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TECHNICAL REPORT 25
Contract N9onr-85801
Project Designation NR031-364
**THE GENERATION OF STEAM
FROM
LIQUID METAL AT HIGH HEAT FLUXES**
Mine Safety Appliances Company
Callery, Pa.

This document has been reviewed in accordance with
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Date: 8/21/52
By direction of JG Harwood
Chief of Naval Research (Code 623)

MSA

MINE SAFETY APPLIANCES COMPANY
Callery, Pennsylvania

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C O N F I D E N T I A L

TECHNICAL REPORT 25

Contract N9onr-85801
Project Designation NR031-364

THE GENERATION OF STEAM FROM LIQUID METAL
AT HIGH HEAT FLUXES

by

E. C. King

R. C. Andrews

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Copy No. 7

File No. 621

Mine Safety Appliances Company
Callery, Pa.

July 28, 1953

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ABSTRACT

Heat was transferred at fluxes as high as 450,000 Btu/(hr)(sq. ft.) from liquid alkali metal (tubeside) to water (shell side) at pressures ranging from 113 psia to 1203 psia using specially designed double wall stainless steel tubes. A single wall tube was also tested under the same conditions and the outside coefficients were calculated from the overall heat transfer coefficients.

Evaluation of the tube design and bond resistance was made and a method was devised to calculate the performance of such tubes.

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THE GENERATION OF STEAM FROM LIQUID METAL AT HIGH HEAT FLUXES

INTRODUCTION

In the generation of steam the use of alkali liquid metals as the heat transfer agent has created many problems of which boiler tube design is no exception. The primary boiler tube design problem is that of safety. Since the alkali metal and water react quite vigorously when mixed, it becomes necessary that the design be such as to reduce to a minimum the possibility of contact between the materials.

At present there are two tube designs being considered, both consisting of a tube within a tube. The first uses concentric tubes with the thin annular space filled with mercury or some other liquid metal which acts both as a heat transfer medium and as a leak detection system should either the inner or outer tube fail. The second design, and the one about which this report is concerned, also uses concentric tubes; the outside of the inner tube is grooved and the tube is then expanded into the outer tube to effect a tight heat transfer bond. Helium is used in the grooves as a leak detector system.

The latter tube design mentioned above was submitted by the Griscom-Russell Company of Massillon, Ohio who has supplied three single tube steam generators plus an air cooled steam condenser for test purposes. The test program to determine the heat fluxes to be expected when using these double walled tubes as compared to a single walled tube, has been completed and is reported on the following pages.

Towards the end of the last test when a single wall tube was used, a leak developed in the steam generator between the NaK and water. The results of this leak will be found under a separate heading later in this report.

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DESCRIPTION OF THE TUBES

Cross sections of the three tube assemblies are shown in Figure 1. The first tube consisted of a 3/4 in. O.D. by 16 B.W.G. and a 5/8 in. O.D. by 16 B.W.G. type 304 stainless steel tube. The 5/8 in. O.D. tube was milled along its length to give 12 slots 0.070 in. wide and an average depth of 0.025 in. After the outer tube was placed in the steam generator the inner tube was put inside the outer tube and expanded to effect a tight heat transfer bond.

The second tube consisted of a 3/4 in. O.D. by 18 B.W.G. and a 5/8 in. O.D. by 18 B.W.G. type 304 stainless steel tube. The 5/8 in. O.D. tube was knurled to effect 38 grooves approximately 0.016 in. wide and 0.008 in. deep. The inside tube was expanded into the outside as before.

The third tube was a single wall 3/4 in. O.D. by 16 B.W.G. type 304 stainless steel tube.

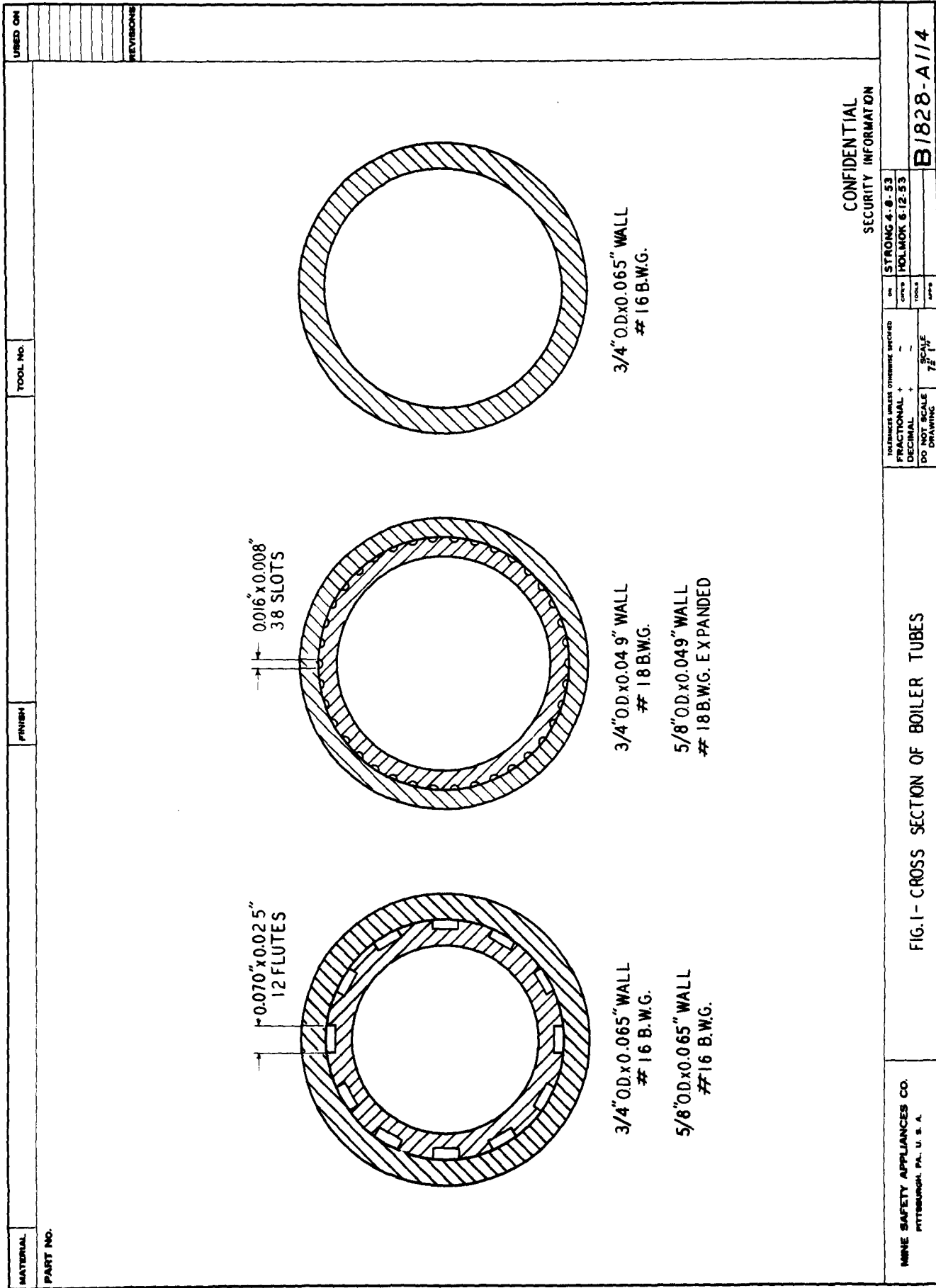
The dimensions of the first and second tube after expansion were measured at the end of the test and are as follows:

