In addition, the lower values in the transition regime could be the result of the failure of the thermal boundary layer to fully develop over the length of the test section.

The problem of boundary-layer development is most pronounced in the range of Reynolds number $2000 < N_{Re} < 4000$, where entrance effects persisted for the entire length of the test section. The same effect could be produced up to $N_{Re} = 5000$ at higher wall heat fluxes. Figure 14 illustrates the apparent effect of heat flux on the entrance region length. At $N_{Re} = 3762$ and a wall heat flux of 2.55×10^5 Btu/hr·ft^2, there is no region of constant heat-transfer coefficient. In contrast, temperature profiles at a similar Reynolds number, $N_{Re} = 3565$ and the lower wall heat flux of 0.74×10^5 Btu/hr·ft^2 show a constant heat-transfer coefficient over most of the test-section length. Since the viscosity of the fluid decreases with increasing temperature, heat transfer from the tube wall may be exerting a stabilizing effect on the laminar boundary layer,[9,10] thus delaying transition.

Future experiments with the fuel salt should include system modifications so that the entrance region effects in transition flow can be better evaluated. Possible modifications would be the insertion of an unheated calming section prior to heat addition to permit establishment of the hydrodynamic boundary layer before changing the temperature profile. This would separate the two effects that now occur simultaneously. Another possibility would be to increase the length of the test section while maintaining a constant heat flux along the length. A sufficiently long tube might allow fully developed flow patterns to be reached before the test-section exit.

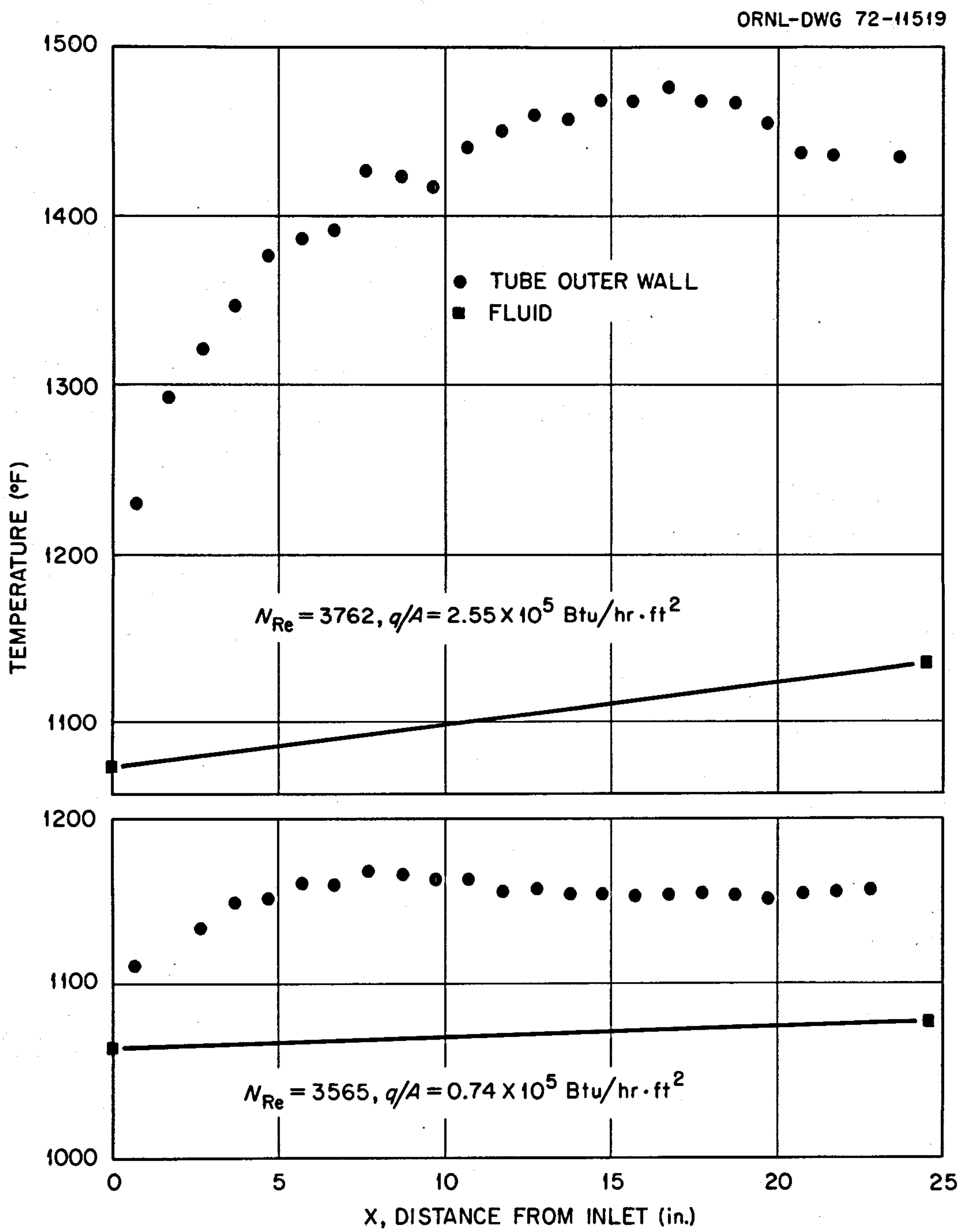

Fig. 14. Comparison of axial temperature profiles of the molten salt at similar N_{Re} with heat flux varied by a factor of 3.5.

CONCLUSIONS

We have found molten fluoride salt mixtures to behave, for the most part, as normal fluids with respect to forced-convection heating in a smooth tube. Although the present results average ~13% below the standard literature heat-transfer correlations, one must realize that some uncertainties exist in the physical properties of the salt and that the standard correlations themselves are based on heat-transfer data using fluids such as air, steam, water, petroleum, etc., which exhibit a ±20% scatter band around the standard curves.

No evidence of the existence or influence of low-conductance surface films, such as corrosion products, gases, or oxides, was found in the present studies. In the Reynolds modulus range from 2000 to 5000, we did find the heat-transfer coefficient to vary along the length of the tube in a manner which appeared related to a delay in the transition to turbulent flow. We believe this delay in transition is abetted by the stabilizing influence of heating a fluid whose viscosity has a large negative temperature coefficient. We intend to make further studies of this phenomenon.

ACKNOWLEDGMENTS

The design, construction, and operation of these experiments were made possible by the able assistance of J. J. Keyes, Jr., H. W. Hoffman, R. L. Miller, J. W. Krewson, W. A. Bird, and L. G. Alexander.

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APPENDIX A

ADDITIONAL DETAILS OF THE EXPERIMENTAL SYSTEM

ORNL-DWG 72-11522

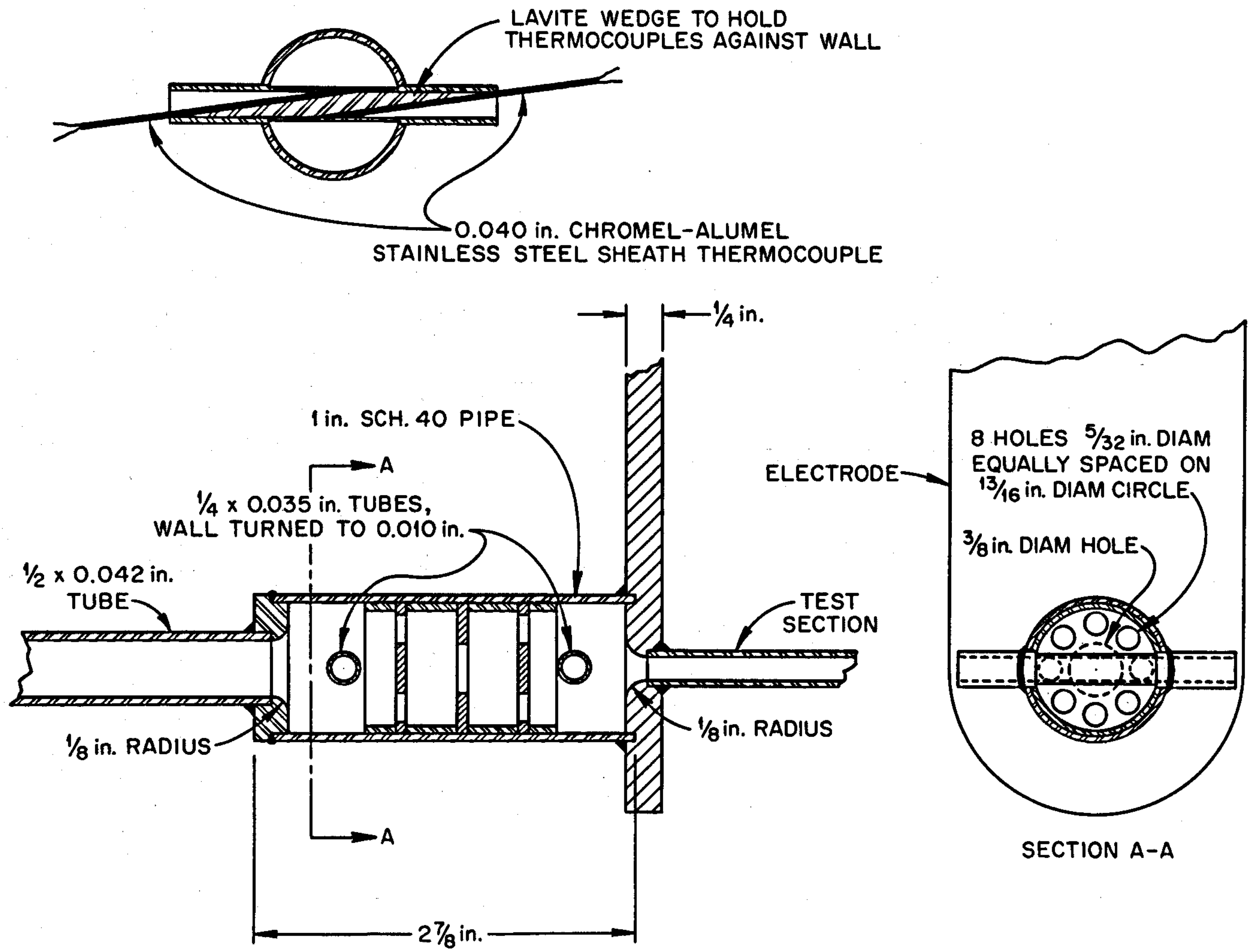

Fig. A-1. Mixing chamber weldment.

