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AEC RESEARCH AND DEVELOPMENT REPORT

TURBULENT HEAT TRANSFER FROM A MOLTEN FLUORIDE SALT MIXTURE TO SODIUM-POTASSIUM ALLOY IN A DOUBLE-TUBE HEAT EXCHANGER

D. F. Salmon

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TURBULENT HEAT TRANSFER FROM A MOLTEN FLUORIDE SALT MIXTURE TO SODIUM POTASSIUM ALLOY IN A DOUBLE TUBE HEAT EXCHANGER

D F Salmon

INTRODUCTION

Circulating fuel reactor systems for high performance high temperature power plants place exacting requirements on the fluids which must serve as heat transfer media It is necessary that the fluids have good heat transfer properties be stable chemically at an elevated temperature have a reasonably low melting point be compatible with container materials and require only a minimum in pumping power Aside from the chemical problem involved in finding materials with which the proper amount of nuclear fuel may be combined there are the research and the experimentation required to determine whether the above mentioned specifications are met

Mixtures of fluoride salts were found to show promise for the circulating fuel application This report is concerned with an experiment to measure the heat transfer characteristics of the fluoride salt mixture NaF ZrF_4 UF_4 (50 46 4 mole %)

The primary purpose of the experiment was to make a correlation of film heat transfer coefficients and a secondary purpose was to determine the effect on heat transfer of deposits resulting from corrosion or mass transfer of container materials

DESCRIPTION OF EQUIPMENT

A schematic diagram of the various components of the test apparatus is shown in Fig 1

The only pump available for the fluoride salt circuit was a type 316 stainless steel sump pump capable of delivering 10 gpm at 40 ft of head and 3600 rpm This pump was designed for high temperature application and for liquids which could not be sealed against directly at the shaft in the ordinary manner It had a water cooled rotary face seal for maintaining an inert gas blanket on the fluid being pumped An automatic level control system was provided for maintaining the liquid level in the pump within prescribed limits

The heat transfer coefficients were measured in a double tube heat exchanger The fluoride salt was cooled in the center tube by a countercurrent flow in the annulus of sodium potassium alloy (hereafter referred to as NaK) The center tube of the heat exchanger made of nickel was 0 269 in in inside diameter with a length to diameter ratio of 40 The outer tube was $\frac{3}{4}$ in schedule 40 type 316 stainless steel pipe which was rigidly connected to the center tube at one end and bellows joined at the other end to allow for differential expansion

Heating of the fluoride salt was accomplished in a length of 1 in schedule 40 Inconel pipe by electrical tube furnace elements assembled on the pipe and covered with preformed insulation The NaK stream was cooled by natural convection of air in a section of finned pipe which was ducted and provided with a damper for control

The NaK was circulated by a conventional electromagnetic pump The fluoride salt and the NaK flow rates were measured by water calibrated venturi tubes the calibrations were corrected to reflect the discharge coefficients and the differences in densities of the respective fluids An electromagnetic flowmeter was also available for determining the NaK flow rate

Inlet and outlet temperatures of the fluoride salt and the NaK were measured by fixed Inconel sheathed Chromel Alumel probes on the center lines of the piping An adjustable probe that was provided in the annulus of the heat exchanger could be brought in touch-contact with the outer surface of the center tube wall for temperature measurement These probes were calibrated to $\frac{1}{2}$°F against a National Bureau of Standards

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certified platinum–platinum-rhodium thermocouple in a calibrating furnace. Thermocouple readings were taken on a Leeds and Northrup K-2 potentiometer, and an ice-bath cold junction was used.

Figures 2, 3, and 4 are photographs of the test equipment.

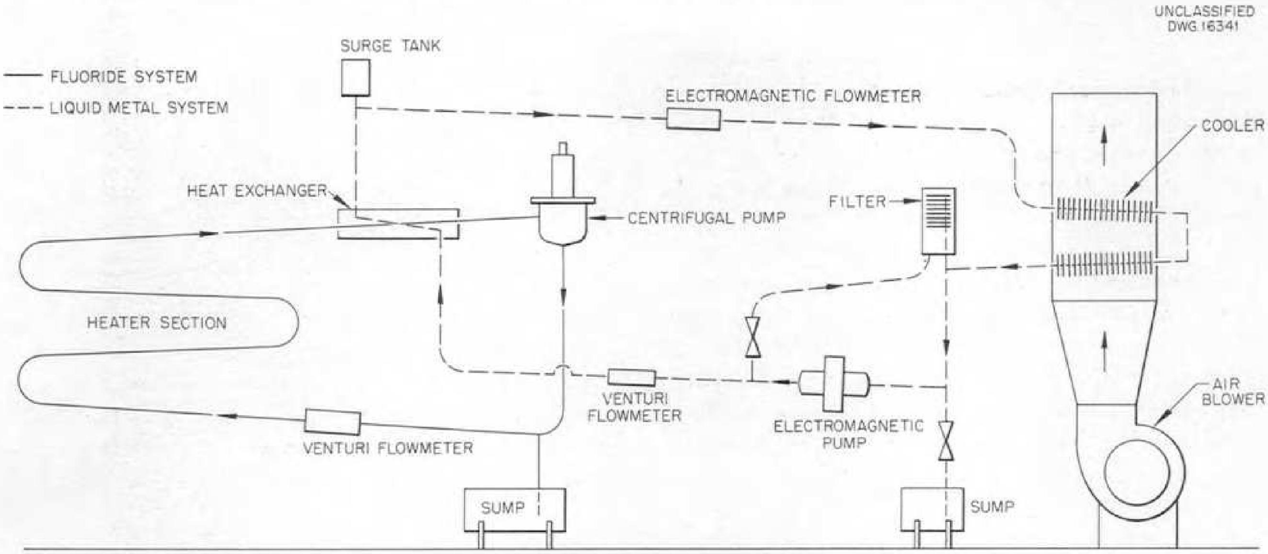

Fig. 1. Schematic Diagram of Bifluid Loop.

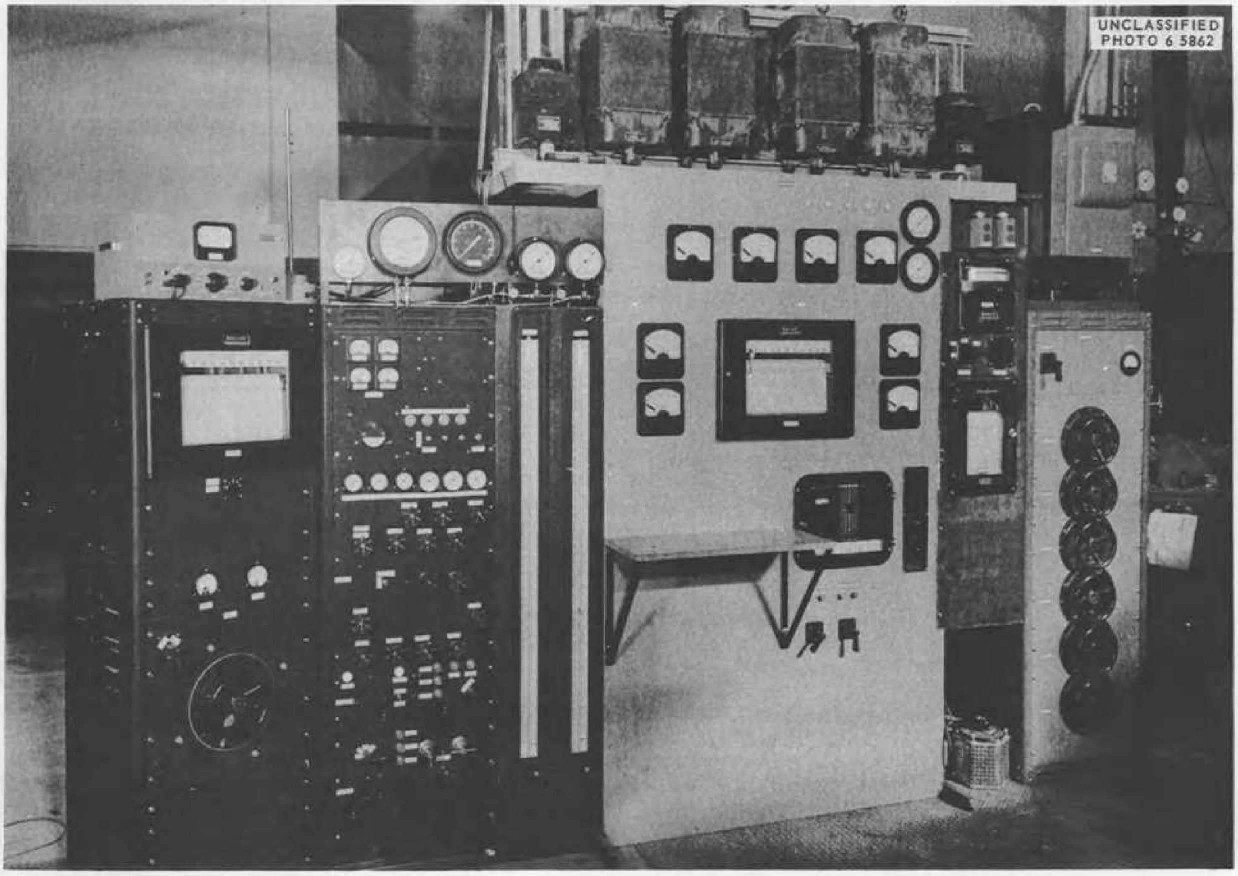

Fig. 2. Instrument and Power Panel.