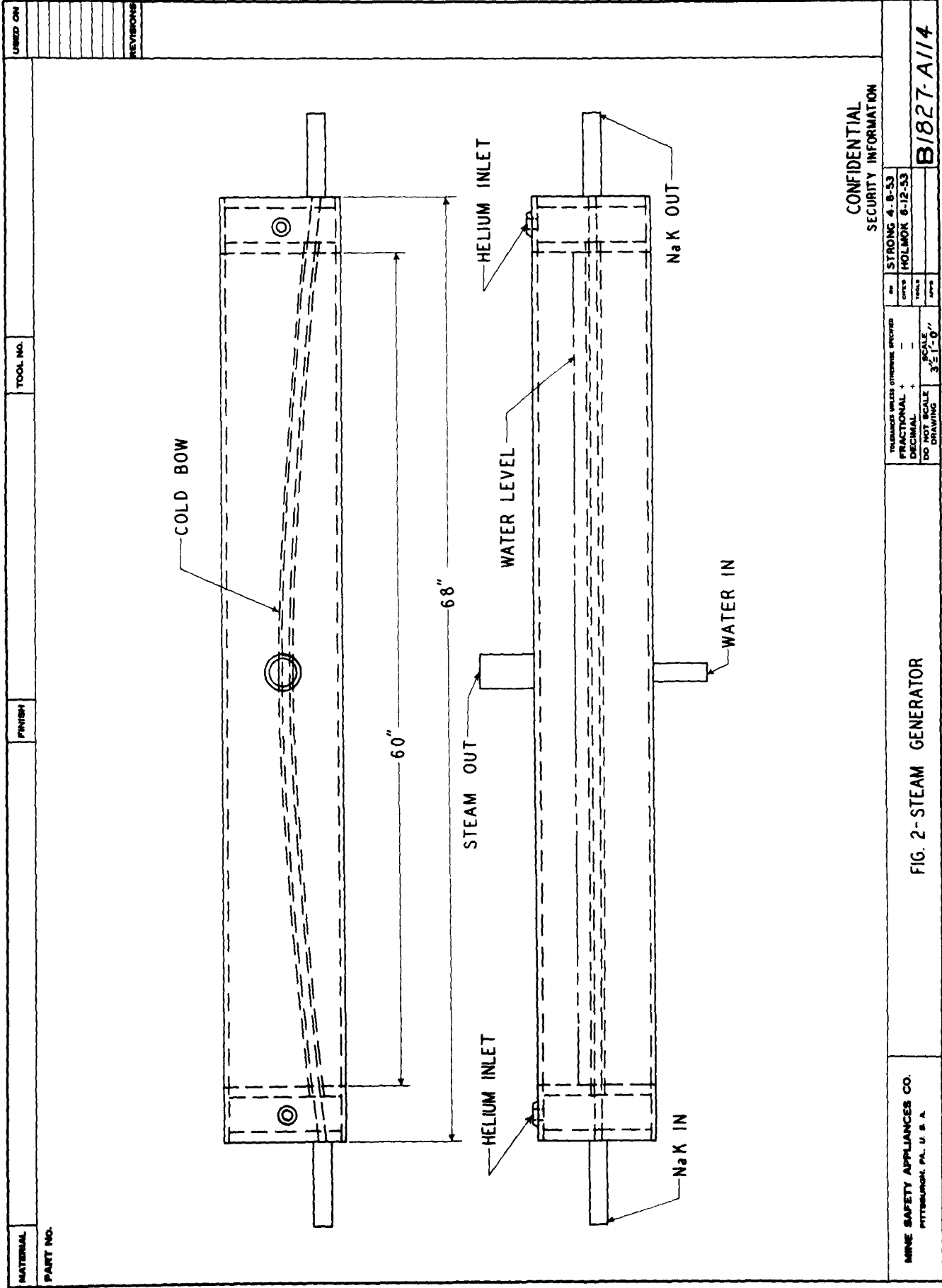
	First Tube	Second Tube
O.D. of the outside tube, in.	0.765	0.756
I.D. of the inside tube, in.	0.510	0.559
The thickness of the outside tube was taken to be its standard dimension, in.	0.065	0.049

The above dimensions were used for all the calculations that follow. The dimensions of the third tube were standard.

DESCRIPTION OF THE STEAM GENERATOR

The steam generator as it was constructed for the first and second tube is shown in Figure 2. The shell was made of 6 in. schedule 40 pipe with two headers on either end. The tube was initially bowed to allow for the differential expansion between the tube and shell. The





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SCALE 3/8" = 1'-0"		B1827-A114
FIG. 2 - STEAM GENERATOR		
MINE SAFETY APPLIANCES CO. PITTSBURGH, PA., U. S. A.		

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water inlet was 3/4 in. pipe entering at the bottom and the steam came off through the 2 in. pipe on the top. The outer tube of the double wall tube was rolled into the inner tube sheets. The inner tube was then inserted into the outer tube and expanded over the entire length of the outer tube. The inner tube was then rolled and seal welded into the outer tube sheet. The seal weld and tube on the outer tube sheet was covered with a 1 in. pipe which made the inlet and outlet pipe connections for the liquid metal.

The same steam generator described above was used for the third tube with the outer tube sheets cut off. The inner tube was rolled but not seal welded into the tube sheet.

The distance between the two inner tube sheets was 5 ft. for all tubes.

DESCRIPTION OF THE SYSTEM

A sketch of the entire system is shown in Figure 3 and a photograph in Figure 4. Starting at the liquid metal pump the NaK was pumped into the furnace up through 40 ft. of 1 in. pipe wrapped in a helix coil. The NaK then left the furnace past a thermocouple and entered the steam generator. After the NaK left the steam generator, it again flowed past a thermocouple, into the expansion tank down through the flowmeter and, finally, back into the pump. All NaK piping outside the steam generator was 1 in. type 304 stainless steel pipe.

The water entered the shell at the bottom and the steam was discharged from the top. The steam was condensed in an air cooled fin tube condenser. The condensate flowed by gravity back into the bottom of the steam generator.