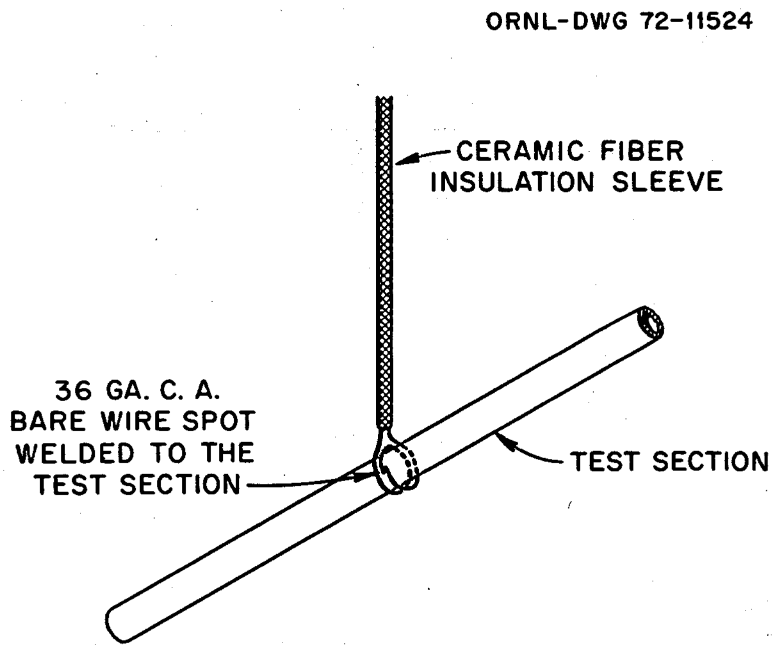

Fig. A-2. Scheme for the attachment of a test-section thermocouple.

ORNL-DWG 72-11523

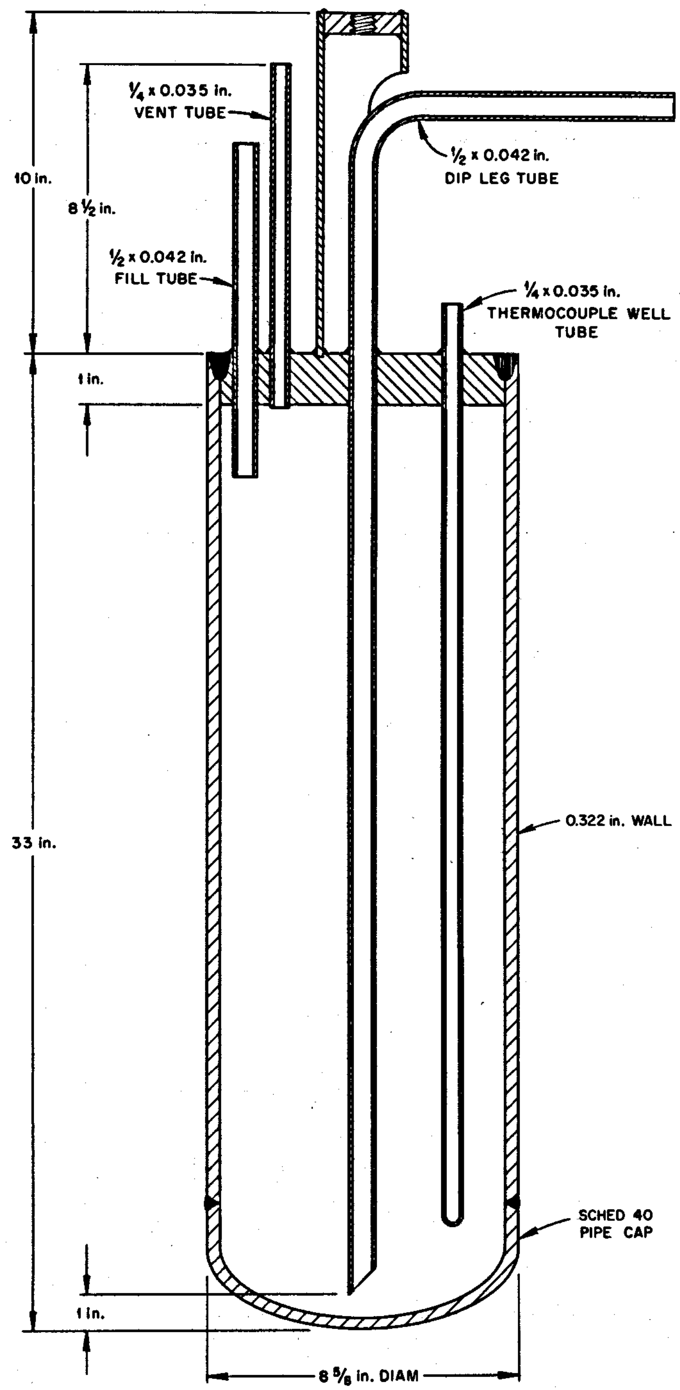

Fig. A-3. Detail of a Salt reservoir.

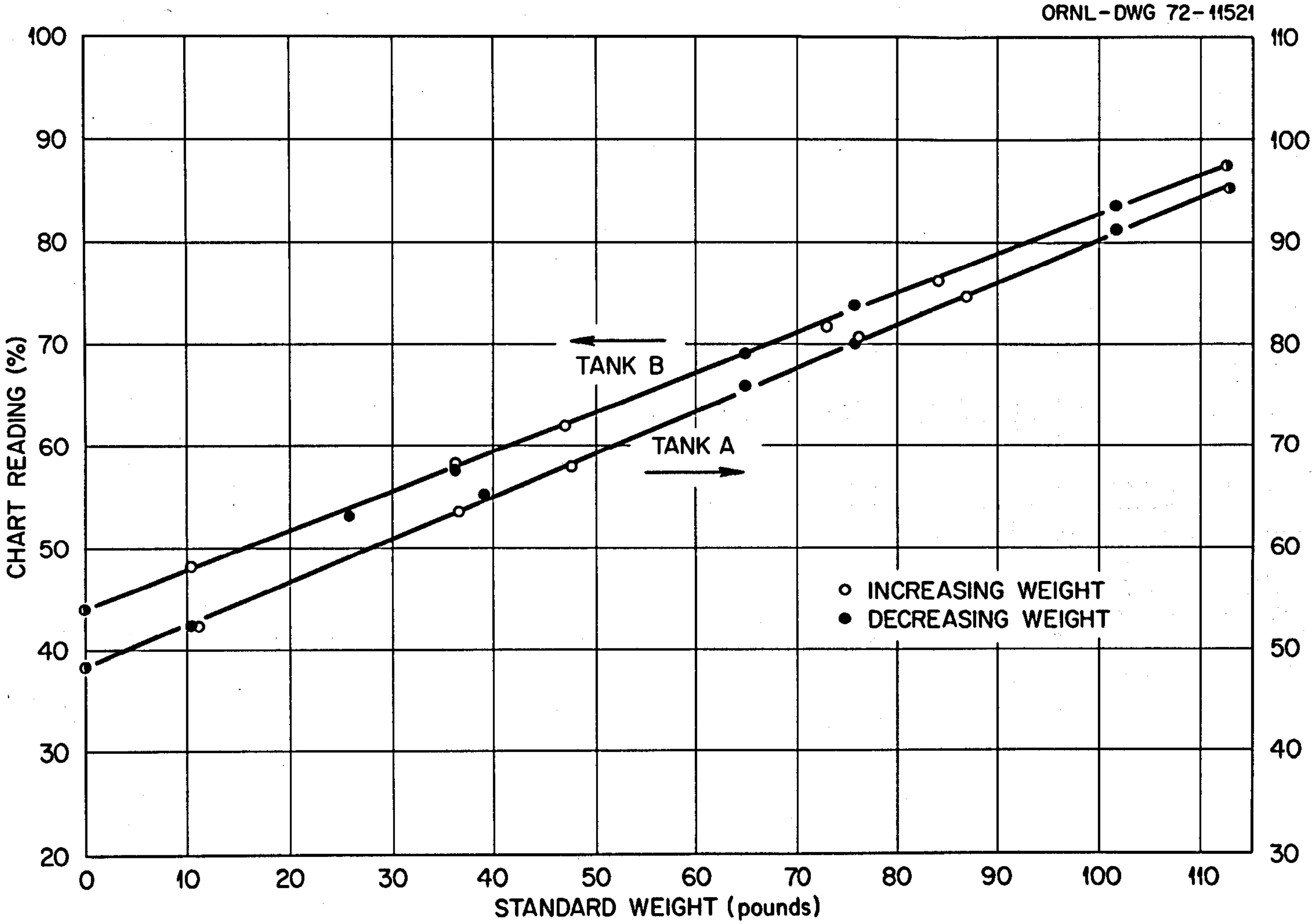

Fig. A-4. Weigh cell calibration curve.