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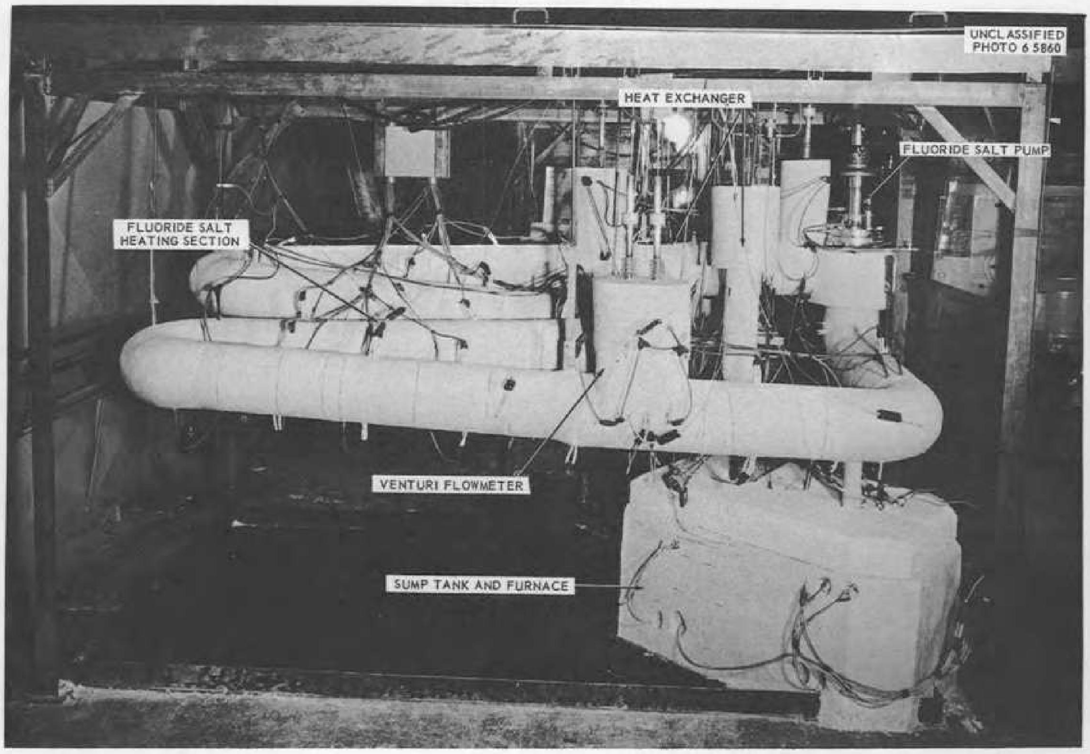

Fig. 3. Fluoride Salt Loop.

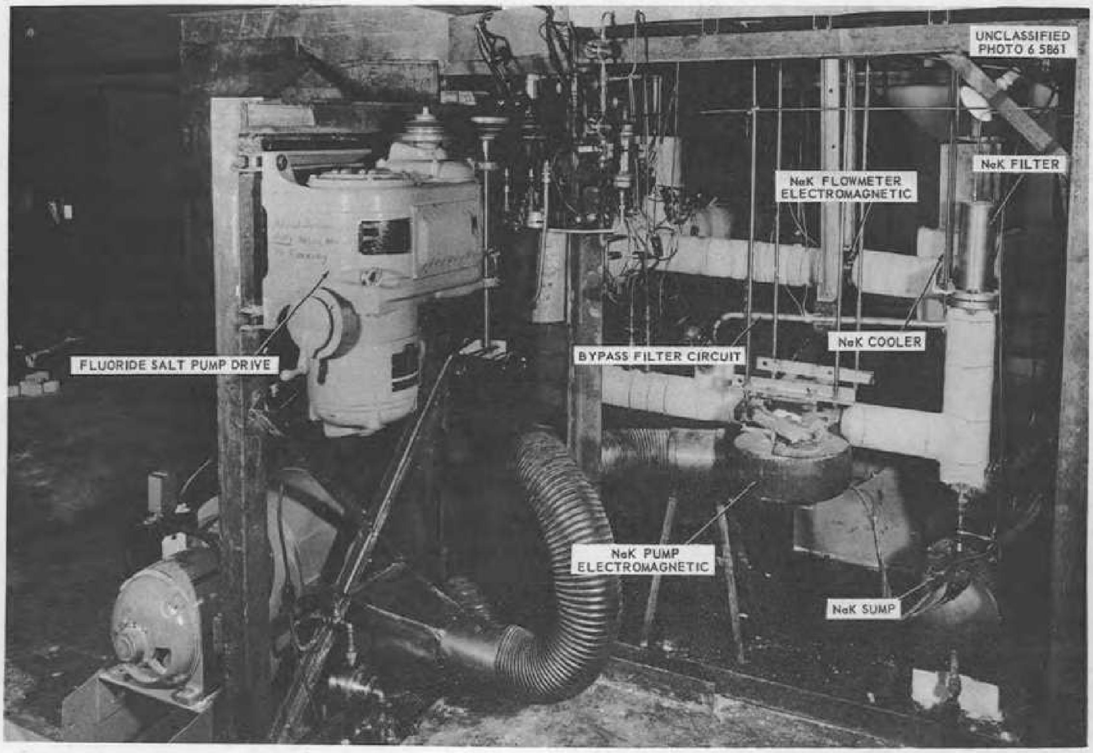

Fig. 4. NaK Loop.

TEST PROCEDURE

The melting point of the fluoride salt was approximately 960°F [1] and consequently it was necessary at all times to maintain the walls of the fluoride salt system above this value In fact the walls were kept at from 50 to 100°F above the melting point as a precaution against freezing For all runs the electrical power to the fluoride salt heaters was controlled to maintain a constant inlet temperature to the heat exchanger The fluoride salt pump speed was set to give a desired flow rate and this flow was maintained for a series of different NaK flow rates The damper to the NaK cooling section was adjusted in each case to hasten attainment of steady state conditions before data were recorded Data were taken during each run at each NaK flow rate a total of 80 data points was taken

METHOD OF CALCULATION

A heat balance on the fluoride salt and NaK streams in the heat exchanger was made initially to serve as a check on the validity of the data and to provide the basis for calculation of the heat flux q/A_o The value of q used for determining the heat flux was an average of that obtained by applying the first two of Eqs 1 to the fluoride salt and NaK streams

$$(1) \qquad \begin{aligned} q &= w_F\, c_F\, \Delta t_F \\ &= w_N\, c_N\, \Delta t_N \\ &= U_o\, A_o\, \Delta t_{LM} \end{aligned}$$

where the subscripts F and N refer to the fluoride salt and the NaK respectively The insulation heat loss from the heat exchanger was neglected since it was in actuality less than 1% The over all heat transfer coefficient was calculated from the third of Eqs 1

$$(2) \qquad U_o = \frac{q/A_o}{\Delta t_{LM}}$$

The adjustable probe located 16 diameters down stream from the fluoride inlet provided the outer surface temperature of the center tube from the outer surface temperature the inside surface temperature was determined by using the conduction equation

$$(3) \qquad t_{wF} = t_{wN} + \frac{q_a \ln \frac{D_o}{D_i}}{2\pi k_w L}$$

A logarithmic axial distribution of temperature was assumed for calculating the stream temperature opposite the measured wall temperature Derivations of the equations for obtaining these temperatures are presented in Appendix 1 The following equations were then used to arrive at a film heat transfer coefficient

$$(4) \qquad h_F = \frac{q_a}{A_i[t_{F(0\ 4)} - t_{wF}]}$$

and

$$(5) \qquad h_N = \frac{q_v}{A_o[t_{wN} - t_{N(0\ 4)}]}$$

An individual heat transfer coefficient may be distinguished from the film coefficients given above in that it is obtained by separation of the over all coefficient defined in Eq 2 Some such separation process is always required when the difficult problem of measuring surface temperature is not attempted In this case the valuable graphical analysis of the over all heat transfer coefficient attributed to Wilson by McAdams[2] is useful The analysis is based on the premise that a plot of $1/U_o$ vs $1/v^{0\ 8}$ will produce a straight line if one of the fluid velocities is held constant and the other is varied over a specific range of values Wilson s method was applied to the data of this experiment as shown in Fig 5 where $1/U_o$ is plotted against $1/v_N^{0\ 8}$ The run with the greatest number of values for NaK velocity was used to

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[1] *Physical Property Charts for Some Reactor Fuels Coolants and Miscellaneous Material (3rd Edition)* ORNL CF 53 3-261 (March 20 1953)

[2] W H McAdams *Heat Transmission* 2d ed p 273 McGraw Hill New York 1942

establish the slope of the lines The lines were extrapolated to $1/v_N^{0\ 8} = 0$ which was equivalent to letting the NaK velocity approach infinity in which case the NaK film resistance $1/h_N$ approached zero

An individual heat transfer coefficient for the fluoride salt was then separated from the extrapolated over all coefficient at $1/v_N^{0\ 8}$ by using the equation (derived in Appendix 2)

$$(6) \qquad h_F = \frac{1\ 22}{\frac{1}{U_{oo}} - 0\ 0000788}$$

By assuming the value of h_F to be constant along each of the Wilson lines an individual coefficient for NaK was separated form the over all coefficient by using the following equation (derived in Appendix 2)