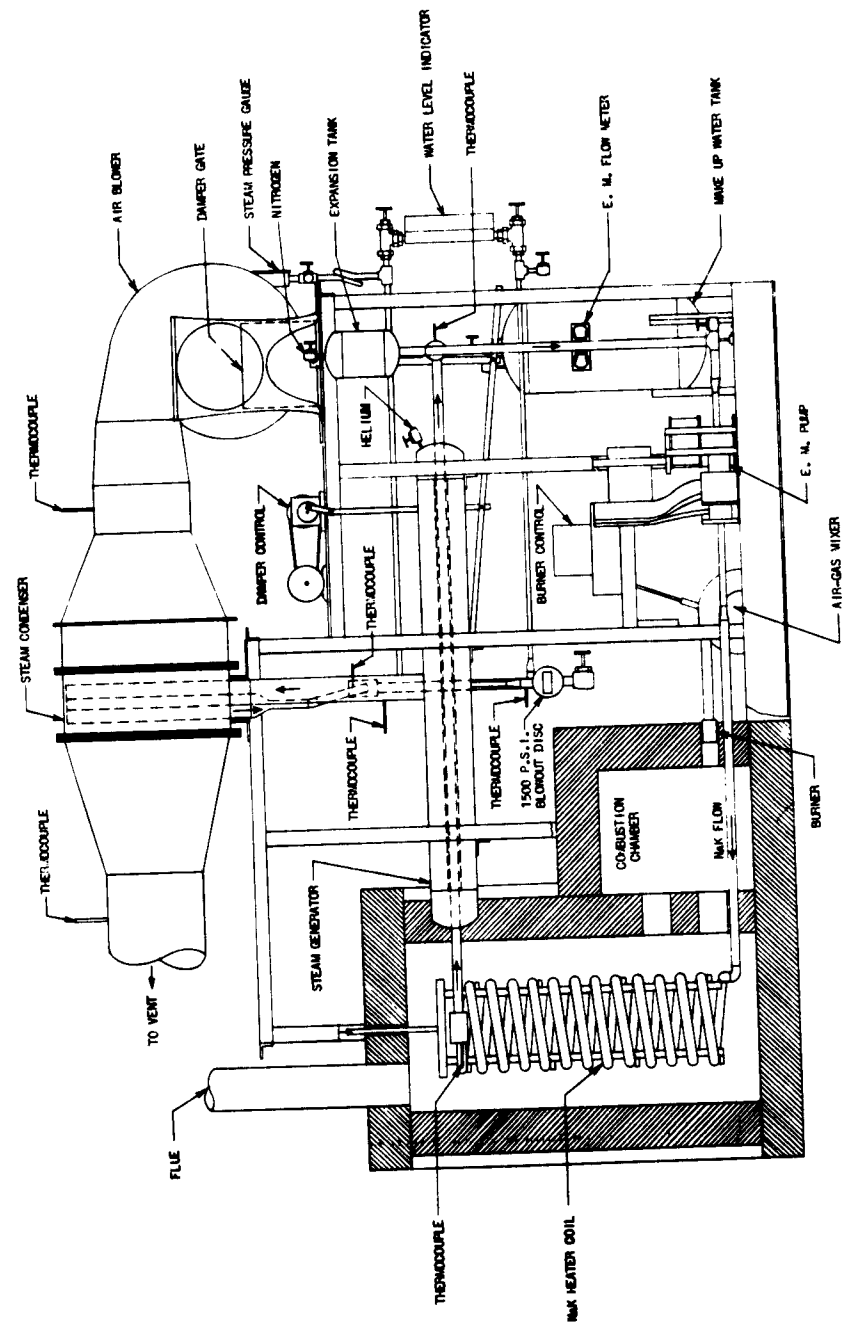
The furnace was heated by burning natural gas. The E. M. pump and E. M. flowmeter were both water cooled. All temperatures, pressures and controls were measured and maintained from a central point.

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Fig. 3 - SINGLE TUBE STEAM GENERATOR

EMERGENCY SAFETY APPLIANCE CO.
PITTSBURGH, PA., U. S. A.

ASSEMBLY
B1227-A114

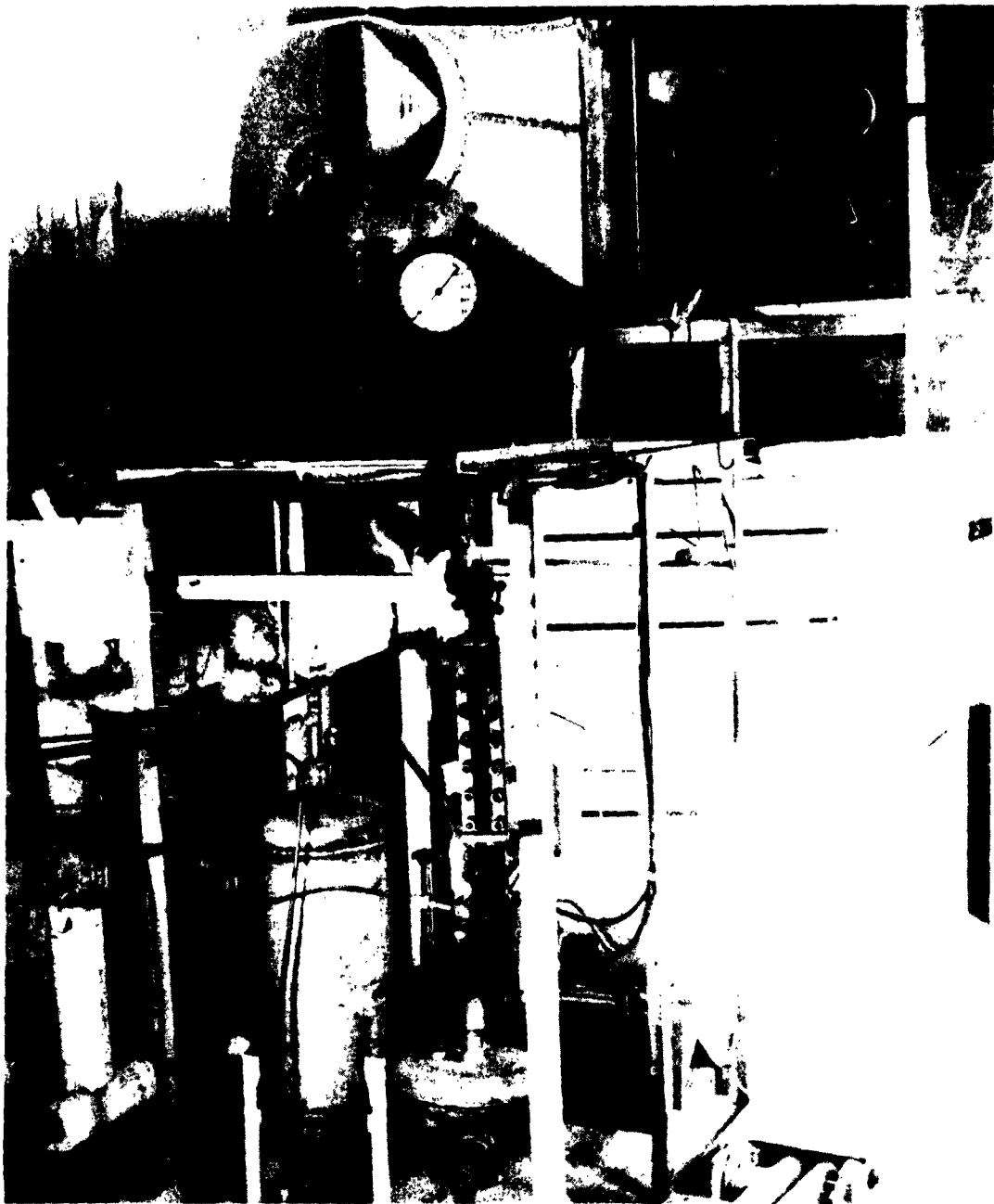


FIG. 4- SINGLE TUBE STEAM
GENERATING SYSTEM

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DESCRIPTION OF THE TEST PROGRAM

The purpose of the test program was to determine the heat flux that could be obtained through double wall tubes in a steam generator. To do this test the heat input to the NaK was varied and the heat extracted from the steam was such as to maintain constant steam pressure. This process was repeated for steam pressures of approximately 100, 300, 500, 700, 900, 1100, and 1200 psi. Runs were made starting at the lowest pressure and the lowest heat flux and completing the range of heat flux as determined by the limit of the equipment before continuing at the next higher pressure. The limit of the equipment was reached when there was no more condensing capacity in the condenser, the temperature at the NaK pump exceeded 1100°F, or the heating capacity of the furnace was reached.

DESCRIPTION OF THE LEAK DETECTING SYSTEM

If at any time a leak developed within either the inner or outer tube of the double wall tube, a helium leak detection system was used to give the alarm so the system could be shut down before further damage would result.