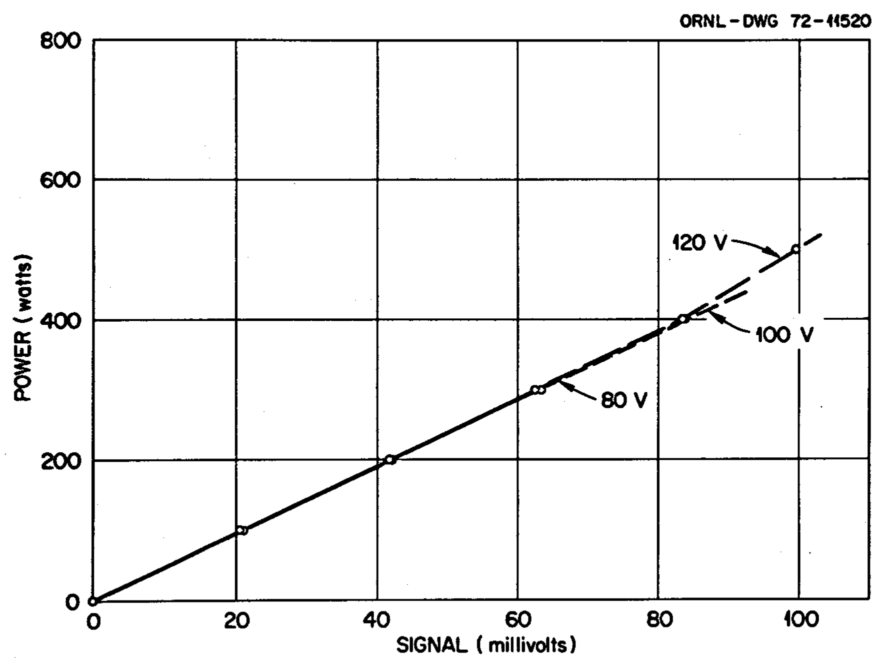

Fig. A-5. Wattmeter calibration curve.

PERTINENT EXPERIMENTAL EQUIPMENT

Equipment	Capacity or Range	Accuracy
Load Cells BLH electronics Type T3P1 and T3P2B	500 lb (150% overload) 3 mv/v input	±0.02% full scale (see Fig. A-4)
Strip Recorder Honeywell Model BY153X2VV-(W7) -(IV)A1 (modified)	L-2 Special	±0.25% full scale
Current Transformer Nothelfer windings Labs, Incorporated Model 14388	25 kva (prim. & sec.) 48 v prim. 4 x 250 amp sec	—
Digital Voltmeter Vidar Model 521	±10 mv to ±1000 v in 6 decade stages	±0.01% of full scale (least count 1.0 μv)
System Coupler Vidar Model 650-12	—	—
Scanner Cunningham Scannex Control Model 000113G	—	—
Tape Digital Printer Franklin Electronics, Inc.	—	—
Tape Punch Process Tally Corporation Model 1665 Tape Drive Model P150 Tape Reader Model 1848	—	—
Wattmeter General Electric Type 4701 Watt Transducer	2.5 — 10.0 in 2.5 steps	(see Fig. A-5)
Thermocouple Reference-Junction Compensator Universal Compensator Model RJ4801-CS	—	—
Thermocouples Chromel-Alumel	—	±0.75%

APPENDIX B

EXPERIMENTAL DATA

Table B-1. Experimental Data for Heat-Transfer Studies Using the Salt $LiF-BeF_2-ThF_4-UF_4$; 67.5-20.0-12.0-0.5 mole %

Run No.	T_{in} (°F)	T_{out} (°F)	δT (°F)	w (lb/hr)	q/A (Btu/hr·ft² x 10^{-5})	Heat Balance[a]	h (Btu/hr·ft²·°F)	$\bar{N}_{Re}$	$\bar{N}_{Pr}$	$\bar{N}_{Nu}$	$\bar{N}_{St}$[b]
107	1388.3	1436.0	47.7	2532.0	4.07	1.05	4882	15,993	6.3	106.1	56.000
115	1362.7	1415.8	53.1	1387.2	2.48	1.12	2831	8,345	6.6	61.5	31.902
117	1383.7	1438.4	54.7	1807.2	3.33	1.01	3617	11,419	6.3	78.6	41.497
119	1379.1	1436.6	57.5	1185.0	2.30	1.05	2302	7,495	6.3	50.0	26.270
121	1418.0	1474.4	56.4	2191.2	4.16	1.04	4590	14,917	5.8	99.8	54.082
122	1456.2	1507.9	51.7	2968.2	5.17	1.04	6192	21,647	5.5	134.6	74.415
123	1488.2	1537.8	49.6	3206.4	5.36	1.00	6462	25,119	5.1	140.4	79.762
127	1097.9	1156.4	58.5	1636.8	3.23	1.05	1936	5,005	13.1	42.1	16.713
129	1082.7	1163.3	80.6	250.8	0.68	1.01	396	738	13.5	8.6	3.359
130	1081.5	1177.1	95.6	279.6	0.90	1.00	427	839	13.3	9.2	3.563
131	1089.8	1159.9	70.1	227.4	0.54	1.02	407	673	13.5	8.8	3.488
132	1090.6	1160.2	69.6	256.2	0.60	0.97	381	760	13.4	8.3	3.265
133	1029.6	1118.7	89.1	221.4	0.66	0.93	357	550	15.9	7.7	2.821
134	1036.3	1134.8	98.5	155.4	0.52	0.93	358	405	15.3	7.8	2.944
143	1062.8	1117.7	54.9	1785.0	3.30	1.04	1940	4,940	14.5	42.2	16.148
144	1075.4	1135.7	60.3	1900.8	3.87	1.04	2200	5,523	13.8	47.8	18.563
145	1048.2	1103.4	55.2	2007.6	3.73	1.04	2129	5,304	15.0	46.3	17.459
146	1064.0	1115.9	51.9	2199.6	3.85	1.04	2513	6,026	14.6	54.7	20.984
147	1076.9	1131.0	54.1	2307.6	4.20	1.04	2727	6,573	14.0	59.2	23.072
148	1093.5	1148.3	54.8	2506.8	4.63	1.03	3068	7,583	13.2	66.7	26.549
149	1460.4	1482.9	22.5	1166.4	0.89	0.94	2230	8,393	5.6	48.5	27.007
150	1460.6	1489.5	28.9	1700.4	1.66	1.03	3434	12,260	5.5	74.7	41.743
151	1469.4	1488.4	19.0	2093.4	1.34	1.01	3977	15,282	5.5	86.4	48.472
152	1477.0	1501.8	24.8	2458.2	2.05	1.00	4573	18,300	5.4	99.5	56.022
153	1486.7	1513.4	26.7	2784.6	2.51	1.09	5426	21,235	5.6	117.9	65.520

Table B-1 (Continued)