$$(7) \qquad h_N = \frac{1}{\frac{1}{U_o} - \frac{1\ 22}{h_F} - 0\ 0000788}$$

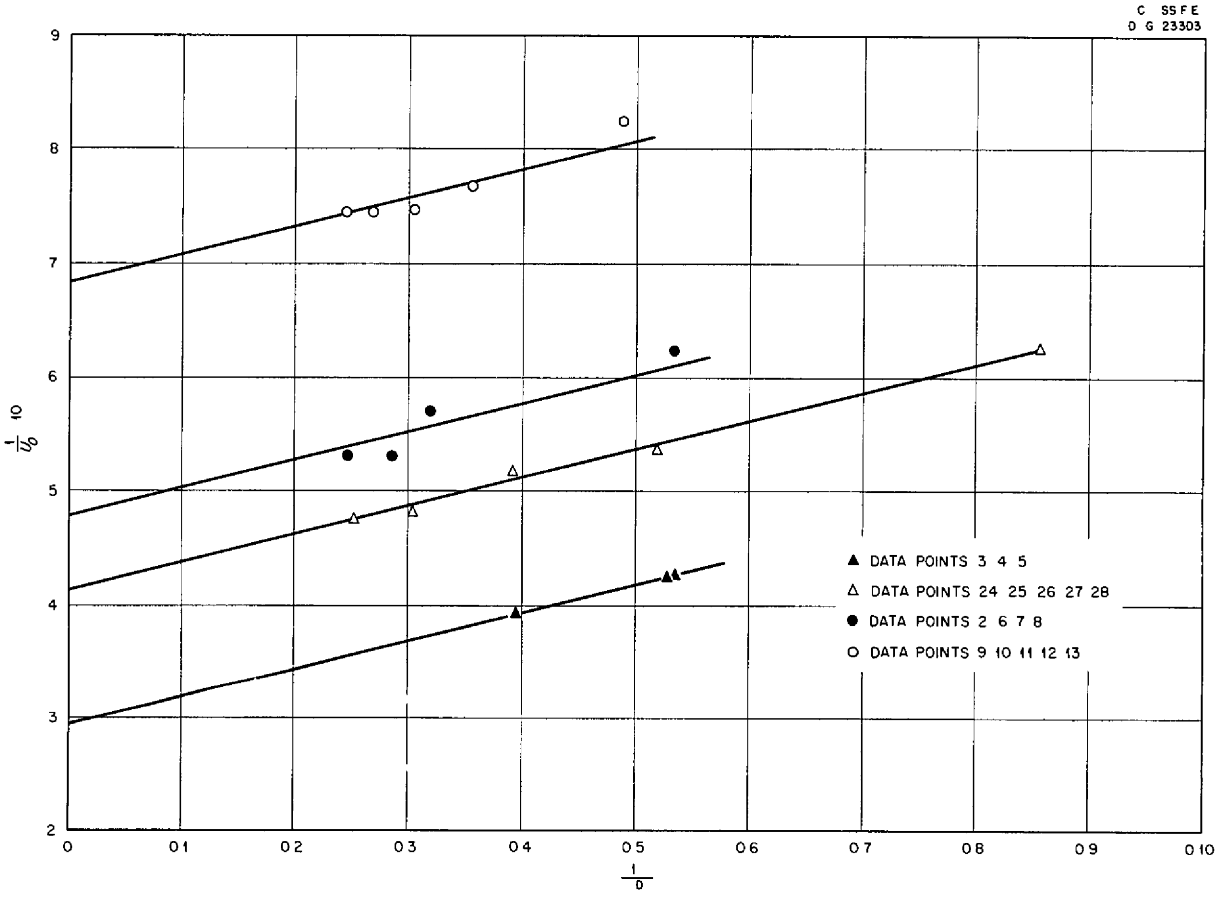

Fig 5 Wilson Line Plot

CORRELATION OF DATA

Dimensional analysis of the physical properties together with the hydrodynamic and geometric factors affecting heat transfer between a turbulently flowing fluid and a bounding surface such as a tube gives a product function of the Nusselt Reynolds and Prandtl moduli The function is usually written as

$$(8) \qquad \mathrm{Nu} = C\mathrm{Re}^{n}\mathrm{Pr}^{p}$$

The relationships of these parameters for ordinary fluids such as water gases or oils as differentiated from liquid metals have been empirically determined from the data of many experimental investigations The generally accepted value for the exponent n is 0 8 However for the constant C and the exponent p there is variation in the evidence the values depend on whether the fluid is being heated or cooled on the magnitude of the fluid viscosity and on whether the evaluation is based on the bulk temperature of the stream or on an average of this temperature and the surface temperature

McAdams recommends[3] for fluids of high viscosity that is presumably higher than twice that of water the Colburn equation

$$(9) \qquad \mathrm{Nu} = 0\ 023\ \mathrm{Re}_f^{0\ 8}\mathrm{Pr}_f^{1/3}$$

or that of Sieder and Tate

$$(10) \qquad \mathrm{Nu} = 0\ 027\left(\frac{\mu}{\mu_w}\right)^{0\ 14}\mathrm{Re}^{0\ 8}\mathrm{Pr}^{1/3}$$

For these equations the Reynolds modulus should be in excess of 10 000 The viscosity correction term $(\mu/\mu_w)^{0\ 14}$ compensates for the variation in the temperature difference between the bulk temperature of the stream and that of the wall In the transition range of Reynolds moduli from approximately 2 100 to 10 000 called by McAdams the dip region [4] there is a dependency on the length to diameter (L/D) ratio of the heat exchange surface the amount being a function of the Reynolds modulus Eckert[5] states that the equation of Hausen

$$(11) \qquad \mathrm{Nu} = 0\ 116\left(\frac{\mu}{\mu_w}\right)^{0\ 14}\left(\mathrm{Re}^{2/3} - 125\right)\mathrm{Pr}^{1/3}\left[1 + \left(\frac{D}{L}\right)^{2/3}\right]$$

will satisfactorily reproduce values in the Reynolds modulus range from 2300 to 6000 Equation 11 is also useful for the entrance region of tubes where the velocity profile has not developed fully although the Reynolds modulus based on mean stream velocity is sufficiently high for full development

The theoretical approach to turbulent heat transfer in a tube has advanced to the stage where experimental values can be predicted with very good agreement von Karman s postulation of three zones in the flow field namely the laminar sublayer the buffer layer and the turbulent core was largely responsible for the advance Although the theoretical approach was not used in this work reference will be made to an extension of von Karman s theory by Boelter Martinelli and Jonassen (as described by Eckert[6]) and by Martinelli [7] The extension concerns the temperature ratio $(t_w - t)/(t_w - t_c)$ which was determined by them and plotted as a function of Reynolds and Prandtl moduli The result gives the amount of deviation expected when center line temperature rather than bulk temperature is used to evaluate physical properties in correlating experimental heat transfer data

The correlations discussed above for ordinary fluids do not hold for liquid metals which have low viscosity and high thermal conductivity and thus very low Prandtl moduli Thermal conductivity is important even in the turbulent core of the stream where for ordinary fluids it is assumed in the equations that all the heat is transferred by mixing action For heat transfer to liquid metals in a tube Martinelli[8] derived an equation which was later greatly simplified by Lyon [9] but there is as

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[3] *Ibid* p 168

[4] *Ibid* p 167

[5] E R G Eckert *Introduction to the Transfer of Heat and Mass* p 115 McGraw Hill New York 1950

[6] *Ibid* p 125

[7] R C Martinelli Heat Transfer to Molten Metals *Trans Am Soc Mech Engrs* 69 955 (1947)

[8] *Ibid* p 947 959

[9] R N Lyon *Forced Convection Heat Transfer Theory and Experiments with Liquid Metals* ORNL 361 (Aug 19 1949)

yet no abundance of data to substantiate their work

There is no widely accepted procedure for calculating heat transfer to turbulently flowing fluids in annuli whether they are ordinary fluids or liquid metals The usual practice is to apply the tube equations with an equivalent diameter substituted and to add a correction term consisting of the ratio of annulus diameters to some power One equation for liquid metals in annuli corroborated in particular with NaK by Werner King and Tidball (described in the work of Claiborne[10]) is the following

$$(12)\quad \mathrm{Nu}_{an} = [4\ 9 + 0\ 0175(\mathrm{Re} \times \mathrm{Pr})^{0\ 8}] \left(\frac{D_1}{D_o}\right)^{0\ 53}$$

The bracketed quantity is equal to 0 7 of Lyon s expression[9] for Nusselt s modulus in a tube and the diameter ratio correction is recommended by Monrad and Pelton who experimented with ordinary fluids in annular spaces The work of Monrad and Pelton is described by Claiborne[10] and also by McAdams [11]

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[10] H C Claiborne *A Review of the Literature on Heat Transfer in Annuli and Noncircular Ducts for Ordinary Fluids and Liquid Metals* ORNL CF 52 8 166

[11] W H McAdams *Heat Transmission* 2d ed p 201 McGraw Hill New York 1942

TEST RESULTS

A total of 80 data points was taken during the test but only 19 of the points were used in the analysis for this report The remaining data were not used because of fouling that occurred on the fluoride salt side of the heat exchanger as a result of mass transfer of iron from the stainless steel pump parts When the heat exchanger was sectioned a layer was found which built up gradually from the hot end to a thickness of approximately 0 030 in at the cold end Spectrographic analysis showed the layer to be pure iron

The basis for selecting the data points that were analyzed is indicated in Fig 6 where the fluoride salt system pressure drop is plotted as a function of volume flow rate The points are compared with a theoretically calculated curve of pressure drop vs volume flow rate The chosen points fall on the curve representing an unfouled condition while the rejected points lie considerably above this curve The sequence of the measurements can be traced Instances can be seen where pressure drop increased sharply without increase in flow and in other cases where pressure drop remained constant while flow increased

The data points used in the analysis and the pertinent calculated quantities are tabulated in Table 1 Physical properties of the fluoride salt and the NaK are plotted as functions of temperature in Appendix 3 A sample calculation of data point 4 is presented in Appendix 4

The fluoride salt flow rate was varied from 1 to 5 gpm and the system pressure drops for these flows were respectively 5 to 55 psi The NaK flow rate was varied from 1 7 to 9 25 gpm the NaK system pressure drop was not measured Reynolds numbers for the ranges of flow rates given were 4 400 to 21 000 for the fluoride salt and 21 000 to 100 000 for the NaK

Limits of the over all heat transfer coefficient based on the outside area of the center tube were 1140 and 2550 Btu/hr ft^2 F Fluoride salt film coefficients from 2000 to 8200 Btu/hr ft^2 F were calculated

Heat fluxes at the outer surface of the center tube from 196 000 to 484 000 Btu/hr ft^2 were obtained

Minimum and maximum fluid velocities in the heat exchanger were 8 to 30 fps for the fluoride salt and 1 to 6 5 fps for the NaK Fluoride salt temperature at the heat exchanger inlet was varied from 1200 to 1400°F and the corresponding outlet NaK temperature was varied from 1050 to 1250°F The range of the axial temperature differences through the heat exchanger was 10 to 42°F for the fluoride and 37 to 300°F for the NaK The logarithmic mean temperature difference varied from 172 to 305°F