The location of the helium connections is shown in Figure 2. Helium was introduced through a 1/4 in. pipe connection to one of the helium headers and was monitored at the header on the other end, the helium passing through the grooves between the double wall tube. The helium system was sealed off at such pressure that, should a leak develop in the outer tube, steam would flow into the helium. Should a leak develop in the inner tube, the helium would flow into the NaK. A drop in helium pressure would therefore indicate a leak between the NaK and the helium while a rise in helium pressure would indicate a leak between the steam and the helium system. It is impossible when using a double wall tube, to produce a leak between the NaK and the water systems without first going through the helium system. The leak mentioned in the introduction occurred when the single wall tube was being tested. Since this last steam generator had no helium system, the leak was not detected until the generator was drained.

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HEAT FLUXES

The following method was used to calculate the heat fluxes and overall heat transfer coefficients for all three tubes.

Knowing the temperatures of the water and of the NaK entering and leaving the exchanger, the log-mean temperature difference was calculated. This method assumes only a modest change in the overall heat transfer coefficients from one end of the tube to the other which, in this case, is not strictly true; however, any error in this assumption should only show itself as an error in method and not as an error in correlation.

The log-mean temperature difference will then be

$$\Delta T_m = \frac{(T_i - T_o)}{\ln \frac{(T_i - T_{H_2O})}{(T_o - T_{H_2O})}} \quad (1)$$

See list of notations for definitions used in this and later equations.

The average NaK temperature was determined from the temperature of the water plus the overall temperature difference as follows:

$$T_{NaK} = T_{H_2O} + \Delta T_m \quad (2)$$

The total heat transferred was the product of the weight of NaK flowing per hour, the specific heat of the NaK and the temperature drop of the NaK stream through the boiler as follows:

$$q = w C_p (T_i - T_o) \quad (3)$$

where w was found by multiplying the millivolt reading from the electromagnetic flowmeter by a calibration factor depending on the

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temperature of the NaK through the flowmeter and where C_p was the value of specific heat at the average NaK temperature.

Since the heat flux is the quantity of heat transferred divided by the area, which, in this case was chosen as the outside area, then

$$\text{heat flux} = q/A. \quad (4)$$

The overall heat transfer coefficient is the heat flux divided by the overall temperature difference,

$$U = \frac{q/A}{\Delta T_m} \quad (5)$$

A plot of the heat flux vs. the overall temperature difference for the three tubes is shown in Figure 5 and a plot of the overall heat transfer coefficients vs. the overall temperature differences is shown in Figure 6. A tabulation of all the calculations for all three tubes is shown in Tables I, II, and III.

CALCULATION OF THE TEMPERATURE DROP FROM THE OUTSIDE WALL TO THE BOILING WATER FOR THE THIRD OR SINGLE WALL TUBE

The outside film coefficient which includes the steam coefficient and any scale on the tube was calculated using the standard heat transfer equation and solving for h_o .

$$\frac{1}{U} = \frac{D_o}{D_i} \times \frac{1}{h_i} + \frac{(D_o - D_i) \times D_o}{2 k_w \times D_m} + \frac{1}{h_o} \quad (6)$$

The values of h_i were obtained by using Lyon's equation for inside film coefficients (1).