Run No.	T_{in} (°F)	T_{out} (°F)	δT (°F)	w (lb/hr)	q/A (Btu/hr·ft² x 10^{-5})	Heat Balance[a]	h (Btu/hr·ft²·°F)	$\bar{N}_{Re}$	$\bar{N}_{Pr}$	$\bar{N}_{Nu}$	$\bar{N}_{St}$[b]
154	1496.1	1523.3	27.2	3057.0	2.80	1.04	5740	23,719	5.1	124.8	71.557
155	1466.3	1484.7	18.4	3205.2	1.99	1.02	5551	23,214	5.5	120.7	67.668
156	1475.0	1488.2	13.2	3262.2	1.45	0.99	5229	23,861	5.5	113.7	63.927
157	1479.7	1502.7	23.0	3505.8	2.72	1.07	6627	26,192	5.4	144.1	81.181
158	1466.3	1483.8	17.5	1282.2	0.76	0.89	2236	9,284	5.5	48.6	27.265
159	1466.7	1492.6	25.9	1401.6	1.22	0.99	2708	10,171	5.5	58.9	32.943
160	1471.3	1492.2	20.9	1512.0	1.06	0.93	2741	11,107	5.5	59.6	33.394
161	1472.4	1494.4	22.0	1615.2	1.20	0.99	3033	11,853	5.5	66.0	36.980
162	1463.7	1522.0	58.3	1254.6	2.46	1.04	2675	9,464	5.2	58.2	32.754
163	1470.0	1527.5	57.5	1425.6	2.76	1.05	3071	10,884	5.2	66.7	37.571
164	1480.0	1535.8	55.8	1513.8	2.85	1.07	3334	11,770	5.1	72.5	41.151
165	1486.9	1539.2	52.3	2105.4	3.71	1.02	4385	16,497	5.1	95.3	54.119
166	1501.6	1546.2	44.6	2803.2	4.21	1.06	5852	22,512	5.0	127.2	72.942
167	1513.9	1561.7	47.8	3471.0	5.60	1.02	6892	28,499	4.9	149.8	86.348
170	1064.6	1080.1	15.5	1797.0	0.94	0.97	1737	4,524	15.9	37.7	14.620
171	1066.3	1082.2	15.9	2346.0	1.26	1.01	2340	5,938	15.7	50.9	19.818
172	1069.8	1084.0	14.2	2722.8	1.31	1.05	2905	6,939	15.6	63.2	24.811
173	1049.0	1081.2	32.2	202.2	0.22	0.96	320	493	16.3	7.0	2.671
186	1061.6	1076.2	14.6	1597.8	0.79	0.94	1445	3,986	16.0	31.4	12.161
191	1062.0	1078.5	16.5	1318.2	0.74	0.94	1041	3,322	15.9	22.6	8.713
192	1064.6	1080.3	15.7	1460.4	0.77	0.99	1337	3,690	15.7	29.0	11.274
193	1235.2	1262.7	27.5	1106.4	1.03	1.01	1591	4,731	9.3	34.6	16.075
195	1247.0	1270.6	23.7	2333.4	1.86	1.04	3560	10,200	9.1	77.4	36.392
198	1255.8	1296.0	40.2	3001.8	4.07	1.04	4645	13,693	8.7	101.0	47.638
199	1273.2	1294.4	21.2	3219.6	2.30	1.09	4752	14,944	8.6	103.3	49.533

Table B-1 (Continued)

Run No.	T_{in} (°F)	T_{out} (°F)	δT (°F)	w (lb/hr)	q/A (Btu/hr·ft^2 x 10^{-5})	Heat Balance[a]	h (Btu/ hr·ft^2·°F)	$\overline{N}_{Re}$	$\overline{N}_{Pr}$	$\overline{N}_{Nu}$	$\overline{N}_{St}$[b]
200	1279.6	1303.7	24.1	3392.4	2.76	1.07	5050	16,088.0	8.4	109.8	53.017
201[c]	1237.8	1263.8	26.0	1351.2	1.18	1.07	2406	5,892.4	9.14	52.3	24.7
202[c]	1250.7	1272.6	21.9	1717.8	1.27	1.01	2762	7,660.9	8.94	60.0	28.6
203[c]	1252.2	1276.2	24.0	2050.2	1.66	1.16	4029	9,200.0	8.89	87.6	41.9
204[c]	1258.4	1282.4	24.0	2299.2	1.86	0.99	3625	10,435.5	8.79	78.8	37.7
205[c]	1229.9	1255.0	25.0	1395.0	1.18	1.01	2119	5,910.9	9.41	46.1	21.5
206[c]	1231.7	1255.4	23.7	1704.0	1.36	1.10	3004	7,238.9	9.39	65.3	30.7
207[c]	1243.6	1268.1	24.5	2036.4	1.68	0.97	3122	8,947.4	9.08	67.9	32.1
208[c]	1247.2	1270.6	23.4	2338.8	1.84	1.12	4337	10,359.7	9.00	94.2	44.9
210	1132.4	1156.1	70.1	2110	1.69	1.01	2416	6,512	12.5	52.5	22.15
211	1168.4	1215.4	150.8	2105	3.38	1.01	3049	7,696	10.8	66.3	28.96
212	1203.4	1226.7	59.9	2102	1.69	1.03	2823	8,230	10.2	61.4	27.89
213	1138.1	1168.7	30.6	2654	2.76	1.04	3477	8,566	12.2	75.6	32.07
214	1097.9	1149.6	51.7	2807	4.92	1.01	3573	8,297	13.3	77.7	31.27
215	1248.1	1256.1	8.0	2887	0.79	0.97	4335	12,374	9.2	94.2	44.98
216	1258.3	1276.2	18.0	2914	1.77	1.03	4490	12,957	8.8	97.6	46.89
217	1280.6	1310.6	30.1	2791	2.85	1.05	4616	13,454	8.2	100.3	49.10
218	1288.1	1341.7	53.6	2753	5.03	1.03	4915	14,035	7.7	106.9	52.56
219	1293.8	1383.2	89.4	1593	5.04	1.03	2999	8,620	7.3	65.2	32.12
220	1118.5	1155.7	136.1	1140	1.51	1.02	1082	3,554	12.8	23.5	9.60

[a] Heat balance = (sensible heat gained by fluid + heat loss)/(electrical heat generation).

[b] $\overline{N}_{St} = \overline{N}_{Nu}(\overline{N}_{Pr})^{-1/3}(\mu/\mu_s)^{-0.14}$.

[c] Test section oriented vertically.

Table B-2. Experimental Data for Heat-Transfer Studies Using the Salt Hitec (KNO_3-$NaNO_2$-$NaNO_3$; 44-49-7 mole %)

Run No.	T_{in} (°F)	T_{out} (°F)	δT (°F)	w (lb/hr)	q/A (Btu/hr·ft² x 10^{-5})	Heat Balance[a]	h (Btu/hr·ft²·°F)	$\bar{N}_{Re}$	$\bar{N}_{Pr}$	$\bar{N}_{Nu}$	$\bar{N}_{St}$[b]
87	537.6	677.3	139.7	157.2	0.85	0.99	283.5	2,314	9.3	17.0	7.34
88	540.8	591.3	50.5	1375.2	2.69	1.05	2499.4	15,450	11.3	150.0	64.3
89	567.5	621.0	53.4	2071.8	4.30	0.98	3516.6	25,640	10.2	211.0	93.1
96	574.8	624.3	49.5	2195.4	4.21	1.08	4450.9	27,578	10.1	267.1	119.7
97	601.4	650.7	49.3	1589.4	3.04	1.00	3045.6	21,716	9.3	182.7	84.2
98	608.4	658.5	50.1	1097.4	2.13	1.06	2473.8	15,349	9.1	148.4	69.3
99	618.5	672.5	54.0	630.6	1.32	1.03	1386.4	9,165	8.7	83.2	39.2
101	608.8	702.4	93.6	592.8	2.15	1.10	1332.4	9,065	8.3	79.9	37.6
102	633.1	657.2	24.1	640.2	0.60	0.99	1656.8	9,142	8.9	99.4	47.7
103	618.8	634.8	16.1	1551.6	0.97	1.05	4151.9	20,848	9.4	249.1	117.6
104	582.2	669.1	86.9	1603.8	5.41	0.99	3096.6	22,357	9.1	185.8	84.1

[a] Heat balance = (sensible heat gained by fluid + heat loss)/(electrical heat generation).

[b] $\bar{N}_{St} = \bar{N}_{Nu}(\bar{N}_{Pr})^{-1/3} (\mu/\mu_s)^{-0.14}$.