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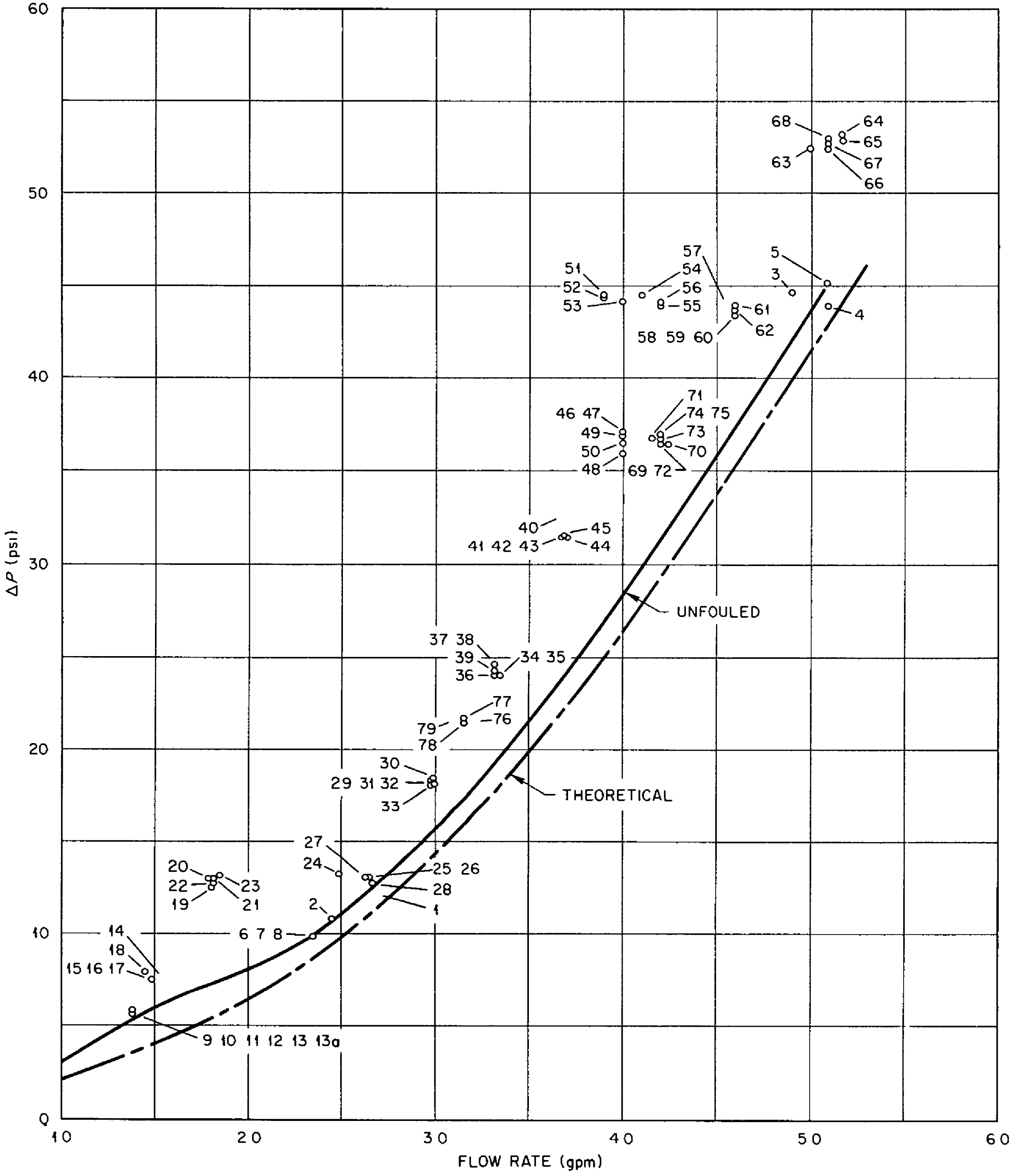

Fig 6 Fluoride Salt System Pressure Drop vs Flow Rate for Each Run

TABLE 1 MEASURED AND CALCULATED RESULTS OF HEAT TRANSFER EXPERIMENTS

MEASURED OR CALCULATED QUANTITY	DATA POINTS (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(13)	(24)	(25)	(26)	(27)	(28)
1	1220 5	1343 3	1323 0	1323 7	1321 5	1317 1	1328 8	1330 8	1315 7	1332 8	1333.4	1333 7	1333.4	1334 2	1429 1	1419 3	1423 0	1420 8	1405 3
*N*1	1154 5	1140 2	1181 9	1179 8	1164 5	1102.4	1118 3	1126 0	1057 4	1058 2	1057 1	1053.2	1054 6	1055 2	1267.4	1232 7	1228.4	1222 9	1200 7
wN	1151 9	1185 1	1195 0	1201.4	1203 5	1115 0	1142 9	1151 9	1083.4	1053 9	1053 6	1049 8	1053 5	1056 1	1253.3	1218 7	1217 6	1214 1	1214 5
Δt_F	10 1	26 8	14 8	14 6	15 6	27 2	29 8	28.3	37 9	41 3	41 5	42.3	41 9	42 4	25.3	26 9	27 0	28 4	27 6
Δt_N	300 0	82 9	108 7	111 9	84 8	57 1	48 2	38 5	81 4	59 8	49 9	43 0	37.4	37 0	150 8	96 6	71.4	54.2	46 6
w_F	4580	4060	8110	8450	8450	3810	3810	3810	2300	2300	2300	2300	2300	2300	4050	4325	4325	4290	4340
w_N	2250	1170	1180	1160	1700	2235	2560	3060	1320	1960	2405	2780	3120	3120	635	1196	1700	2360	2950
q_F	14 320	33 700	37 200	38 240	40 850	32 150	35 200	33 420	27 000	29,400	29 600	30 150	29 900	30 200	31 780	36 040	36 200	37 750	37 100
q_N	16 720	24 000	31 800	32 190	35 750	31 640	30 600	29 200	26 600	29 050	29 760	29 620	28 950	28 620	23 750	28 620	30 040	31 700	34 100
q	15 520	28 850	34 500	35 220	38 300	31 895	32 900	31 310	26 800	29 225	29 680	29 885	29 425	29 400	27 765	32,330	33 120	34 725	35 600
Δ_{LM}	172.4	230 2	184 1	188 6	189.6	230 0	220 6	209 9	279 4	284 0	280 2	280 9	276.4	276 9	218.6	219 9	216 1	210.3	214 4
U	1138	1582	2362	2357	2553	1750	1882	1882	1212	1300	1338	1342	1342	1340	1600	1858	1931	2080	2096
F(0 4)	1218.3	1333 4	1318 0	1318 8	1315 9	1306 7	1317 0	1319 6	1301 1	1316 7	1316 8	1316 8	1317 8	1316 5	1420.3	1410 3	1412 8	1409 9	1394 6
N(0 4)	1091.2	1111 5	1145.6	1142 3	1134.3	1080 6	1099 2	1110 8	1026 2	1034 8	1037 2	1032 6	1040 6	1039 8	1215.4	1200.4	1197 1	1202 0	1182 6
wF	1168 2	1215 5	1231 2	1236 6	1243 7	1148 5	1177 5	1184 8	1111 6	1084 7	1084 8	1081 2	1084 5	1087 0	1282.4	1252 7	1252.4	1250 6	1251 9
b_F	4780	3785	6150	6620	8190	3110	3640	3590	2182	1950	1977	1961	1950	1980	3108	3165	3182	3360	3855
b_N	3230	4950	8830	7520	7160	11 700	9500	9610	5910	19 320	22 840	21 970	28 800	22 800	9240	22,280	20 400	36 200	14 100
$b_{F(W\ I\ \ )}$			5740	5740	5740	3055	3055	3055	2025	2025	2025	2025	2025	2025	3672	3672	3672	3672	3672
$b_{N(W\ I\ \ )}$			7700	7500	10 100	10 880	19 230	19 230	7040	11 570	15 400	16 120	16 120	15 880	4700	8580	9430	14 600	/ 15 400
N $_F$	8 12	6 25	10 30	11 17	13 80	5 25	6 15	6 01	3 72	3 26	3 31	3 28	3.26	3 32	4 78	4 86	4 86	5 16	6 01
N $_N$	8 03	12 3	21 95	18.45	17 80	29 10	23 60	23 64	14 80	48.3	57 1	54 8	71 9	57 0	22 83	55 15	50 5	89 50	34 95
N $_{F(W\ I\ \ )}$			9 55	9 55	9 55	5 16	5 16	5 16	3 39	3 39	3 39	3 39	3 39	3 39	5 64	5 64	5 64	5 64	5 64
N $_{N(W\ I\ \ )}$			19 14	18 73	25 1	26 1	47 8	47 4	17 60	28 8	38 4	40 2	40 2	39 65	11 63	21 2	23 35	36 1	38.15
R $_F$	9040	10 260	19 970	20 800	20 620	9100	9300	9380	5450	5640	5640	5640	5640	5640	12 200	12 800	12 880	12 700	12 470
R $_{Ff}$	8610	9080	18 170	19 080	19 180	7680	8000	8090	4435	4400	4400	4390	4400	4400	10 680	10 880	10 980	10 750	10 780
R $_N$	72 700	38 750	39 100	38 420	56,300	72 100	82 600	101 300	41 600	61 800	75 900	87 700	98 400	98 400	21 580	40 600	57 700	80 100	100 200
P $_F$	6 75	5 13	5 35	5 35	5 43	5 55	5 43	5 35	5 64	5 36	5 36	5 36	5 36	5 36	3 93	4 07	4 02	4 08	4.26
P $_{Ff}$	7 09	5 79	5 87	5 83	5 85	6 57	6 31	6 20	6 91	6 86	6 86	6 89	6 86	6 86	4.50	4 80	4 72	4 81	4.93
P $_N$	0 00611	0 00596	0 00596	0 00596	0 00596	0 00611	0 00611	0 00596	0 0063	0 00629	0 00629	0 00629	0 00629	0 00629	0 00579	0 00579	0 00579	0 00579	0 00580

N mb i dl l whi h d k h f h b Fi ur 6.
R me reme d l l i f d p i 13

DISCUSSION OF RESULTS

The fluoride salt results are compared with Eq 9 in Fig 7 and with Eqs 10 and 11 in Fig 8 A least squares analysis of the data in Fig 7 determines a line to within 4% of Eq 9 while the averaging line compared with Eqs 10 and 11 is approximately 20% low It appears then that evaluating the physical constants at an average of the bulk temperature and the wall temperature produces a better comparison of the results for the fluoride salt with correlating equations for ordinary fluids

The scatter of the fluoride salt data is no doubt a reflection of the erratic nature of the heat balances Although the axial temperature differences measured were small and would result in large percentage errors for a small discrepancy in absolute value they would tend to be consistent The electromagnetic flowmeter readings for the NaK would likewise be consistent even if in error The fluoride salt flow rate on the other hand although measured with an accurately calibrated venturi was quite likely the cause of the scattering The pressure measuring technique on this venturi involved closely controlling liquid levels in the transmitters by means of floats and automatically operated solenoid gas valves

The length to diameter ratio of the center tube warrants some consideration here For short tubes where the velocity profile and boundary layer have not developed fully the heat transfer coefficients will be greater than those for established flow Investigations cited by Brown and Marco[12] indicate the limiting (L/D) ratio for this condition to be 40 Hoffman[13] shows entrance length that is number of tube diameters where the film coefficient is 1 1 times the established value plotted as a function

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[12] A I Brown and S M Marco *Introduction to Heat Transfer* 2d ed p 110 McG aw Hill New York 1951

[13] H W Hoffman *Turbulent Forced Convection Heat Transfer in Circular Tubes Containing Molten Sodium Hydroxide* ORNL 1370 (Oct 3 1952)

[redacted]