$$\frac{h D}{k} = 7 + 0.025 (P_e)^{0.8} \quad (7)$$

where

$$\frac{h D}{k} = \text{Nusselt number} \quad (8)$$

and

$$P_e = \text{Peclet number} \quad (9)$$

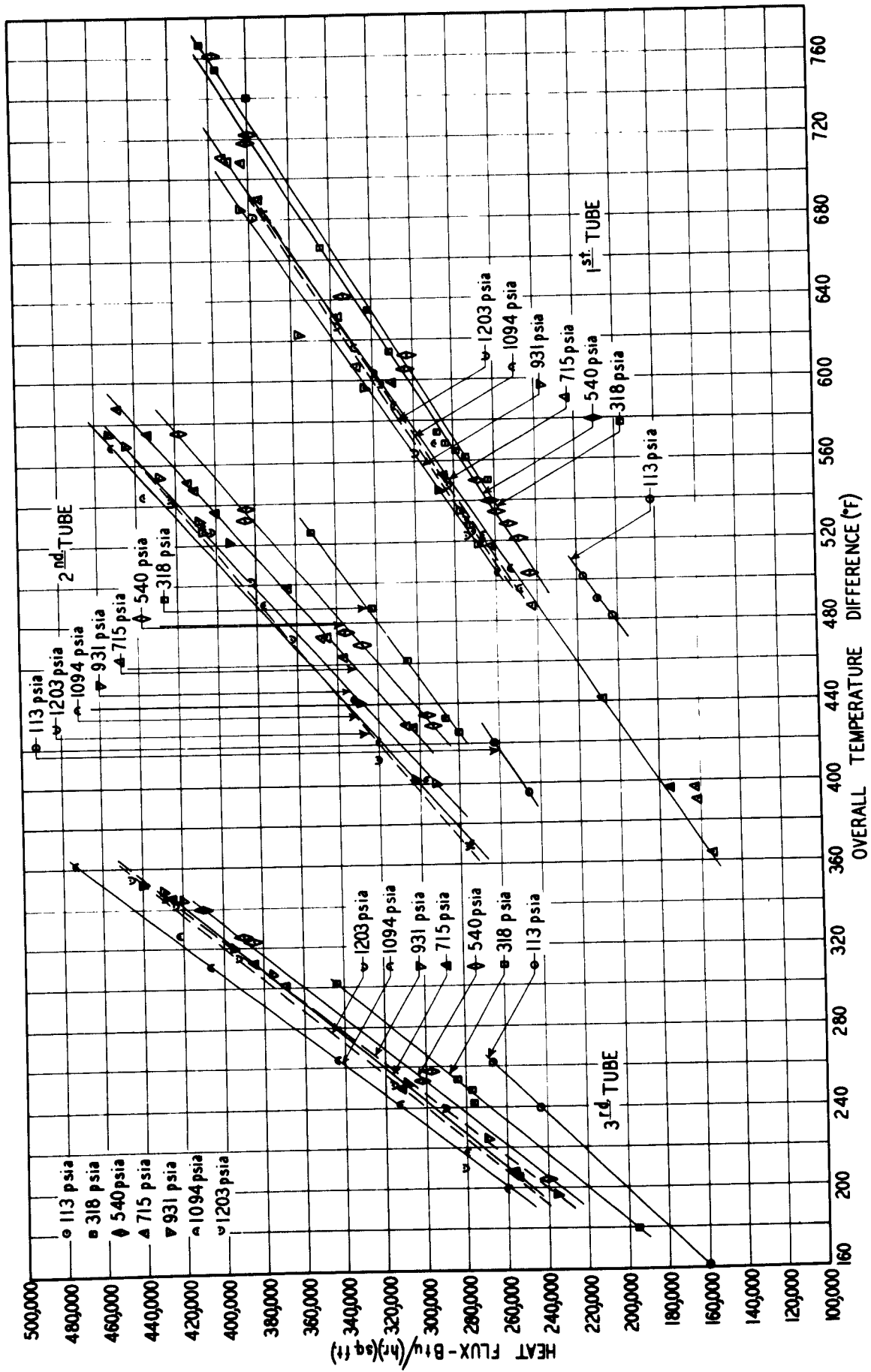


FIG. 5- PLOT OF THE HEAT FLUX THROUGH EACH OF THE THREE TUBES v.s. THE OVERALL TEMPERATURE DIFFERENCE

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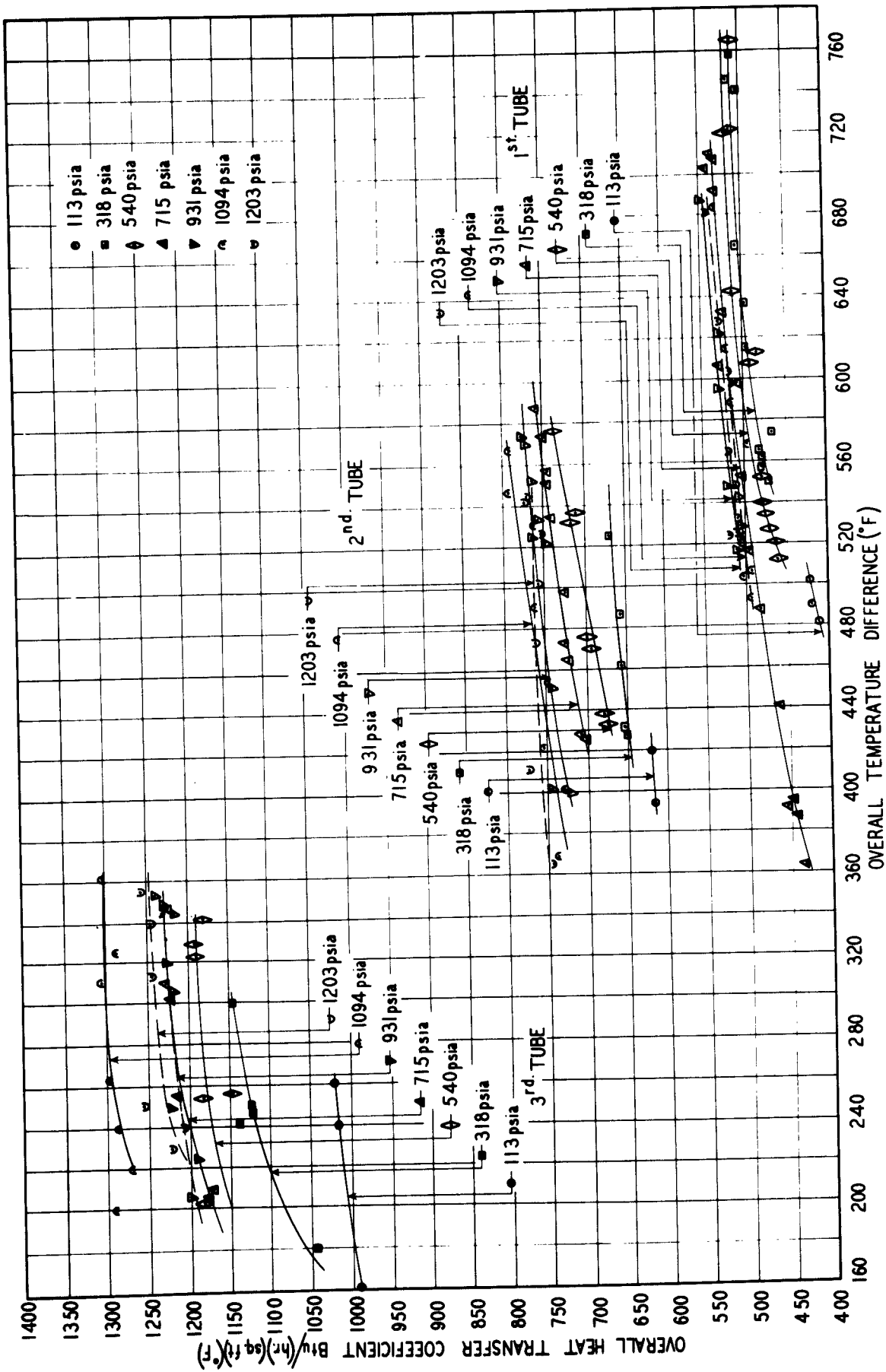


FIG. 6- PLOT OF OVERALL HEAT TRANSFER COEFFICIENT FOR ALL THREE TUBES v.s. THE OVERALL TEMPERATURE DIFFERENCE
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Table 2 - Calculations for the Second or Knurled Tube