APPENDIX C

COMPUTER PROGRAM

```
COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C I AM A MOLTEN SALT HEAT TRANSFER PROGRAM                                                  5
ISN 0002            REAL L,MDOT,K1,K2,K3,K4,NUNC,MU,NUAVG,NNC,K1NOW                                      10
ISN 0003            DIMENSION TO(30),XL(30),TI(30),TB(30),H(30),IN(200),DU(200),D(200)                  12
ISN 0004            DIMENSION NUNO(30)                                                                   13
ISN 0005            INTEGER FTC,CTC                                                                      15
ISN 0006          6 DO 10 J=1,13                                                                         30
ISN 0007                IL=5*(J-1)+1                                                                     40
ISN 0008                IU=5*J                                                                           50
ISN 0009                READ 7,(IN(I),DU(I),I=IL,IU)                                                     60
ISN 0010          7     FORMAT(5(I3,F5.2,2X))                                                            70
ISN 0011         10     CONTINUE                                                                         75
ISN 0012            DO 20 I=1,IU                                                                         76
ISN 0013                I1=IN(I)+1                                                                       77
ISN 0014                IF(DU(I).GE.0.01) D(I1)=DU(I)                                                  77A1
ISN 0016         20 CONTINUE                                                                           77A2
ISN 0017            IF (D(45).LT.900.) GO TO 21                                                         77B
ISN 0019            GO TO 22                                                                            77C
ISN 0020         21 D(46)=-D(46)                                                                        77D
ISN 0021         22 CONTINUE                                                                            77E
ISN 0022            DO 30 I=1,50                                                                        78A
ISN 0023                DU(I)=D(I)                                                                      78B
ISN 0024         30 CONTINUE                                                                            78C
              C TEMP FIT FOLLOWS FOR 150 F REF JUNCTION UP TO 1900 DEGREES F                             79
ISN 0025            DO 420 I=1,46                                                                       79A
ISN 0026                IF (D(I).LT.1.99) GO TO 400                                                     79B
ISN 0028                IF (D(I).GE.1.99.AND.D(I).LT.5.30) GO TO 401                                    79C
ISN 0030                IF (D(I).GE.5.01.AND.D(I).LT.10.01) GO TO 402                                   79D
ISN 0032                IF (D(I).GE.10.01.AND.D(I).LT.13.01) GO TO 403                                  79E
ISN 0034                IF (D(I).GE.13.01.AND.D(I).LT.17.01) GO TO 404                                  79F
ISN 0036                IF (D(I).GE.17.01.AND.D(I).LT.22.99) GO TO 405                                  79G
ISN 0038                IF (D(I).GE.22.99.AND.D(I).LT.29.99) GO TO 406                                  79H
ISN 0040                IF (D(I).GE.29.99.AND.D(I).LT.33.00) GO TO 407                                  79I
ISN 0042                IF (D(I).GE.33.0.AND.D(I).LT.36.0) GO TO 408                                    79J
ISN 0044                IF (D(I).GE.36.0.AND.D(I).LT.39.0) GO TO 409                                    79K
ISN 0046                IF (D(I).GE.39.0) GO TO 410                                                     79L
ISN 0048        400     D(I)=150.+(236.-150.)/1.99*(D(I)-0.)                                           79L1
ISN 0049                GO TO 420                                                                       79M
ISN 0050        401     D(I)=236.+(371.-236.)/(5.01-1.99)*(D(I)-1.99)                                   79N
ISN 0051                IF (D(I).GE.258..AND.D(I).LE.290.) D(I)=D(I)-0.6                               79N1
ISN 0053                IF (D(I).GE.280..AND.D(I).LE.314.) D(I)=D(I)-0.5                               79N2
ISN 0055                GO TO 420                                                                       79O
ISN 0056        402     D(I)=371.+(592.-371.)/(10.01-5.01)*(D(I)-5.01)                                  79P
ISN 0057                IF (D(I).GE.532.00)  D(I)=D(I)-0.80                                            79P1
ISN 0059                D(I)=D(I)+1.0                                                                  79P2
ISN 0060                IF (D(I).LE.425.) D(I)=D(I)-0.20                                               79P3
ISN 0062                GO TO 420                                                                       79Q
ISN 0063        403     D(I)=592.+(721.-592.)/(13.01-10.01)*(D(I)-10.01)                                79R
ISN 0064                GO TO 420                                                                       79S
ISN 0065        404     D(I)=721.+(891.-721.)/(17.01-13.01)*(D(I)-13.01)                                79T
ISN 0066                GO TO 420                                                                       79U
ISN 0067        405     D(I)=891.+(1143.-891.)/(22.99-17.01)*(D(I)-17.01)                               79V
ISN 0068                GO TO 420                                                                       79W
ISN 0069        406     D(I)=1143.+(1444.-1143.)/(30.00-22.99)*(D(I)-23.00) -0.10                       79X
ISN 0070                IF (D(I).GE.1396.) D(I)=D(I)+.3                                                79X1
ISN 0072                IF(D(I).LE.1234.) D(I)=D(I)+.30                                                79X2
ISN 0074                GO TO 420                                                                       79Y
ISN 0075        407     D(I)=1444.+(1576.-1444.)/(33.00-29.99)*(D(I)-29.99)                             79Z
ISN 0076                IF (D(I).LE.1528.) D(I)=D(I)-0.5                                               79Z1
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ISN 0078              GO TO 420                                                   79AA
ISN 0079      408     D(I)=1576.+(1710.-1576.)/(36.00-33.00)*(D(I)-33.00)          79BB
ISN 0080              IF (D(I).GE.1635..AND.D(I).LE.1670.) D(I)=D(I)+0.4          79BB0
ISN 0082              GO TO 420                                                  79BB1
ISN 0083      409     D(I)=1710.+(1848.-1710.)/(39.00-36.00)*(D(I)-36.00)+.10      79CC
ISN 0084              GO TO 420                                                  79CC1
ISN 0085      410     D(I)=1848.+(1941.-1848.)/(41.00-39.00)*(D(I)-39.00) -.10   79CC2
ISN 0086              IF (D(I).GE.1892.) D(I)=D(I)+0.5                           79CC3
ISN 0088      420 CONTINUE                                                        79DD
ISN 0089          PRINT 23                                                          80
ISN 0090       23 FORMAT(1H1)                                                      80A
ISN 0091          DO 25 I=1,20                                                    80A1
ISN 0092              J=D(50)+.2                                                   80B
ISN 0093              PRINT 24,J                                                   80C
ISN 0094       24     FORMAT(1H0,'NEXT IS RUN ',I4)                                80D
ISN 0095       25     CONTINUE                                                     80E
ISN 0096          D(41)=DU(41)                                                     81A
ISN 0097          D(42)=DU(42)                                                     81B
ISN 0098          FTC=DU(41)+0.2                                                   100
ISN 0099          CTC=DU(42)+0.2                                                   101
ISN 0100          UWAVG=AVG(D,1,24,.750,23.750)                                    110
ISN 0101          CALL TKER(D,46,UWAVG)                                            120
ISN 0102          PRINT 51                                                         132
ISN 0103       51 FORMAT (1H1,4X,9HSUBSCRIPT,6X,6HU DATA,9X,6HC DATA)              133
ISN 0104          DO 58 I=1,50                                                     134
ISN 0105              PRINT 52,I,DU(I),D(I)                                        135
ISN 0106       52     FORMAT(7X,I3,8X,F8.2,8X,F8.2)                                136
ISN 0107       58     CONTINUE                                                     137
       C CONSTANTS FOLLOW.  THE THERMAL K'S ARE TEMP DEPENDENT                     139
ISN 0108          R1=.180/2.                                                       140
ISN 0109          D1=0.180/12.                                                     141
ISN 0110          R2=.250/2.                                                       150
ISN 0111          R3=6.00/2.                                                       160
ISN 0112          R4=3.0598                                                        170
       C          K1 IS GIVEN ON CARD 845                                          180
ISN 0113          K2=0.06                                                          190
ISN 0114          K3=9.00                                                          200
ISN 0115          K4=14.32                                                         210
ISN 0116          N=2                                                              220
ISN 0117          L=24.5                                                           230
ISN 0118          SPH1=0.324                                                       236
ISN 0119          DXA=0.5                                                          240
ISN 0120          DXB=0.5                                                          250
       C END OF CONSTANTS                                                          255
ISN 0121          XL(1)=.750                                                       260
ISN 0122          DX=1.00                                                          270
ISN 0123          DO 60 I=2,24                                                     280
ISN 0124              M=I-1                                                        285
ISN 0125              XL(I)=XL(M)+DX                                               290
ISN 0126       60     CONTINUE                                                     300
ISN 0127          TAO=(D(27)+D(28))/2.                                             305
ISN 0128          TAI=(D(29)+D(30))/2.                                             310
ISN 0129          TBBI=(D(31)+D(32))/2.                                            315
ISN 0130          TBBO=(D(33)+D(34))/2.                                            320
ISN 0131          IF(TAO.GT.TAI)GO TO 61                                           325
ISN 0133          TA=TAI                                                           330
ISN 0134          GO TO 62                                                         335
ISN 0135       61 TA=TAO                                                           340
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ISN 0136      62 IF(TBBO.GT.TBBI) GO TO 63                                      345
ISN 0138         TBB=TBBI                                                       350
ISN 0139         GO TO 64                                                       355
ISN 0140      63 TBB=TBBO                                                       360
ISN 0141      64 CONTINUE                                                       365
ISN 0142         IF (TA-TBB)66,68,68                                            390
ISN 0143      66 TIN=TA                                                         400
ISN 0144         TOUT=TBB                                                       410
ISN 0145         GO TO 70                                                       420
ISN 0146      68 TIN=TBB                                                        430
ISN 0147         TOUT=TA                                                        440
ISN 0148      70 CONTINUE                                                       450
ISN 0149         IF (TA-TBB) 73,71,71                                           460
ISN 0150      71 DO 72 I=1,24                                                   470
ISN 0151               M=25-I                                                   475
ISN 0152               TO(I)=D(M)                                               480
ISN 0153      72       CONTINUE                                                 490
ISN 0154         GO TO 80                                                       500
ISN 0155      73 DO 75 I=1,24                                                   510
ISN 0156               TO(I)=D(I)                                               520
ISN 0157      75       CONTINUE                                                 530
ISN 0158      80 CONTINUE                                                       540
            C CARE MUST BE TAKEN WITH REGARD TO SIGN CONVENTION FOR FOLLOWING Q AND DT   550
ISN 0159         QWM=400./83.6*D(47)*200.*3.412/D(49)                           560
ISN 0160         MDOT=D(48)*60.                                                 570
ISN 0161         DT=UWAVG - D(46)                                               575
ISN 0162         QLCAL=-((0.2757E-3)*CT*DT + 0.1100*DT - 0.1724E-1)             576
ISN 0163         QLF=QLCAL/(2.*3.14*R2*L/144.)                                  577
ISN 0164         QLF=-QLF                                                       578
ISN 0165         QEL=K4*.375*17./8./12.*((D(43)-D(25))/DXA+(D(44)-D(26))/DXB)   580