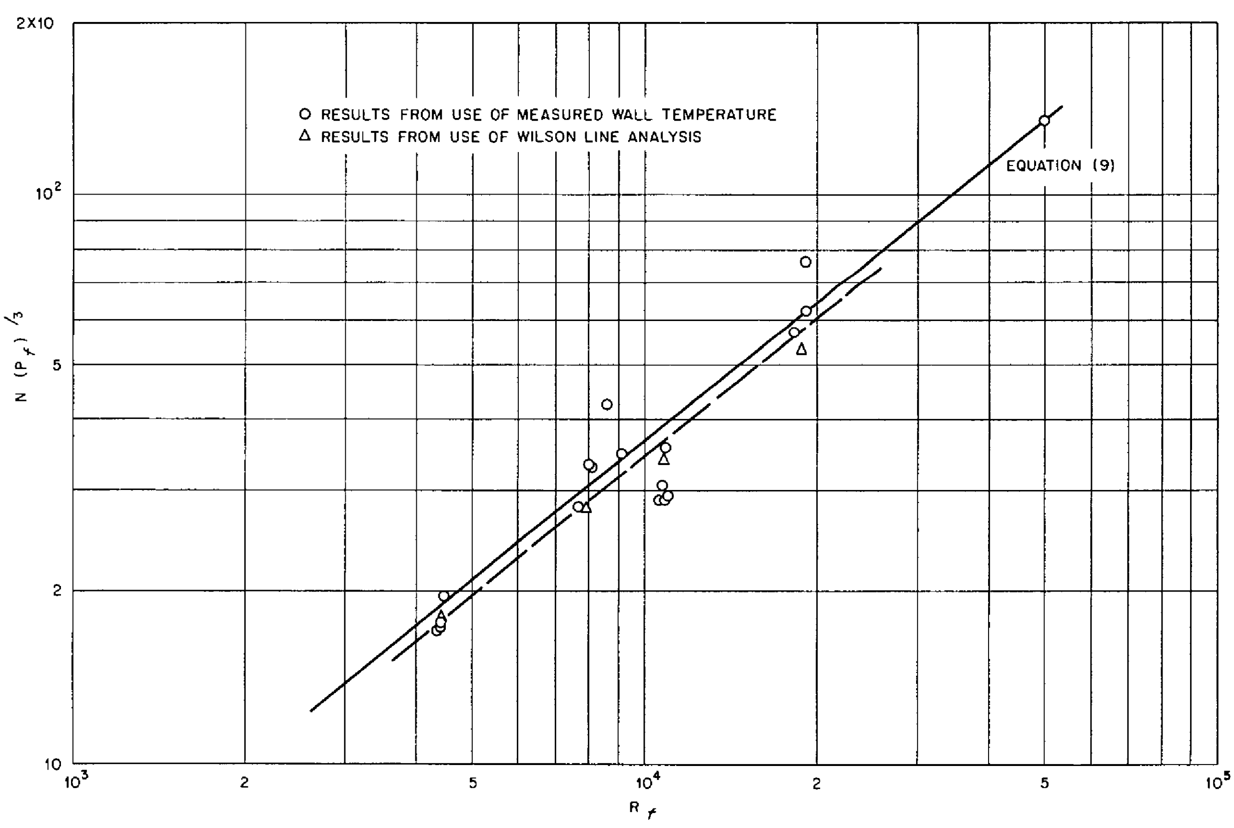

Fig 7 Comparison of Fluoride Salt Results with the Colburn Equation

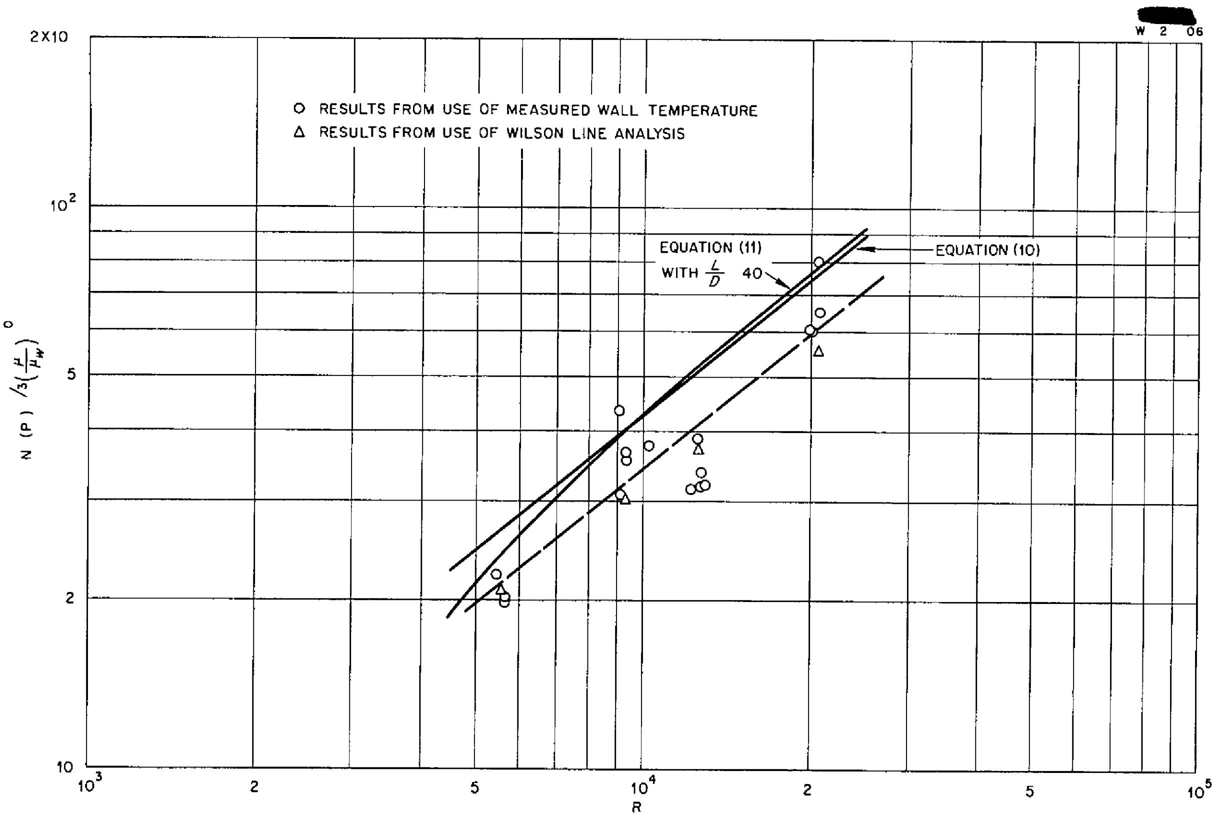

Fig 8 Comparison of Fluoride Salt Results with the Sieder and Tate Equation and with the Hausen Equation

of Reynolds modulus times Prandtl modulus for molten sodium hydroxide Since the fluoride salt has a comparable Prandtl modulus the plot should be applicable and for the range of data of this experiment entrance lengths up to 50 are indicated Therefore it would be expected that the fluoride salt results would be slightly high and it is possible that such a condition is masked by the fouling that occurred

Another point to be discussed is that in all the correlating equations a bulk temperature was used for evaluating the results while center line or axis temperatures were measured in the equipment The work of Boelter *et al* [6,7] when applied to salts indicates the ratio $(t_w - t)/(t_w - t_c)$ for the fluoride salt results to be 0 92 and the ratio for the NaK to be approximately 0 58 For the fluoride salt data therefore the discrepancy involved in using an axis temperature rather than a bulk temperature is small and certainly within the accuracy of the experiment but a large amount of uncertainty arises for the NaK data This uncertainty is borne out in the comparison of the NaK results with Eq 12 in Fig 9 The relationship between axis and bulk temperature however has limited meaning for the NaK stream since it was flowing in an annular space

Failure of the measured NaK heat transfer coefficients to coincide with the theoretical equations does not necessarily reflect on the accuracy of the fluoride salt measurements but it indicates the difficulty involved and the greater precision required in making liquid metal heat transfer correlations