Temp of the Water	Temp of the NAK in	Temp of the NAK Out	Temp of the NAK	W	ΔT_m	Average NAK Temperature	Heat Extracted from NAK	Heat Flux	Overall Heat Transfer Coefficient	Overall Heat Transfer Resistance	1/u	NAK Film Coefficient	NAK Resistance	Steam Film and Scale Resistance	Wall Resistance (Actual)	Wall Resistance (Solid)	Bond and Groove Resistance	Wall Resistance (Including NAKs)	Bond Resistance	Temp Drop Through the Wall
T _{no}	T _i	T _o	T _m	W	ΔT_m	T _{NAK}	Q	q/A	U	R _o	1/u	R _f	R _{NAK}	R _{sf}	R _w	R _{ws}	R _{bg}	R _w	R _b	ΔT_w
° F	° F	° F	° F	lbs/hr	° F	° F	Btu/hr	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	Btu/hr-sq ft	° F
336.6	852.2	673.6	6105.1	419.96	756.56	258.417	261.132	621.80	1.60823	6885.00	0.19642	0.20500	1.20681	0.88214	0.32467	0.97934	0.22747	314.19	296.49	
337.3	823.6	655.4	6080.1	396.24	733.54	242.373	244.920	618.11	1.61783	6872.80	0.19677	0.20700	1.21406	0.88558	0.32848	0.98316	0.23090	296.49		
422.8	953.1	760.4	6040.3	426.71	849.57	274.695	277.581	650.51	1.53725	6858.20	0.19719	0.13500	1.20506	0.85686	0.34820	0.95127	0.25379	335.66		
422.8	961.1	763.7	6015.3	432.07	854.87	280.231	283.176	655.39	1.52580	6833.60	0.19790	0.13550	1.19440	0.85557	0.33883	0.94984	0.24456	337.40		
422.4	997.4	785.4	6015.3	460.82	883.22	299.682	302.831	657.15	1.52172	6832.40	0.19793	0.12950	1.19429	0.85256	0.34193	0.94628	0.24801	360.79		
423.0	1033.7	806.4	5940.4	488.20	911.20	317.427	320.762	657.02	1.52202	6794.10	0.19905	0.12600	1.19697	0.84949	0.34748	0.94309	0.25388	383.06		
423.0	1080.0	835.0	6039.8	524.96	947.96	347.741	351.395	669.37	1.49394	6870.29	0.19684	0.12000	1.17710	0.84475	0.33235	0.93783	0.23927	412.61		
475.0	1016.5	807.5	5853.1	428.52	903.52	287.475	290.496	677.90	1.47514	6757.66	0.20012	0.09600	1.17902	0.82934	0.34968	0.92072	0.25830	341.72		
475.0	1022.4	813.9	5928.0	434.80	909.80	290.457	293.509	675.04	1.48139	6787.01	0.19926	0.09700	1.18455	0.8737	0.30718	0.97404	0.21051	347.08		
475.0	1071.0	837.1	5863.2	469.33	944.33	322.297	325.684	693.93	1.447106	6830.60	0.17799	0.09900	1.14407	0.87065	0.27342	0.96658	0.17449	371.76		
475.0	1078.5	842.4	6071.3	475.66	950.66	329.644	333.333	700.50	1.42795	6873.69	0.18745	0.10000	1.13120	0.83544	0.29796	0.920371	0.20371	375.99		
475.3	1157.2	883.6	5897.7	533.41	1008.71	377.712	381.681	715.54	1.39875	6781.45	0.19942	0.10300	1.10633	0.82934	0.26699	0.92072	0.17561	416.96		
475.0	1162.2	886.9	5862.3	537.82	1012.82	377.650	381.618	709.56	1.40932	6760.27	0.20005	0.10300	1.10627	0.82933	0.27694	0.92071	0.18556	421.14		
505.1	1213.2	919.4	5897.2	548.09	1053.19	403.332	408.075	744.54	1.34311	6786.46	0.19927	0.06500	1.07534	0.81976	0.25558	0.91008	0.16577	437.83		
504.8	1216.4	921.1	5897.2	550.76	1055.56	405.893	410.158	747.71	1.34289	6787.06	0.19926	0.06800	1.07554	0.81858	0.25696	0.90817	0.16777	440.05		
505.4	1195.0	910.8	5924.6	534.91	1040.31	392.318	396.440	741.13	1.34929	6802.62	0.19880	0.07050	1.07999	0.82154	0.25845	0.91206	0.16793	427.19		
505.1	1143.6	885.2	5900.6	498.12	1003.22	356.783	360.532	723.75	1.38169	6783.92	0.19935	0.07500	1.10484	0.82512	0.27172	0.91603	0.18881	397.41		
504.8	1196.6	866.2	5988.0	472.66	977.46	341.050	344.634	729.13	1.37149	6828.43	0.19805	0.08000	1.10364	0.82813	0.27551	0.91958	0.18426	375.98		
505.1	1096.5	859.5	5950.5	462.91	968.01	331.133	334.612	722.84	1.38345	6808.46	0.19863	0.08250	1.10232	0.82692	0.27540	0.91803	0.18400	368.00		
504.8	1109.6	865.9	5950.5	472.59	977.29	339.332	342.898	725.57	1.37822	6807.16	0.19867	0.08100	1.09855	0.82813	0.27042	0.91938	0.17917	375.73		
504.8	1046.2	830.3	5926.5	429.31	929.11	300.689	302.849	707.76	1.41290	6788.40	0.19922	0.08800	1.12568	0.83360	0.29208	0.92545	0.20023	356.26		
505.4	1045.6	835.1	5988.9	426.30	931.70	296.255	299.368	702.24	1.42401	6825.76	0.19813	0.08800	1.13708	0.83299	0.30409	0.92477	0.21231	339.63		
504.8	1265.9	946.3	5910.7	586.82	1091.62	440.150	444.775	757.94	1.31936	6798.59	0.19892	0.06150	1.05894	0.81682	0.24212	0.90682	0.15212	469.95		
505.1	1251.2	939.6	5885.8	576.26	1081.36	427.325	431.815	749.34	1.33450	6778.18	0.19952	0.06400	1.07098	0.81858	0.25240	0.90877	0.16221	461.44		
505.1	1213.2	919.4	5897.2	548.09	1053.19	403.332	408.075	744.54	1.34311	6786.46	0.19927	0.06500	1.07534	0.81976	0.25558	0.91008	0.16577	437.83		
504.8	1216.4	921.1	5897.2	550.76	1055.56	405.893	410.158	747.71	1.34289	6787.06	0.19926	0.06800	1.07554	0.81858	0.25696	0.90817	0.16777	440.05		
505.4	1195.0	910.8	5924.6	534.91	1040.31	392.318	396.440	741.13	1.34929	6802.62	0.19880	0.07050	1.07999	0.82154	0.25845	0.91206	0.16793	427.19		
505.1	1143.6	885.2	5900.6	498.12	1003.22	356.783	360.532	723.75	1.38169	6783.92	0.19935	0.07500	1.10484	0.82512	0.27172	0.91603	0.18881	397.41		
504.8	1196.6	866.2	5988.0	472.66	977.46	341.050	344.634	729.13	1.37149	6828.43	0.19805	0.08000	1.10364	0.82813	0.27551	0.91958	0.18426	375.98		
505.1	1096.5	859.5	5950.5	462.91	968.01	331.133	334.612	722.84	1.38345	6808.46	0.19863	0.08250	1.10232	0.82692	0.27540	0.91803	0.18400	368.00		
504.8	1109.6	865.9	5950.5	472.59	977.29	339.332	342.898	725.57	1.37822	6807.16	0.19867	0.08100	1.09855	0.82813	0.27042	0.91938	0.17917	375.73		
504.8	1046.2	830.3	5926.5	429.31	929.11	300.689	302.849	707.76	1.41290	6788.40	0.19922	0.08800	1.12568	0.83360	0.29208	0.92545	0.20023	356.26		
505.4	1045.6	835.1	5988.9	426.30	931.70	296.255	299.368	702.24	1.42401	6825.76	0.19813	0.08800	1.13708	0.83299	0.30409	0.92477	0.21231	339.63		
504.8	1265.9	946.3	5910.7	586.82	1091.62	440.150	444.775	757.94	1.31936	6798.59	0.19892	0.06150	1.05894	0.81682	0.24212	0.90682	0.15212	469.95		
505.1	1251.2	939.6	5885.8	576.26	1081.36	427.325	431.815	749.34	1.33450	6778.18	0.19952	0.06400	1.07098	0.81858	0.25240	0.90877	0.16221	461.44		
505.1	1213.2	919.4	5897.2	548.09	1053.19	403.332	408.075	744.54	1.34311	6786.46	0.19927	0.06500	1.07534	0.81976	0.25558	0.91008	0.16577	437.83		
504.8	1216.4	921.1	5897.2	550.76	1055.56	405.893	410.158	747.71	1.34289	6787.06	0.19926	0.06800	1.07554	0.81858	0.25696	0.90817	0.16777	440.05		
505.4	1195.0	910.8	5924.6	534.91	1040.31	392.318	396.440	741.13	1.34929	6802.62	0.19880	0.07050	1.07999	0.82154	0.25845	0.91206	0.16793	427.19		
505.1	1143.6	885.2	5900.6	498.12	1003.22	356.783	360.532	723.75	1.38169	6783.92	0.19935	0.07500	1.10484	0.82512	0.27172	0.91603	0.18881	397.41		
504.8	1196.6	866.2	5988.0	472.66	977.46	341.050	344.634	729.13	1.37149	6828.43	0.19805	0.08000	1.10364	0.82813	0.27551	0.91958	0.18426	375.98		
505.1	1096.5	859.5	5950.5	462.91	968.01	331.133	334.612	722.84	1.38345	6808.46	0.19863	0.08250	1.10232	0.82692	0.27540	0.91803	0.18400	368.00		
504.8	1109.6	865.9	5950.5	472.59	977.29	339.332	342.898	725.57	1.37822	6807.16	0.19867	0.08100	1.09855	0.82813	0.27042	0.91938	0.17917	375.73		
504.8	1046.2	830.3	5926.5	429.31	929.11	300.689	302.849	707.76	1.41290	6788.40	0.19922	0.08800	1.12568	0.83360	0.29208	0.92545	0.20023	356.26		
505.4	1045.6	835.1	5988.9	426.30	931.70	296.255	299.368	702.24	1.42401	6825.76	0.19813	0.08800	1.13708	0.83299	0.30409	0.92477	0.21231	339.63		
504.8	1265.9	946.3	5910.7	586.82	1091.62	440.150	444.775	757.94	1.31936	6798.59	0.19892	0.06150	1.05894	0.81682	0.24212	0.90682	0.15212	469.95		
505.1	1251.2	939.6	5885.8	576.26	1081.36	427.325	431.815	749.34	1.33450	6778.18	0.19952	0.06400	1.07098	0.81858	0.25240	0.90877	0.16221	461.44		
505.1	1213.2	919.4	5897.2	548.09	1053.19	403.332	408.075	744.54	1.34311	6786.46	0.19927	0.06500	1.07534	0.81976	0.25558	0.91008	0.16577	437.83		
504.8	1216.4	921.1	5897.2	550.76	1055.56	405.893	410.158	747.71	1.34289	6787.06	0.19926	0.06800	1.07554	0.81858	0.25696	0.90817	0.16777	440.05		
505.4	1195.0	910.8	5924.6	534.91	1040.31	392.318	396.440	741.13	1.34929	6802.62	0.19880	0.07050	1.07999	0.82154	0.25845	0.91206	0.16793	427.19		
505.1	1143.6	885.2	5900.6	498.12	1003.22	356.783	360.532	723.75	1.38169	6783.92	0.19935	0.07500	1.10484	0.82512	0.27172	0.91603	0.18881	397.41		
504.8	1196.6	866.2	5988.																	