ISN 0166         DT=AVG(D,1,24,.750,23.750) - D(46)                             585
ISN 0167         QINS=2.*3.14*(L-0.5)/12.*(-DT)/(ALOG(R3/R2)/K2+ALOG(R4/R3)/K3) 590
ISN 0168         QLEST=QEL + QINS                                               610
ISN 0169         QF=MDOT*SPH1*(TOUT-TIN)                                        640
ISN 0170         QODP=      QF       /(2.*3.14*R1*L)*144.                       650
ISN 0171         QBAL=(QF-QLCAL)/QWM                                            660
ISN 0172         X1=FTC                                                         710
ISN 0173         X1=X1-.250                                                     720
ISN 0174         X2=FTC+CTC-1                                                   730
ISN 0175         X2=X2-.250                                                     740
ISN 0176     110 PRINT 111                                                      810
ISN 0177     111 FORMAT (1H1,09X,1HX,11X,3HX/D,10X,1HH,11X,2HTB,11X,2HTI,11X,2HTO  820
               8                   ,12X,2HNU,11X,2HRE,12X,2HPR)                  821
ISN 0178         DO 115 I=1,24                                                  830
ISN 0179               X=XL(I)                                                  840
ISN 0180               ATT=TO(I) - 25.                                          841
ISN 0181     112       K1=TK(ATT)                                               845
ISN 0182               TI(I)=TO(I)-(QF - CLCAL)    /(2.*3.14*L/12.*K1)*         850
               8                (R2*R2/(R2*R2-R1*R1)*ALOG(R2/R1)-0.500)          851
               8                  +QLF*R2/12./K1*ALOG(R2/R1)                     852
ISN 0183               ATT=(TI(I)+TO(I))/2.                                     862
ISN 0184               K1NOW=TK(ATT)                                            863
ISN 0185               DK=ABS(K1NOW-K1)                                         864
ISN 0186               IF(DK.GE.0.1) GO TC 112                                  865
ISN 0188               XOD=X/(2.*R1)                                            870
ISN 0189               TB(I)=TIN + QODP*3.14*2.*R1*X/MDOT/SPH1/144.             880
ISN 0190               H(I)=QODP/(TI(I)-TB(I))                                  890
ISN 0191               CALL PRCP(RENO,PRNC,MU,RHO,TB(I),R1,CCND,SPH1,MDOT)      895
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ISN 0192              NUNO(I)=H(I)*2.*R1/12./CCND                                          897
ISN 0193              PRINT 114,X,XOD,H(I),TB(I),TI(I),TO(I),NUNO(I),RENO,PRNO            900
ISN 0194        114   FORMAT (1H0,9F13.4)                                                  910
ISN 0195        115   CONTINUE                                                             920
ISN 0196              HAVG=AVG(H,FTC,CTC,X1,X2)                                            930
ISN 0197              PRINT 450,HAVG                                                       935
ISN 0198        450   FORMAT(1H0,'AVG H BTU/HRSQFTDEGF = ',F10.2)                          940
ISN 0199              WAVG=AVG(TI,FTC,CTC,X1,X2)                                           950
ISN 0200              PRINT 451,WAVG                                                       955
ISN 0201        451   FORMAT(1H0,'AVG INNER WALL TEMP DEGF = ',F10.3)                      960
ISN 0202              BAVG=AVG(TB,FTC,CTC,X1,X2)                                           970
ISN 0203              PRINT 452,BAVG                                                       975
ISN 0204        452   FORMAT(1H0,'AVG BULK TEMP DEGF = ',F10.3)                            980
ISN 0205              OAVG=AVG(TO,FTC,CTC,X1,X2)                                           990
ISN 0206              PRINT 453,OAVG                                                       995
ISN 0207        453   FORMAT(1H0,'AVG OUTER WALL TEMP DEGF = ',F10.3)                     1000
ISN 0208              NUAVG=AVG(NUNO,FTC,CTC,X1,X2)                                       1005
ISN 0209              PRINT 454,NUAVG                                                     1010
ISN 0210        454   FORMAT (1H0,'AVG NUSSELT NO. = ',F10.5)                             1015
ISN 0211              CALL PROP(RENO,PRNO,MU,RHO,BAVG,R1,CCND,SPH1,MDOT)                  1017
ISN 0212              VRAT=MU                                                             1018
ISN 0213              BETA=0.02328/RHO                                                    1019
ISN 0214              PRINT 90,QWM                                                       1020A
ISN 0215         90   FORMAT    (1H1,'WATTMETER BTU/HR = ',T35,F10.3)                    1020B
ISN 0216              PRINT 91,QF                                                       1020B1
ISN 0217         91   FORMAT(1H0,'HEAT TO SALT BTU/HR = ',T35,F10.3)                    1020B2
ISN 0218              PRINT 93,QLCAL                                                     1020C
ISN 0219         93   FORMAT(1H0,'CAL HEAT LOSS BTU/HR = ',T35,F10.3)                    1020D
ISN 0220              PRINT 94,QLEST                                                     1020E
ISN 0221         94   FORMAT(1H0,'EST HEAT LOSS BTU/HR = ',T35,F10.3)                    1020F
ISN 0222              PRINT 96,N                                                         1020I
ISN 0223         96   FORMAT(1H0,'TEST SECTION NO. = ',T35,I10)                          1020J
ISN 0224              G=MDOT/(3.14*R1*R1)*144.                                          1020J3
                C     PRINT 97,G                                                        1020J4
ISN 0225         97   FORMAT(1H0,'G LB/HRFT2 = ',T33,E12.5)                             1020J5
ISN 0226              VEL=MDOT/RHO/(3.14*R1*R1/144.)/3600.                              1020L1
                C     PRINT 98,VEL                                                      1020L2
ISN 0227         98   FORMAT(1H0,'TEST VELOCITY FT/SEC = ',T35,F10.3)                   1020L3
ISN 0228              PRINT 99,RHO                                                        1050
ISN 0229         99   FORMAT (1H0,'BULK SALT DENSITY LB/FT3 = ',T35,F10.2)                1055
ISN 0230              PRINT 100,MU                                                        1060
ISN 0231        100   FORMAT (1H0,'BULK SALT VISCOSITY LB/HRFT = ',T35,F10.3)             1065
ISN 0232              PRINT 101,COND                                                      1080
ISN 0233        101   FORMAT (1H0,'BULK SALT CCND BTU/HRFTDEGF = ', T35,F10.3)            1090
ISN 0234              PRINT 472,TIN                                                       1110
ISN 0235        472   FORMAT(1H0,'INLET TEMP DEGF = ',T35,F10.3)                          1120
ISN 0236              PRINT 473,TOUT                                                      1130
ISN 0237        473   FORMAT(1H0,'OUTLET TEMP DEGF = ',T35,F10.3)                         1140
ISN 0238              TCHG=TOUT-TIN                                                       1150
ISN 0239              PRINT 474,TCHG                                                      1160
ISN 0240        474   FORMAT(1H0,'TOUT - TIN DEGF = ',T35,F10.3)                          1170
ISN 0241              PRINT 471,MDOT                                                      1180
ISN 0242        471   FORMAT(1H0,'MASS FLOW RATE LB/HR = ',T35,F10.3)                     1185
ISN 0243              PRINT 477,RENO                                                      1190
ISN 0244        477   FORMAT (1H0,'BULK REYNOLDS NO. = ',T35,F10.2)                       1200
ISN 0245              PRINT 478,PRNO                                                      1210
ISN 0246        478   FORMAT (1H0,'BULK PRANDTL NO. = ',T35,F10.3)                        1220
ISN 0247              PRINT 470,CODP                                                      1230
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ISN 0248      470 FORMAT(1HO,'NET HEAT FLUX BTU/HRSQFT = ',T33,E12.5)              1235
ISN 0249          PRINT 476,QBAL                                                   1240
ISN 0250      476 FORMAT (1HO,'HEAT BALANCE = ',T35,F10.3)                         1245
ISN 0251          DEFH=MDOT*SPH1*(TOUT-TIN)/(2.*3.14*R1*L/144.*(WAVG-BAVG))        1250
ISN 0252          PRINT 475,DEFH                                                   1260
ISN 0253      475 FORMAT(1H1,'H BY DEF BTU/HRSQFTDEGF = ',T35,F10.2)               1270
ISN 0254          NNO=DEFH*2.*R1/12./COND                                          1290
ISN 0255          PRINT 4751,NNO                                                   1291
ISN 0256     4751 FORMAT (1HO,'NUSSELT NO. = ',T35,F10.2)                          1292
              C FROM HERE ON THE NNO USED WILL BE THE INTEGRATED VALUE             1292A
ISN 0257          NNO=NUAVG                                                        1292B
ISN 0258          GRNO=    D1      **3*BETA*32.2*RHO**2*(WAVG-BAVG)/(MU/3600.)**2  1293
ISN 0259          PRINT 981,GRNO                                                   1294
ISN 0260      981 FORMAT(1HO,'GRASHOF NO. = ',T35,F10.4)                           1295
ISN 0261          GZNO=3.14/4.*RENO*PRNO*2.*R1/(X2-X1)                             1296
ISN 0262          PRINT 4752,GZNO                                                  1297
ISN 0263     4752 FORMAT (1HO,'GRAETZ NO.(M-B) = ',T35,F10.4)                      1298
ISN 0264          BTRM=0.0722*(GRNO*PRNO*2.*R1/(X2-X1))**0.75                      1299
ISN 0265          PRINT 4753,BTRM                                                  1300
ISN 0266     4753 FORMAT (1HO,'BUOYANCY TERM FOR VERT,LAM = ',T35,F10.4)           1301
ISN 0267          STF=NNO/(PRNO**0.33)/(MU**0.14)                                  1310
ISN 0268          DBF=NNO/PRNO**0.4                                                1320
ISN 0269          DBH=COND/(2.*R1/12.)*0.023*(RENO**0.8)*(PRNO**0.4)               1330
ISN 0270          PRINT 481,DBH                                                    1340
ISN 0271      481 FORMAT       (1HO,'MC ADAMS H BTU/HRSQFTDEGF = ',T35,F10.2)      1350
ISN 0272          STTH=COND/(2.*R1/12.)*0.027*(RENO**0.8)*(PRNO**0.33)*(MU**0.14)  1355
ISN 0273          HTRH=COND/(2.*R1/12.)*0.116*(RENO**.667 - 125.)*PRNO**.33        1357
                8                                                 *(MU**0.14)      1358
ISN 0274          STH=COND/(2.*R1/12.)*1.86*(RENO*PRNO*2.*R1/(X2-X1))**0.33        1360
ISN 0275          IF (TA-TBB) 200,210,210                                          1360A
ISN 0276      200 DLH=COND/D1*1.75*(GZNO - BTRM)**0.33                             1360B
ISN 0277          GO TO 220                                                        1360C
ISN 0278      210 DLH=COND/D1*1.75*(GZNO + BTRM)**0.33                             1360D
ISN 0279      220 CONTINUE                                                         1360E
ISN 0280          STH=STH*(MU**0.14)                                               1361
ISN 0281          COLH=0.023*(D1*G)**0.8/D1*COND**0.667*SPH1**0.33                 1361A
ISN 0282          CLMH=1.65*COND/D1*(GZNO*MU)**0.33                                1361A00
ISN 0283          FGRNO=GRNO*MU**2                                                 1361A0
ISN 0284          CF=NNO/(PRNO**0.33)*(MU**0.33)                                   1361A1
ISN 0285          FILM=(WAVG+BAVG)/2.                                              1361B
              C DIM GROUPS AND PROPS THAT FOLLOW ARE NO LONGER AT BULK TEMP        1361B1
ISN 0286          CALL PROP(RENO,PRNO,MU,RHO,FILM,R1,COND,SPH1,MDOT)               1361C
ISN 0287          COLH=COLH*MU**0.33/MU**0.8                                       1361D
ISN 0288          FGRNO=FGRNO/MU**2                                                11361D1
ISN 0289          IF (TA-TBB) 230,240,240                                          1361D2
ISN 0290      230 CLMH=CLMH/MU**0.33*(1. - 0.015*(FGRNO)**0.33)                    1361D3
ISN 0291          GO TO 250                                                        1361D4
ISN 0292      240 CLMH=CLMH/MU**0.33*(1. + 0.015*(FGRNO)**0.33)                    1361D5
ISN 0293      250 CONTINUE                                                         1361D6
ISN 0294          CF=CF/MU**0.33                                                   1361D7
ISN 0295          CRENO=RENO                                                       1361D8
ISN 0296          PRINT 4811,COLH                                                  1361E
ISN 0297     4811 FORMAT (1HO,'COLBURN TURB H BTU/HRSQFTDEGF = ',T35,F10.2)        1361F
ISN 0298          CALL PROP(RENO,PRNO,MU,RHO,WAVG,R1,COND,SPH1,MDOT)               1362
ISN 0299          STTH=STTH/(MU**0.14)                                             1362B
ISN 0300          HTRH=HTRH/(MU**0.14)                                             1362C
ISN 0301          STH=STH/(MU**0.14)                                               1363
ISN 0302          PRINT 482,STTH                                                   1364
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ISN 0303      482 FORMAT(1HO,'S-T TURBULENT H BTU/HRSQFTDEGF = ',T35,F10.2)      1365
ISN 0304          PRINT 4821,HTRH                                                1366
ISN 0305     4821 FORMAT (1HO,'HAUSEN TR H BTU/HRSQFTDEGF = ',T35,F10.2)        1366A
ISN 0306          PRINT 483,STH                                                  1367
ISN 0307      483 FORMAT (1HO,'S-T LAMINAR H BTU/HRSQFTDEGF = ',T35,F10.2)       1368
ISN 0308          PRINT 484,DLH                                                 1369A
ISN 0309      484 FORMAT(1HO,'MART VER,LAM H BTU/HRSQFTDEGF = ',T35,F10.2)      1369B
ISN 0310          PRINT 4840,CLMH                                              1369B1
ISN 0311     4840 FORMAT (1HO,'COL VERT,LAM H BTU/HRSQFTDEGF = ',T35,F10.2)    1369B2