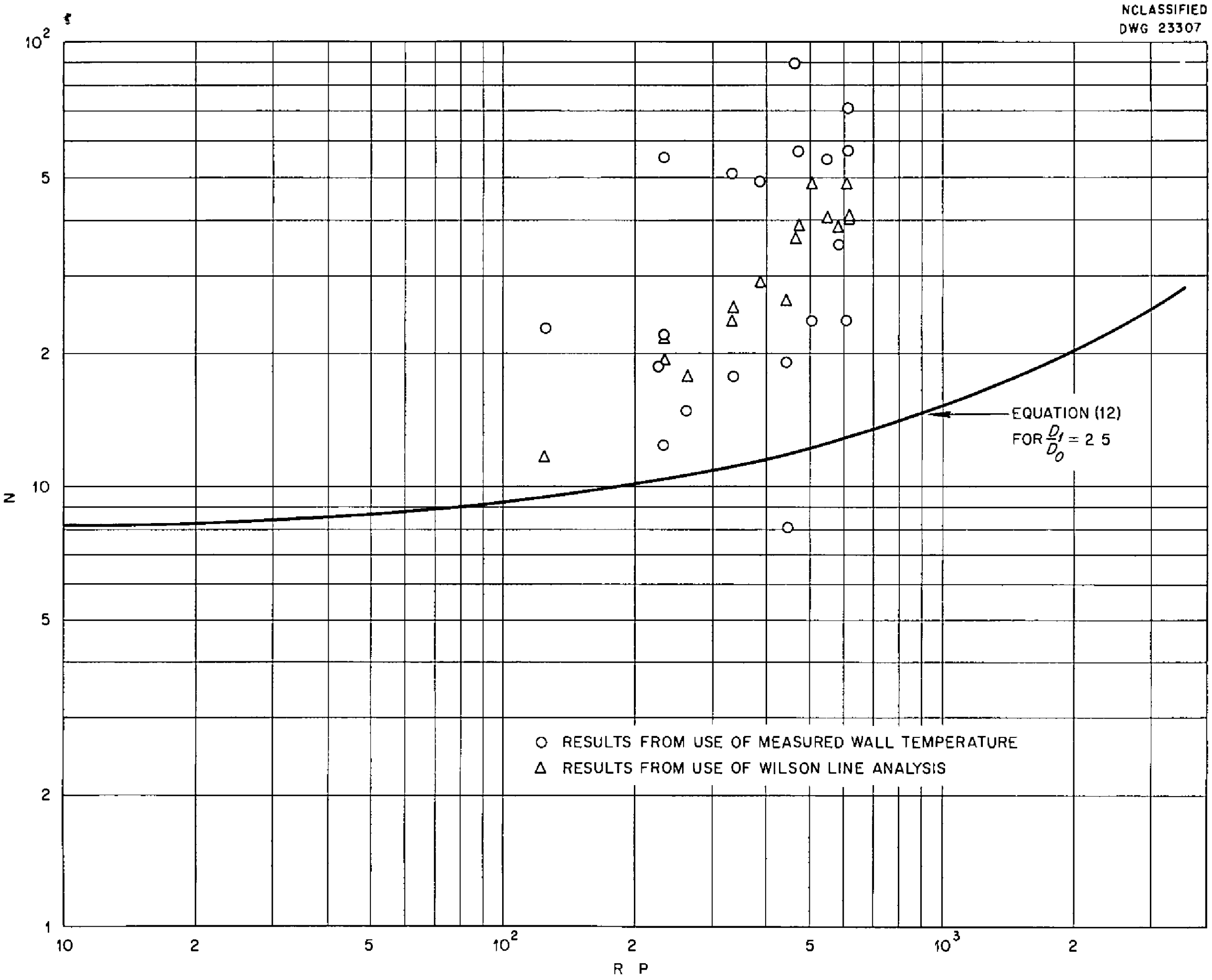

Fig 9 Comparison of the NaK Results with the Werner King and Tidball Equation

CONCLUSIONS

The fluoride salt can be considered to be an ordinary fluid with respect to heat transfer and the equations in the literature can be used to design heat exchange equipment or to predict its performance A similar conclusion was made by other workers at ORNL for the nonuranium bearing fluoride salt mixture NaF KF LiF (11 5 42 0 46 5 mole %)[14] This would not include cases where the fluid had self generating heat sources

Use of iron bearing alloys such as type 316 stainless steel together with material not containing iron in high temperature fluoride salt circulating systems will result in mass transfer of the iron to cold surfaces if there is turbulent flow and if there exist large temperature differences Frictional resistance to flow will be greatly increased and heat transfer performance of equipment will be likewise impaired

The Wilson Line approach can be used to determine heat transfer coefficients of fluoride salts at elevated temperatures in a double tube heat exchanger where sodium potassium alloy is used as the cooling or heating fluid

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[14] H W Hoffman *Preliminary Results on Flinak Heat Transfer* ORNL CF 53 8 106 (Aug 18 1953)

NOMENCLATURE

a	Constant
A_o	Outer area of heat exchanger center tube ft^2
A_i	Inner area of heat exchanger center tube ft^2
A_{an}	Transverse flow area of heat exchanger annulus ft^2
b	Constant
c_F	Specific heat of the fluoride salt Btu/lb °F
c_N	Specific heat of the NaK Btu/lb F
C	Constant
C_F	Product of specific heat and mass flow rate for the fluoride salt Btu/hr °F
C_N	Product of specific heat and mass flow rate for the NaK Btu/hr °F
D	Tube or pipe diameter in general ft
D_i	Inner diameter of center tube ft
D_o	Outer diameter of center tube inner diameter of annulus ft
D_1	Outer diameter of annulus ft
D_e	Equivalent diameter of the annulus or hydraulic diameter $(D_1 - D_o)$ ft
h_F	Film heat transfer coefficient for the fluoride salt Btu/hr ft^2 F
h_N	Film heat transfer coefficient for the NaK Btu/hr ft^2 °F
k_w	Thermal conductivity of center tube wall material Btu/hr ft °F
k_F	Thermal conductivity of the fluoride salt Btu/hr ft °F
k_N	Thermal conductivity of the NaK Btu/hr ft °F
L	Length of heat exchanger center tube ft
dL	Differential length of center tube ft
M	Constant equivalent to $(U_o \pi D_o)$, Btu/hr ft F
n	Constant
p	Constant
q_F	Rate of heat transfer from the fluoride salt stream Btu/hr
q_N	Rate of heat transfer to the NaK Btu/hr
q	Average rate of heat transfer between the fluoride salt and NaK streams Btu/hr
d_q	Differential rate of heat transfer Btu/hr
t	Bulk temperature of stream °F
t_F	Bulk temperature of fluoride °F
t_N	Bulk temperature of NaK F
t_c	Axis or center line temperature of stream °F
t_w	Temperature of tube wall surface °F
t_{F1}	Inlet fluoride axis temperature to heat exchanger F

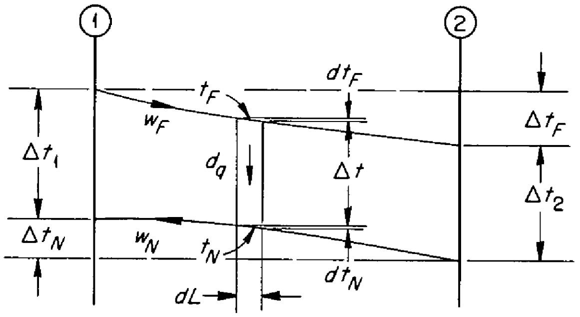
t_{F2}	Outlet fluoride axis temperature from heat exchanger °F
t_{N1}	Outlet NaK axis temperature from heat exchanger °F
t_{N2}	Inlet NaK axis temperature to heat exchanger °F
$t_{F(0\ 4)}$	Fluoride axis temperature at 0 4L °F
$t_{N(0\ 4)}$	NaK axis temperature at 0 4L °F
t_{wF}	Center tube surface temperature on fluoride salt side at 0 4L °F
t_{wN}	Center tube surface temperature on NaK side at 0 4L °F
t_{Ff}	Fictive fluoride salt film temperature at 0 4L $\left[\frac{t_{F(0\ 4)} + t_{wF}}{2}\right]$ °F
dt_F	Differential fluoride salt bulk temperature °F
dt_N	Differential NaK bulk temperature F
U_o	Over all heat transfer coefficient based on outer area of heat exchanger center tube Btu/hr ft^2 °F
U_{oo}	Over all heat transfer coefficient at zero ordinate of Wilson plot Btu/hr ft^2 F
v	Mean flow velocity ft/hr
v_N	Mean NaK velocity in annulus fps
w_F	Mass flow rate of fluoride salt lb/hr
w_N	Mass flow rate of NaK lb/hr
Δt	Temperature difference of fluoride salt and NaK at any cross section of heat exchanger °F
Δt_F	Temperature drop of fluoride salt through the exchanger °F
Δt_N	Temperature rise of NaK through the exchanger °F
Δt_1	Temperature difference of fluoride salt and NaK at hot end of exchanger °F
Δt_2	Temperature difference of fluoride salt and NaK at cold end of exchanger °F
Δt_{LM}	Logarithmic mean of Δt_1 and Δt_2 F
β	Constant $\left(\frac{1}{C_F} + \frac{1}{C_N}\right)$ hr °F/Btu
π	Constant 3 1416
ρ	Mass density evaluated at bulk temperature lb/ft^3
ρ_F	Mass density of fluoride salt evaluated at axis temperature lb/ft^3
ρ_N	Mass density of NaK evaluated at axis temperature lb/ft^3
μ	Absolute viscosity evaluated at bulk temperature lb/hr ft
μ_F	Absolute viscosity of fluoride salt evaluated at axis temperature lb/hr ft
μ_N	Absolute viscosity of NaK evaluated at axis temperature lb/hr ft
μ_{Ff}	Absolute viscosity of fluoride salt evaluated at film temperature lb/hr ft

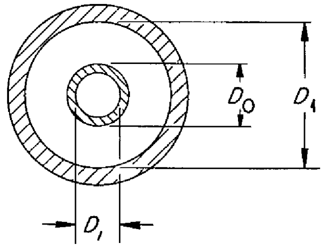
μ_w		Absolute viscosity evaluated at tube surface temperature lb/hr ft
Nu	$\frac{hD}{k}$	Nusselt modulus (tube)
Nu_F	$\frac{h_F D_i}{k_F}$	Nusselt modulus for fluoride salt
Nu_N	$\frac{h_N D_e}{k_N}$	Nusselt modulus for NaK
Nu_{an}	$\frac{hD_e}{k}$	Nusselt modulus for an annular passage
Re	$\frac{\rho D v}{\mu}$	Reynolds modulus
Re_F	$\frac{\rho_F D_i v_F}{\mu_F}$	Reynolds modulus for fluoride salt
Re_{Ff}	$\frac{\rho_F D_i v_F}{\mu_{Ff}}$	Reynolds modulus for fluoride salt with viscosity evaluated at t_{Ff}
Re_N	$\frac{\rho_N D_e v_N}{\mu_N}$	Reynolds modulus for NaK
Pr	$\frac{C_p \mu}{k}$	Prandtl modulus
Pr_F	$\frac{C_F \mu_F}{k_F}$	Prandtl modulus for fluoride salt
Pr_{Ff}	$\frac{C_F \mu_{Ff}}{k_F}$	Prandtl modulus for fluoride salt with viscosity evaluated at t_{Ff}
Pr_N	$\frac{C_N \mu_N}{k_N}$	Prandtl modulus for NaK

APPENDIX 1

EQUATION FOR INTERMEDIATE AXIAL STREAM TEMPERATURE WITH LOGARITHMIC DISTRIBUTION

To evaluate the temperature difference across the film at the point in the heat exchanger where the center wall temperature was measured it was necessary to determine the stream temperature at this position





By assuming a constant over all heat transfer coefficient with steady state operation and neglecting heat losses the basic equation for this configuration is

$$d_q = -w_F c_F dt_F = -w_N c_N dt_N = U_o \pi D_o dL \Delta t \tag{1}$$

For the fluoride stream

$$dt_F = -\frac{U_o \pi D_o dL \Delta t}{w_F c_F} \tag{2}$$

To integrate Eq 2 Δt must be written as a function of L This is done in the usual derivation of the logarithmic mean temperature difference found in the literature therefore

$$\Delta t = \Delta t_1 e^{-\beta M L} \tag{3}$$

The constants have been grouped and simplified as follows

$$w_F c_F = C_F \quad \text{and} \quad w_N c_N = C_N$$

$$\beta = \frac{1}{C_F} - \frac{1}{C_N}$$

$$M = U_o \pi D_o$$

Substituting Eq 3 in Eq 2 gives

$$dt_F = -\frac{M \Delta t_1}{C_F} e^{-\beta M L} dL \tag{4}$$

Integrating and considering the boundary condition when $L = 0$ and $t_F = t_{F1}$ Eq 4 becomes

$$(5) \qquad t_F = t_{F1} - \frac{\Delta t_1}{\beta C_F}\left(1 - e^{-\beta ML}\right)$$