TABLE 3 - CALCULATIONS FOR THE THIRD OR SINGLE WALL TUBE

Temp. of the Water	Temp. of the NAK IN	Temp. of the NAK OUT	NAK Flow Rate	ΔT_M	T_{NAK}	$\frac{q}{A} = \frac{Wcp(T_2 - T_1)}{A}$	Overall Heat Transfer Coefficient	Overall Heat Transfer Resistance	NAK Film Coefficient	NAK Resistance	Wall Resistance	Steam Film and Scale Resistance	ΔT_{s+d}	
$^{\circ}F$	$^{\circ}F$	$^{\circ}F$	lbs/hr	$^{\circ}F$	$^{\circ}F$	BTU/(hr)(sq.ft)	BTU/(hr)(sq.ft)($^{\circ}F$)	BTU/(hr)(sq.ft)($^{\circ}F$)	BTU/(hr)(sq.ft)($^{\circ}F$)	BTU/(hr)(sq.ft)($^{\circ}F$)	BTU/(hr)(sq.ft)($^{\circ}F$)	BTU/(hr)(sq.ft)($^{\circ}F$)	$^{\circ}F$	
336.6	557.7	450.0	6157.9	161.76	498.36	157,515	160,484	922.11	1,007.95	5843.6	0.20701	0.57986	0.22108	35.47
337.3	667.0	505.0	6138.9	239.60	576.90	238,681	243,514	1016.33	1,005.70	5826.7	0.20761	0.56923	0.20709	50.42
336.9	697.8	519.5	6125.0	261.66	598.56	261,555	266,484	1018.44	0.98189	5820.8	0.20782	0.56743	0.20664	55.06
422.5	777.9	594.7	6369.9	252.78	675.28	278,905	284,905	1124.15	0.88956	5936.6	0.20377	0.55208	0.13371	37.99
422.5	851.6	624.1	6269.0	301.10	723.60	338,001	344,380	1143.74	0.87432	5887.6	0.20546	0.54825	0.12061	41.53
424.4	677.1	547.5	6212.5	180.16	604.56	192,830	196,465	1090.50	0.91701	5856.5	0.20656	0.55812	0.15233	29.92
422.8	770.0	590.5	6369.9	247.02	669.82	272,357	277,490	1123.30	0.89023	5918.5	0.20439	0.55294	0.13290	36.83
422.8	850.3	642.6	6081.7	210.27	715.39	242,225	246,791	1173.57	0.85210	5796.1	0.20871	0.53917	0.10422	25.72
504.8	880.7	669.7	6117.2	256.04	760.84	305,901	311,667	1217.25	0.82152	5814.8	0.20804	0.53714	0.07635	23.79
505.1	810.3	642.6	6081.7	210.27	715.39	242,225	246,791	1173.57	0.85210	5796.1	0.20871	0.53917	0.10422	25.72
504.8	880.7	669.7	6117.2	256.04	760.84	305,901	311,667	1217.25	0.82152	5814.8	0.20804	0.53714	0.07635	23.79
505.1	949.2	698.8	6115.2	301.73	806.83	361,374	368,186	1220.02	0.81965	5814.5	0.20804	0.53392	0.07769	28.59
505.8	966.9	705.8	6115.2	312.53	818.33	376,814	383,916	1228.41	0.81406	5815.5	0.20801	0.53313	0.07292	27.99
504.8	1015.0	726.0	6114.7	345.74	850.54	416,163	424,007	1226.37	0.81541	5814.4	0.20803	0.53233	0.07505	31.82
535.3	823.6	662.2	6056.2	196.65	731.95	231,660	236,027	1200.23	0.83317	5587.4	0.21650	0.53593	0.08074	19.05
535.3	865.0	681.0	6052.8	225.28	760.58	263,727	268,698	1192.72	0.83842	5785.7	0.20908	0.53314	0.09620	25.34
535.3	907.6	695.5	6027.8	251.48	786.78	302,236	307,932	1224.47	0.81667	5771.5	0.20960	0.53114	0.07593	23.38
535.6	990.0	730.4	5990.4	306.45	842.05	366,383	373,289	1218.10	0.82095	5759.0	0.21005	0.52645	0.08445	31.52
535.6	1010.2	739.2	6052.8	320.16	855.76	386,129	393,406	1228.77	0.81382	5785.1	0.20910	0.52645	0.07827	30.79
535.6	1045.6	754.8	6026.9	344.32	879.92	411,865	419,629	1218.71	0.82053	5776.8	0.20940	0.52377	0.08776	36.82
535.3	1053.1	756.9	6051.8	348.95	884.25	421,216	429,186	1229.93	0.81305	5789.7	0.20894	0.52337	0.08074	34.65
535.6	1062.9	759.5	6051.8	354.08	889.68	431,628	439,764	1241.99	0.80515	5789.3	0.20895	0.52298	0.07322	32.19
556.7	853.0	684.6	6366.3	200.41	757.11	254,084	258,873	1291.71	0.77477	5932.0	0.20392	0.53472	0.03552	9.19
556.4	883.6	699.2	6327.4	219.22	775.62	274,191	279,359	1274.33	0.78473	5913.9	0.20455	0.53312	0.04705	13.14
556.4	913.7	709.7	6327.4	241.04	797.44	304,884	310,631	1288.71	0.77596	5918.5	0.20439	0.53114	0.04043	12.55
556.4	949.2	723.7	6327.4	264.16	820.56	336,731	343,078	1298.75	0.76997	5918.0	0.20441	0.52528	0.04028	13.81
557.1	1024.7	752.2	6240.0	311.78	868.88	399,934	407,472	1306.92	0.76515	5879.1	0.20576	0.52413	0.03526	14.36
557.1	1101.8	783.3	6212.5	362.49	919.59	464,105	472,852	1304.45	0.76660	5869.5	0.20610	0.51955	0.04095	19.36
557.6	1047.2	763.0	6188.5	327.12	884.72	413,311	421,101	1287.29	0.77682	5853.4	0.20666	0.52451	0.04565	19.22
567.9	907.0	715.6	6115.2	230.26	798.16	276,615	281,828	1223.95	0.81702	5803.9	0.20846	0.52606	0.08250	23.25
567.9	920.4	723.0	6115.2	240.40	808.30	284,885	290,255	1207.38	0.82823	5804.4	0.20840	0.53313	0.08670	25.16
567.9	942.8	727.3	6115.2	251.94	819.84	311,007	316,869	1257.71	0.79509	5815.3	0.20802	0.52567	0.06140	19.45
567.5	1034.0	767.6	6139.2	314.68	882.18	384,500	391,747	1244.90	0.80327	5820.6	0.20783	0.57031	0.07513	29.43
567.9	1075.4	783.5	6076.3	340.93	908.83	416,459	424,309	1244.56	0.80349	5801.4	0.20852	0.51768	0.07729	32.79
567.5	1081.6	787.4	6076.3	346.38	913.88	419,741	427,650	1234.63	0.80995	5802.2	0.20849	0.51693	0.08453	36.14
567.9	1100.9	791.6	6050.8	356.20	924.10	439,243	447,522	1256.37	0.79594	5791.1	0.20889	0.51580	0.07125	31.88

C O N F I D E N T I A L

The Lyons equation is rewritten as

$$h_i = \frac{k_{\text{NaK}}}{D_i} \left[7 + 0.030 \left(\frac{W}{D_i} \right)^{0.8} \left(\frac{C_p}{k_{\text{NaK}}} \right)^{0.8} \right] \quad (10)$$

For the first estimate of the general heat transfer equation the value of k_w ⁽²⁾ was assumed to be at the temperature $T_{\text{H}_2\text{O}} + 1/2 \times \Delta T_m$.