ISN 0312          PRINT 4841,DBF                                               1369C1
ISN 0313     4841 FORMAT (1HC,'MC ADAMS FACTCR = ',T35,F10.3)                  1369C2
ISN 0314          PRINT 4842,CF                                                1369C3
ISN 0315     4842 FORMAT (1HO,'COLBURN FACTOR = ',T35,F10.3)                   1369C4
ISN 0316          PRINT 4843,CRENO                                             1369C5
ISN 0317     4843 FORMAT (1HO,'CLBRN RENC = ',T35,F10.2)                       1369C6
ISN 0318          STF=STF*(ML**0.14)                                            1370A
ISN 0319          PRINT 485,STF                                                 1370B
ISN 0320      485 FORMAT (1HO,'S-T FACTOR = ',T35,F10.3)                        1370C
ISN 0321          ETL=X2-X1                                                      1372
ISN 0322          PRINT 486,ETL                                                  1373
ISN 0323      486 FORMAT(1HO,'EFF TUBE LENGTH IN = ',T35,F10.3)                  1374
ISN 0324          VRAT=(VRAT/MU)**0.14                                           1375
ISN 0325          PRINT 487,VRAT                                                 1376
ISN 0326      487 FORMAT (1HO,'VIS RATIO TO 0.14 = ',T35,F10.4)                  1377
ISN 0327          DFACT=STF*VRAT                                                 1378
ISN 0328          PRINT 488,CFACT                                                1379
ISN 0329      488 FORMAT (1HO,'MART FACTCR = ',T35,F10.3)                        1380
C A LOOK AT A SMCOTH CURVE THRU THE DATA POINTS MAY BE EDUCATIONAL                1390
ISN 0330          CALL YLS(TC,FTC,CTC,2)                                         1391
ISN 0331          GO TO 6                                                        1400
ISN 0332          END                                                            1401
ADCONS FOR EXTERNAL REFERENCES
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         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C THIS FUNCTION COMMITS 3RD ORDER ORTHOGONAL SINS BY AVERAGING VALUES      A10
              C BEGINNING WITH NO. M AT X1 AND ENDING WITH I CONSECUTIVE VALUES AT X2    A11
ISN 0002            FUNCTION AVG(Y,M,I,X1,X2)                                            A20
ISN 0003            DIMENSION Y(50),X(50),A(4),P(50,4),SP2(50,4)                         A30
ISN 0004            REAL NP,LS                                                           A35
ISN 0005            A(1)=0                                                               A40
ISN 0006            A(2)=0                                                               A50
ISN 0007            A(3)=0                                                               A60
ISN 0008            A(4)=0                                                               A70
ISN 0009            P(1,1)=1.                                                            A72
ISN 0010            P(1,2)=1.                                                            A73
ISN 0011            P(1,3)=1.                                                            A74
ISN 0012            P(1,4)=1.                                                            A75
ISN 0013            NP=I-1                                                               A90
ISN 0014            DO 490 L=2,I                                                         A95
ISN 0015            X(L)=L-1                                                             A97
ISN 0016            P(L,1)= 1.                                                          A100
ISN 0017            P(L,2)=1.-2.*X(L)/NP                                                A110
ISN 0018            P(L,3)=1.-6.*X(L)/NP+6*X(L)*(X(L)-1.)/NP/(NP-1.)                    A120
ISN 0019            P(L,4)=1.-12.*X(L)/NP+30.*X(L)*(X(L)-1.)/NP/(NP-1.)                 A130
                   8            -20.*X(L)*(X(L)-1.)*(X(L)-2.)/NP/(NP-1.)/(NP-2.)        A131
ISN 0020        490 CONTINUE                                                            A135
ISN 0021            SP2(I,1)=NP+1.                                                      A140
ISN 0022            SP2(I,2)=(NP+1.)*(NP+2.)/(3.*NP)                                    A150
ISN 0023            SP2(I,3)=(NP+1.)*(NP+2.)*(NP+3.)/(5.*NP)/(NP-1.)                    A160
ISN 0024            SP2(I,4)=(NP+1.)*(NP+2.)*(NP+3.)*(NP+4.)/(7.*NP)/(NP-1.)/(NP-2.)    A170
ISN 0025            DO 550 J=1,4                                                        A200
ISN 0026               DO 500 K=1,I                                                     A210
ISN 0027               A(J)=A(J)+Y(K+M-1)*P(K,J)                                        A220
ISN 0028        500    CONTINUE                                                         A230
ISN 0029            A(J)=A(J)/SP2(I,J)                                                  A240
ISN 0030        550 CONTINUE                                                            A250
ISN 0031            PRINT 600                                                           A270
ISN 0032        600 FORMAT (1H1,10HORIGINAL  ,13HLEAST SQUARES,10H      PDEV)           A280
ISN 0033            DO 700 J=1,I                                                        A290
ISN 0034               LS=A(1)*P(J,1)+A(2)*P(J,2)+A(3)*P(J,3)+A(4)*P(J,4)               A300
ISN 0035               PDEV=(LS-Y(J+M-1))*100./Y(J+M-1)                                 A305
ISN 0036               PRINT 650,Y(J+M-1),LS,PDEV                                       A310
ISN 0037        650    FORMAT (F8.2,5X,F8.2,5X,F8.2)                                    A320
ISN 0038        700 CONTINUE                                                            A330
ISN 0039            X3=X2-X1                                                            A340
ISN 0040        750 AINT=A(1)*X3 + A(2)*(X3-X3**2/NP)      +                            A350
                   8             A(3)*(X3-3.*X3**2/NP+6./NP/(NP-1.)*(X3**3/3.-X3**2     A351
                   8                   /2.))       +                                    A352
                   8            A(4)*(X3-6.*X3**2/NP+30./NP/(NP-1.)*(X3**3/3.-X3**2     A353
                   8             /2.)-20./NP/(NP-1.)/(NP-2.)*(X3**4/4.-X3**3+X3*X3))    A354
ISN 0041            AVG=AINT/X3                                                         A390
ISN 0042            RETURN                                                              A440
ISN 0043            END                                                                 A450
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,NOID,NOXREF
               C THIS FUNCTION DETERMINES THERMAL K FOR INCR-8                            K10
ISN 0002            FUNCTION TK(TEMPF)                                                   K20
ISN 0003            TEMPC=(TEMPF-32.)*5./9.                                              K30
ISN 0004            IF (TEMPC-440.)10,10,20                                              K40
ISN 0005         10 TK=0.128+(.155-.128)/200.*(TEMPC-200.)                               K50
ISN 0006            GO TO 80                                                             K60
ISN 0007         20 IF (TEMPC-500.)30,30,40                                              K70
ISN 0008         30 TK=0.160+(.174-.160)/60.*(TEMPC-440.)                                K80
ISN 0009            GO TO 80                                                             K90
ISN 0010         40 IF (TEMPC-680.)50,50,60                                             K100
ISN 0011         50 TK=0.174+(.193-.174)/100.*(TEMPC-500.)                              K110
ISN 0012            GO TO 80                                                            K120
ISN 0013         60 IF (TEMPC-740.)70,70,75                                             K130
ISN 0014         70 TK=0.208+(.230-.208)/60.*(TEMPC-680.)                               K140
ISN 0015            GO TO 80                                                            K150
ISN 0016         75 TK=0.230+(.248-.230)/160.*(TEMPC-740.)                              K160
ISN 0017         80 TK=TK*57.82                                                         K170
ISN 0018            RETURN                                                              K300
ISN 0019            END                                                                 K301
```

```
   COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SOURCE,EBCDIC,NOLIST,DECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C THIS SUBROUTINE TAKES AN ARRAY Y WHOSE 1ST VALUE IS AT M WITH I TOTAL      A10
              C CONSECUTIVE VALUES AND REPLACES THIS ARRAY WITH AN NTH ORDER FIT            A11
ISN 0002            SUBROUTINE YLS(Y,M,I,N)                                                 A20
ISN 0003            DIMENSION Y(50),X(50),A(4),P(50,4),SP2(50,4)                            A30
ISN 0004            REAL NP,LS                                                              A35
ISN 0005            A(1)=0                                                                  A40
ISN 0006            A(2)=0                                                                  A50
ISN 0007            A(3)=0                                                                  A60
ISN 0008            A(4)=0                                                                  A70
ISN 0009            P(1,1)=1.                                                               A72
ISN 0010            P(1,2)=1.                                                               A73
ISN 0011            P(1,3)=1.                                                               A74
ISN 0012            P(1,4)=1.                                                               A75
ISN 0013            NP=I-1                                                                  A90
ISN 0014            DO 490 L=2,I                                                            A95
ISN 0015            X(L)=L-1                                                                A97
ISN 0016            P(L,1)= 1.                                                              A100
ISN 0017            P(L,2)=1.-2.*X(L)/NP                                                    A110
ISN 0018            P(L,3)=1.-6.*X(L)/NP+6*X(L)*(X(L)-1.)/NP/(NP-1.)                        A120
ISN 0019            P(L,4)=1.-12.*X(L)/NP+30.*X(L)*(X(L)-1.)/NP/(NP-1.)                     A130
                   8             -20.*X(L)*(X(L)-1.)*(X(L)-2.)/NP/(NP-1.)/(NP-2.)          A131
ISN 0020        490 CONTINUE                                                                A135
ISN 0021            SP2(I,1)=NP+1.                                                          A140
ISN 0022            SP2(I,2)=(NP+1.)*(NP+2.)/(3.*NP)                                        A150
ISN 0023            SP2(I,3)=(NP+1.)*(NP+2.)*(NP+3.)/(5.*NP)/(NP-1.)                        A160
ISN 0024            SP2(I,4)=(NP+1.)*(NP+2.)*(NP+3.)*(NP+4.)/(7.*NP)/(NP-1.)/(NP-2.)        A170
ISN 0025            DO 550 J=1,4                                                            A200
ISN 0026                DO 500 K=1,I                                                        A210
ISN 0027                A(J)=A(J)+Y(K+M-1)*P(K,J)                                           A220
ISN 0028        500     CONTINUE                                                            A230
ISN 0029            A(J)=A(J)/SP2(I,J)                                                      A240
ISN 0030        550 CONTINUE                                                                A250
ISN 0031            PRINT 600                                                               A270
ISN 0032        600 FORMAT (1H1,10HORIGINAL  ,13HLEAST SQUARES,10H      PDEV)               A280
ISN 0033            DO 700 J=1,I                                                            A290
ISN 0034                IF (N.LT.3) A(4)=0                                                  A294
ISN 0036                IF(N.LT.2) A(3)=0                                                   A295
ISN 0038                IF(N.LT.1) A(2)=0                                                   A296
ISN 0040                LS=A(1)*P(J,1)+A(2)*P(J,2)+A(3)*P(J,3)+A(4)*P(J,4)                  A300
ISN 0041                PDEV=(LS-Y(J+M-1))*100./Y(J+M-1)                                    A305
ISN 0042                PRINT 650,Y(J+M-1),LS,PDEV                                          A310
ISN 0043        650     FORMAT (F8.2,5X,F8.2,5X,F8.2)                                       A320
ISN 0044                Y(J+M-1)=LS                                                         A330
ISN 0045        700 CONTINUE                                                                A350
ISN 0046            RETURN                                                                  A370
ISN 0047            END                                                                     A371
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                              SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                     C  THIS SUBROUTINE USES THERMOPHYSICAL DATA FROM ORNL-TM-2316 AND ORNL-4449
 ISN 0002                SUBROUTINE PROP(RE,PR,V,RHO,TEMPF,R,COND,CP,W)                     P20
 ISN 0003                T=(TEMPF-32.0)/1.8
 ISN 0004                T=T+273.0
 ISN 0005                V=0.077*EXP(4430.0/T)
 ISN 0006                V=2.419*V
 ISN 0007                RHO=3.687-(6.5E-04*T)
 ISN 0008                RHO=RHO*62.428
 ISN 0009                COND=0.69
 ISN 0010                PR=CP*V/COND                                                       P140
 ISN 0011                RE=4./V/3.14/(2.*R/12.)*W                                          P150
 ISN 0012                RETURN                                                             P199
 ISN 0013                END                                                                P200
```