In like manner for the NaK stream

$$(6) \qquad t_N = t_{N1} - \frac{\Delta t_1}{\beta C_N}\left(1 - e^{-\beta ML}\right)$$

Equations 5 and 6 can be written for the position where the wall temperatures were measured at $0.4L$ and also changed to involve only the measured temperature quantities By noting that

$$\beta C_F = 1 - \frac{\Delta t_N}{\Delta t_F} \quad \text{and} \quad \beta C_N = \frac{1 - \dfrac{\Delta t_N}{\Delta t_F}}{\dfrac{\Delta t_N}{\Delta t_F}}$$

and by using Eq 5

$$(7) \qquad t_{F(0.4)} = t_{F1} - \frac{\Delta t_1}{1 - \dfrac{\Delta t_N}{\Delta t_F}}\left[1 - \left(\frac{\Delta t_2}{\Delta t_1}\right)^{0.4}\right]$$

and by using Eq 6

$$(8) \qquad t_{N(0.4)} = t_{N1} - \frac{\Delta t_1 \dfrac{\Delta t_N}{\Delta t_F}}{1 - \dfrac{\Delta t_N}{\Delta t_F}}\left[1 - \left(\frac{\Delta t_2}{\Delta t_1}\right)^{0.4}\right]$$

APPENDIX 2

DERIVATION OF EQUATIONS FOR WILSON LINE ANALYSIS

In a liquid to liquid heat exchanger where neither fluid changes phase if one of the fluid velocities is held constant and the other is varied over a range of settings in turbulent flow the film coefficient of the fluid at constant velocity can be determined by a graphical method called the Wilson Line or Wilson plot

When the mean temperature of the constant velocity fluid does not vary appreciably the film coefficient will be essentially constant The film coefficient of the other fluid where there are not large changes of physical properties with temperature is a function solely of the velocity

The graphical method was used in this experiment to obtain coefficients of the fluoride salt and thus separate the over all heat transfer coefficient to obtain a NaK film coefficient If the series resistance concept is used the over all coefficient is related to the film coefficients as follows

(1)
$$\frac{1}{U_o} = \frac{D_o}{h_F D_i} + \frac{D_o \ln \frac{D_o}{D_i}}{2k_w} + \frac{1}{h_N}$$

Equation 1 neglects the resistance of any foreign deposits on the heat exchanger walls but such deposits would enter the equation in a term similar to that for the wall resistance that is the middle term in the right side of the expression

The equation relating the NaK coefficient (Eq 12 in the text) reduces to

(2)
$$h_N = a + b v_N^{0\ 8}$$

For $D_o = 0\ 329$ in $D_i = 0\ 269$ in and $k_w = 34\ 8$ Btu/hr ft °F Eq 1 above becomes

(3)
$$\frac{1}{U_o} = \frac{1\ 222}{h_F} + 0\ 0000788 + \frac{1}{a + b v_N^{0\ 8}}$$

Since the NaK velocity is the only significant variable a plot of $1/U_o$ vs $1/(a + b v_N^{0\ 8})$ should produce a straight line For such a plot the constants a and b must be known They could be taken from Eq 12 of the text instead $1/U_o$ was plotted against $1/v_N^{0\ 8}$, as is usually done with ordinary fluids The data of the experiment proved to be fairly well correlated by straight lines

Inspection of Eq 3 above shows that when the term involving $v_N^{0\ 8}$ approaches zero or when the Wilson Line is extrapolated to the zero ordinate it is possible to write for all the intercepts

(4)
$$\frac{1}{U_{oo}} = \frac{1\ 222}{h_F} + 0\ 0000788$$

From Eq 4 it is possible to solve for the fluoride salt film coefficient that is

(5)
$$h_F = \frac{1\ 222}{\frac{1}{U_{oo}} - 0\ 0000788}$$

Since the fluoride salt film coefficient is essentially constant along any of the lines it is possible to separate the NaK film coefficient from any of the over all coefficients Substitution in Eq 1 above gives

$$(6) \qquad h_N = \frac{1}{\frac{1}{U_o} - \frac{1\ 222}{h_F} - 0\ 0000788} = \frac{1}{\frac{1}{U_o} - \frac{1}{U_{oo}}}$$

APPENDIX 3

PHYSICAL PROPERTIES OF THE FLUORIDE SALT NaF ZrF_4 UF_4 (50-46-4 mole %) AND OF SODIUM POTASSIUM EUTECTIC ALLOY

The physical properties of the fluoride salt were taken from the third edition charts of the ANP Physical Properties Group[1] and are represented as a function of temperature in Fig 10 The charts are revised periodically as new data become available The NaK properties given in Fig 11 were taken from the second edition of the *Liquid Metals Handbook*[15]

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[15] R N Lyon (ed) *Liquid Metals Handbook* NAVEXOS P 733 (Rev) (June 1952)