APPENDIX D

CHEMICAL ANALYSES AND PHYSICAL PROPERTIES OF THE SALT

Table D.1. Analyses of the Fluoride Salt Mixture ($LiF-BeF_2-ThF_4-UF_4$; 67.5-20.0-12.0-0.5 mole %) Before, During, and After Heat-Transfer Determinations

Impurity	Weight %		
	Before	During[a]	After
Li	7.14	7.27	6.64
Be	2.57	2.53	2.46
Th	42.1	41.3	43.5
U	1.87	1.84	1.72
F	45.4	46.4	45.4
Ni	20 ppm	—	—
Cr	<25 ppm	—	—
Fe	78 ppm	—	—
S	<10 ppm	—	—
Na	—	0.66	0.55

[a]Analysis made just prior to removal of the first test section.

Table D.2. Thermophysical Property Data for Molten Salt Mixture $LiF-BeF_2-ThF_4-UF_4$ (67.5-20-12-0.5 Mole %)

	Uncertainty	Ref.
μ (lb/ft·hr) = 0.187 exp [8000/T(°R)][a]	±25%	12
k (Btu/hr·ft·°F) = 0.69[b]	±12%	13
ρ (lb/ft^3) = 230.89 − 22.54 x 10^{-3} t (°F)[a]	± 3%	12
C_p (Btu/lb·°F) = 0.324[a]	± 4%	12
Liquidus temperature ≅ 895°F[a]	±10°F	12

[a]Estimated values for the salt mixture $LiF-BeF_2-ThF_4-UF_4$ (68-20-11.7-0.3 mole %).

[b]Measured value for the subject salt mixture.

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