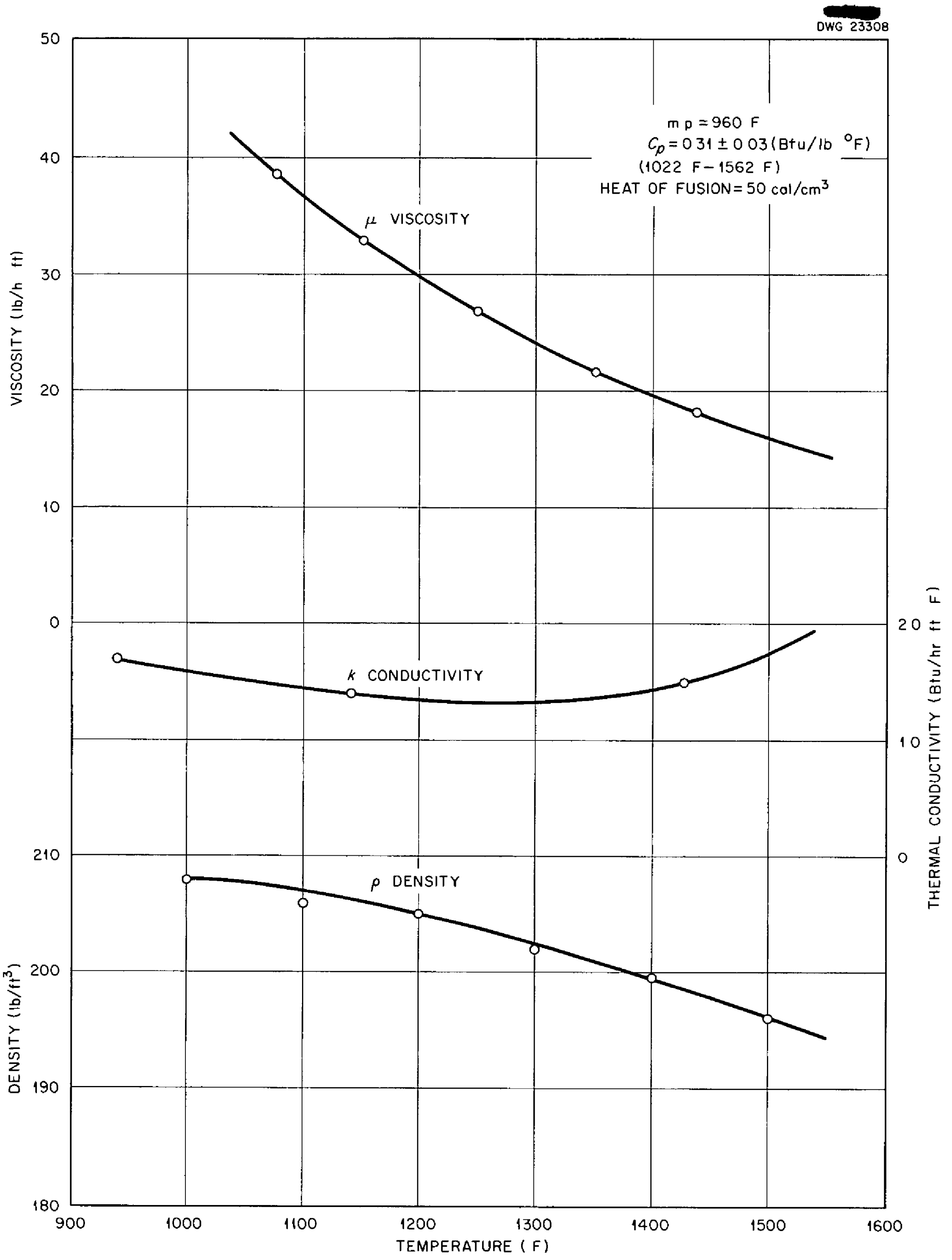

Fig 10 Physical Properties of the Fluoride Salt vs Temperature

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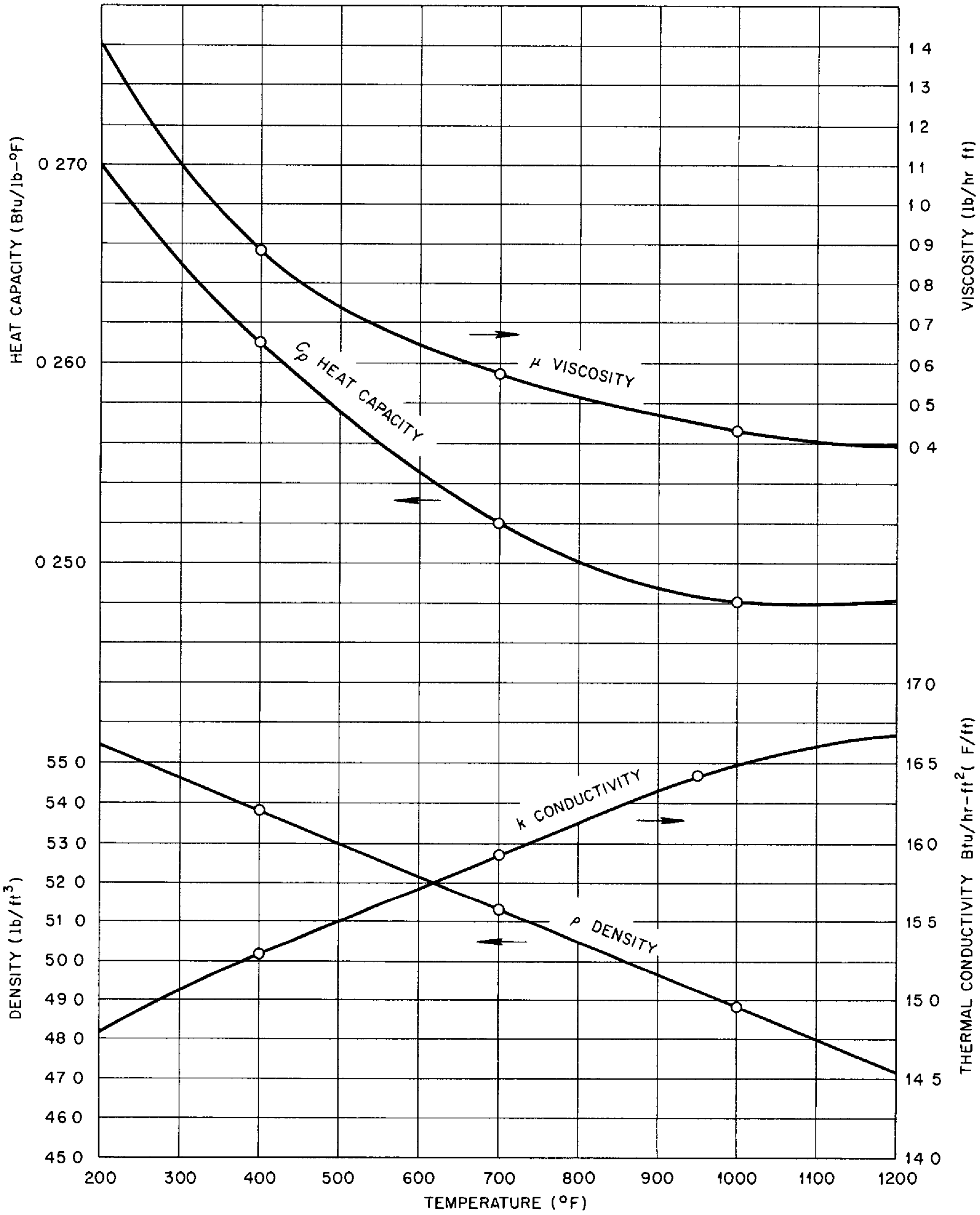

Fig 11 Physical Properties of NaK (56 wt% Na–44 wt% K) vs Temperature

APPENDIX 4

SAMPLE CALCULATION OF DATA POINT 4

Experimental Data

$$t_{F1} = 1323\ 7^\circ\mathrm{F}$$
$$t_{F2} = 1309\ 1^\circ\mathrm{F}$$
$$t_{N1} = 1179\ 8^\circ\mathrm{F}$$
$$t_{N2} = 1067\ 9^\circ\mathrm{F}$$
$$w_F = 8450\ \mathrm{lb/hr}$$
$$w_N = 1160\ \mathrm{lb/hr}$$
$$t_{wN} = 1201\ 4^\circ\mathrm{F}$$

Heat Balance

$$\begin{aligned} q_F &= w_F c_F (t_{F1} - t_{F2}) \\ &= (8450)(0\ 31)(14\ 6) = 38\ 240\ \mathrm{Btu/hr} \end{aligned}$$

$$\begin{aligned} q_N &= w_N c_N (t_{N1} - t_{N2}) \\ &= (1160)(0\ 248)(111\ 9) = 32\ 190\ \mathrm{Btu/hr} \end{aligned}$$

(Heat loss less than 1% and therefore neglected)

$$\frac{q_F - q_N}{q_F} = \frac{6\ 050}{38\ 240} = 16\%$$

$$q = 35\ 220\ \mathrm{Btu/hr}$$

Over all Heat Transfer Coefficient

$$U_o = \frac{q_{av}}{A_o \Delta t_{LM}}$$

$$\Delta t_{LM} = \frac{(t_{F1} - t_{N1}) - (t_{F2} - t_{N2})}{\ln \dfrac{t_{F1} - t_{N1}}{t_{F2} - t_{N2}}} = \frac{143\ 9 - 241\ 2}{\ln \dfrac{143\ 9}{241\ 2}} = 188\ 6^\circ\mathrm{F}$$

$$U_o = \frac{35\ 220}{0\ 0792(188\ 6)} = 2357\ \mathrm{Btu/hr\ ft^2\ {}^\circ F}$$

Wall Temperatures

$$t_{wN} = 1201\ 4\ \text{(measured)}$$

$$t_{wF} = t_{wN} + \frac{q_{av} \ln \dfrac{D_o}{D_i}}{2\pi k_w L}$$

$$= 1201\ 4 + \frac{35\ 220 \ln \dfrac{0\ 329}{0\ 269}}{2\pi(34\ 8)(0\ 922)} = 1236\ 6^\circ\mathrm{F}$$

Stream Temperatures

$$t_{F(0.4)} = t_{F1} - \frac{\Delta t_1}{1 - \dfrac{\Delta t_N}{\Delta t_F}} \left[1 - \left(\frac{\Delta t_2}{\Delta t_1} \right)^{0.4} \right]$$

$$= 1323.7 - \frac{143.9}{(1 - 7.66)} \; [1 - 1.229] = 1318.8\text{°F}$$

$$t_{N(0.4)} = t_{N1} - \frac{\Delta t_1 \dfrac{\Delta t_N}{\Delta t_F}}{1 - \dfrac{\Delta t_N}{\Delta t_F}} \left[1 - \left(\frac{\Delta t_2}{\Delta t_1} \right)^{0.4} \right]$$

$$= 1179.8 - (4.9)(7.66) = 1142.3\text{°F}$$

Film Coefficients

$$h_F = \frac{q_{av}}{A_i[t_{F(0.4)} - t_{wF}]}$$

$$= \frac{35\,220}{0.0647(82.2)} = 6620 \text{ Btu/hr ft}^2 \text{ °F}$$

$$h_N = \frac{q_{av}}{A_o[t_{wN} - t_{N(0.4)}]}$$

$$= \frac{35\,220}{0.0792(59.1)} = 7520 \text{ Btu/hr ft}^2 \text{ °F}$$

Wilson Line

$$\frac{1}{U_o} = \frac{1}{2357} = 0.000425 \text{ hr ft}^2 \text{ °F/Btu}$$

$$v_N = \frac{w_N}{\rho_N A_{an}} = \frac{1160(144)}{(48.2)(0.448)(3600)} = 2.15 \text{ ft/sec}$$

$$\frac{1}{v_N^{0.8}} = \frac{1}{1.84} = 0.542$$

From Fig. 5 $\dfrac{1}{U_{oo}}$ at $\dfrac{1}{v_N^{0.8}} = 0$ for this line is 0.000292

$$h_F = \frac{1.222}{\dfrac{1}{U_{oo}} - 0.0000788} = 5740 \text{ Btu/hr ft}^2 \text{ °F}$$

$$h_N = \frac{1}{\dfrac{1}{U_o} - \dfrac{1\ 222}{h_F} - 0\ 0000788} = 7500 \text{ Btu/hr ft}^2\ {}^\circ\text{F}$$

Dimensionless Moduli

At $t_{Ff} = 1278^\circ\text{F}$

$$c_F = 0\ 31 \text{ Btu/lb }{}^\circ\text{F}$$

$$\mu_{Ff} = 25\ 2 \text{ lb/hr ft}$$

$$k_F = 1\ 34 \text{ Btu/hr ft }{}^\circ\text{F}$$

$$\text{Nu}_F = \frac{h_F D_i}{k_F} = \frac{6620(0\ 269)}{1\ 34(12)} = 11\ 17$$

$$\text{Re}_{Ff} = \frac{4w_F}{\pi \mu_{Ff} D_i} = \frac{4(8450)(12)}{\pi(25\ 2)(0\ 269)} = 19\ 080$$

$$\text{Pr}_{Ff} = \frac{c_F \mu_{Ff}}{k_F} = \frac{0\ 31(25\ 2)}{1\ 34} = 5\ 83 \qquad (\text{Pr}_F)^{1/3} = 1\ 801$$

$$\text{Nu}_F (\text{Pr}_{Ff})^{-1/3} = 6\ 2$$

At $t_{F(0\ 4)} = 1319^\circ\text{F}$

$$c_F = 0\ 31 \text{ Btu/lb }{}^\circ\text{F}$$

$$\mu_F = 23\ 1 \text{ lb/hr ft}$$

$$k_F = 1\ 34 \text{ Btu/hr ft }{}^\circ\text{F}$$

At $t_{wF} = 1237^\circ\text{F}$

$$\mu_{wF} = 27\ 5 \text{ lb/hr ft}$$

$$\text{Nu}_F = \frac{h_F D_i}{k_F} = \frac{6620(0\ 269)}{1\ 34(12)} = 11\ 17$$

$$\text{Re}_F = \frac{4w_F}{\pi \mu_F D_i} = \frac{4(8450)(12)}{\pi(23\ 1)(0\ 269)} = 20\ 800$$

$$\text{Pr}_F = \frac{c_F \mu_F}{k_F} = \frac{0\ 31(23\ 1)}{1\ 34} = 5\ 35$$

$$(\mathrm{Pr}_F)^{1/3} = 1\ 75$$

$$\left(\frac{\mu}{\mu_w}\right)_F = \frac{23\ 1}{27\ 5} = 0\ 84$$

$$\left(\frac{\mu}{\mu_w}\right)_F^{0\ 14} = 0\ 976$$

$$\mathrm{Nu}_F(\mathrm{Pr}_F)^{-1/3}\left(\frac{\mu}{\mu_w}\right)_F^{-0\ 14} = 6\ 48$$

At $t_{N(0\ 4)} = 1142°\mathrm{F}$

$$c_N = 0\ 248\ \mathrm{Btu/lb\ °F}$$

$$\rho_N = 47\ 7\ \mathrm{lb/ft^3}$$

$$\mu_N = 0\ 4\ \mathrm{lb/hr\ ft}$$

$$k_N = 16\ 65\ \mathrm{Btu/hr\ ft\ °F}$$

$$\mathrm{Nu}_N = \frac{h_N D_e}{k_N} = \frac{7520(0\ 495)}{16\ 65(12)} = 18\ 45$$

$$\mathrm{Re}_N = \frac{\rho_N D_e V_N}{\mu_N} = \frac{47\ 7(0\ 495)(2\ 15)(3600)}{(12)(0\ 4)} = 38\ 420$$

$$\mathrm{Pr}_N = \frac{c_N \mu_N}{k_N} = \frac{0\ 248(0\ 4)}{16\ 65} = 0\ 00596$$

$$\mathrm{Re}_N \times \mathrm{Pr}_N = 229$$