Each section to the right of the equal sign in equation 6 represents a resistance to heat transfer. The temperature drop across each of these resistances is a proportion of the resistance over the overall resistance times the overall temperature drop which can be written

$$\Delta T_{\text{NaK}} = R_{\text{NaK}} \times \Delta T_m \times U \quad (11)$$

$$\Delta T_w = R_w \times \Delta T_m \times U \quad (12)$$

$$\Delta T_{s+d} = R_{s+d} \times \Delta T_m \times U \quad (13)$$

Knowing the temperature drop through the three resistances the average inside and outside wall temperatures can be found.

$$T_w \text{ (inside)} = T_{\text{NaK}} - \Delta T_{\text{NaK}} \quad (14)$$

$$T_w \text{ (outside)} = T_{\text{H}_2\text{O}} + \Delta T_{s+d} \quad (15)$$

Using the inside and outside wall temperature the average wall temperature is the log mean.

$$T_w = \frac{\Delta T_w}{\ln \frac{T_w \text{ (inside)}}{T_w \text{ (outside)}}} \quad (16)$$

7

C O N F I D E N T I A L

Using the new wall temperature a second k_w was found and a second calculation of the heat transfer equation was made. A third estimate of the wall temperatures was found unnecessary.

A plot of the heat flux vs. the temperature drop across the outside film is shown in Figure 7. Also included in the plot is Addoms' data for film boiling at various pressures from platinum wire⁽³⁾.

CALCULATIONS OF THE RESISTANCE TO HEAT TRANSFER DUE TO THE EFFECT OF THE GROOVES AND MECHANICAL BOND

In order to estimate the bond and groove resistance certain assumptions had to be made.

1. The outside resistance is the same for like values of heat flux and pressure for all three tubes.
2. The resistance of the bond and groove is the difference between the experimental values obtained for the metal wall including the bond and groove and the calculated value assuming the wall to be solid.

The calculations were made in the following manner.

In order to estimate the resistance to heat transfer of the steam film and scale on the outside of the first and second tube, a plot was made of the calculated resistance of the single wall tube vs. the heat flux (see Figure 8).

Knowing the dimension of the tube and the flow rate, the inside film coefficient for the two double wall tubes was calculated for the NaK using Lyon's equation⁽¹⁾. The outside coefficient was taken from the plot mentioned above (Figure 8). The sum of the inside and outside resistance was subtracted from the total resistance and the remainder was assumed to be the resistance of the metal wall plus the resistance of the bond and grooves.

$$1/U - R_{\text{NaK}} - R_{s+d} = R_w \quad (17)$$

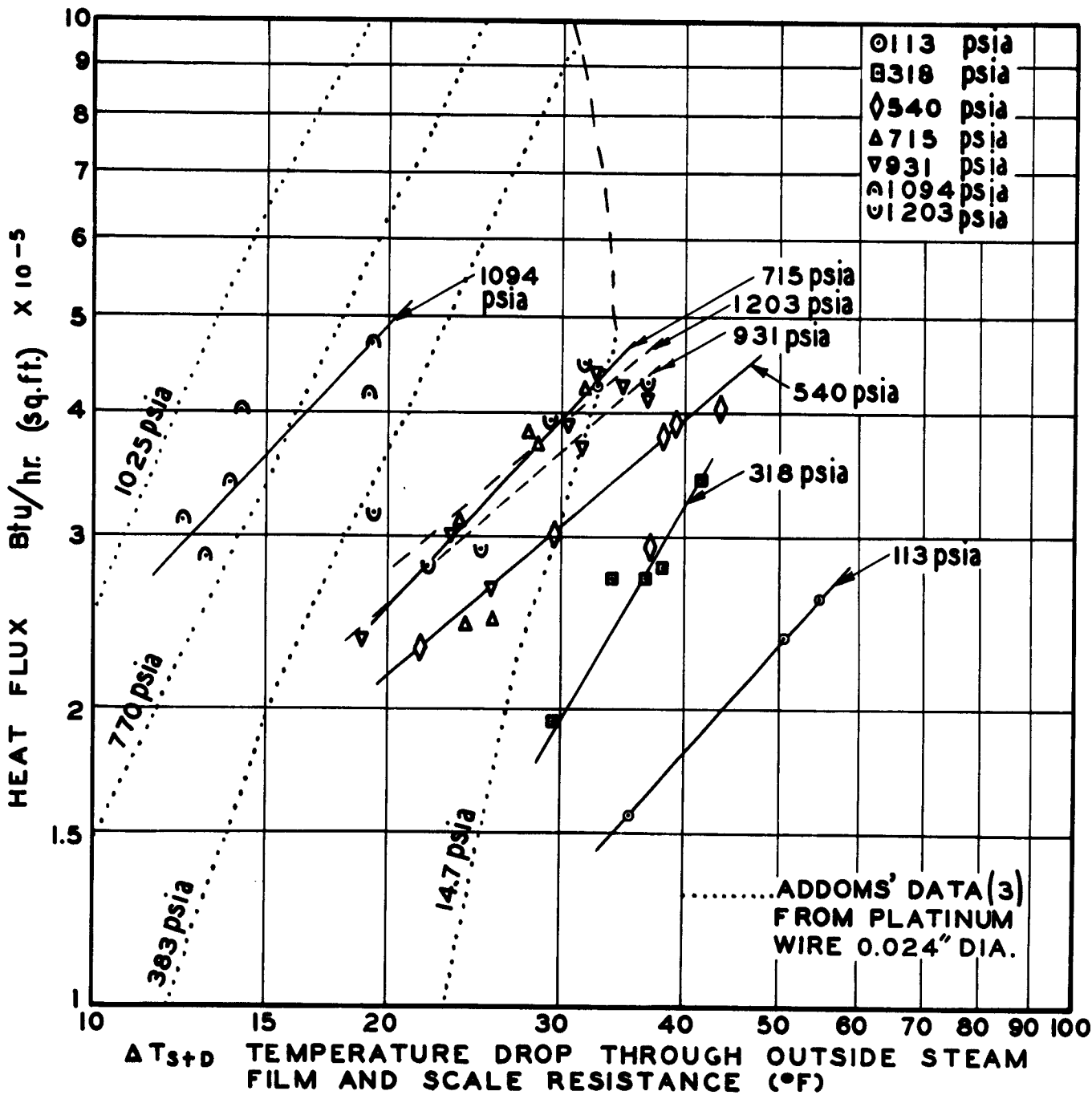


FIG. 7 PLOT OF HEAT FLUX vs THE TEMPERATURE DROP THROUGH THE OUTSIDE RESISTANCE FROM TYPE 304 STAINLESS STEEL AND COMPARED WITH ADDOMS' DATA FROM PLATINUM WIRE

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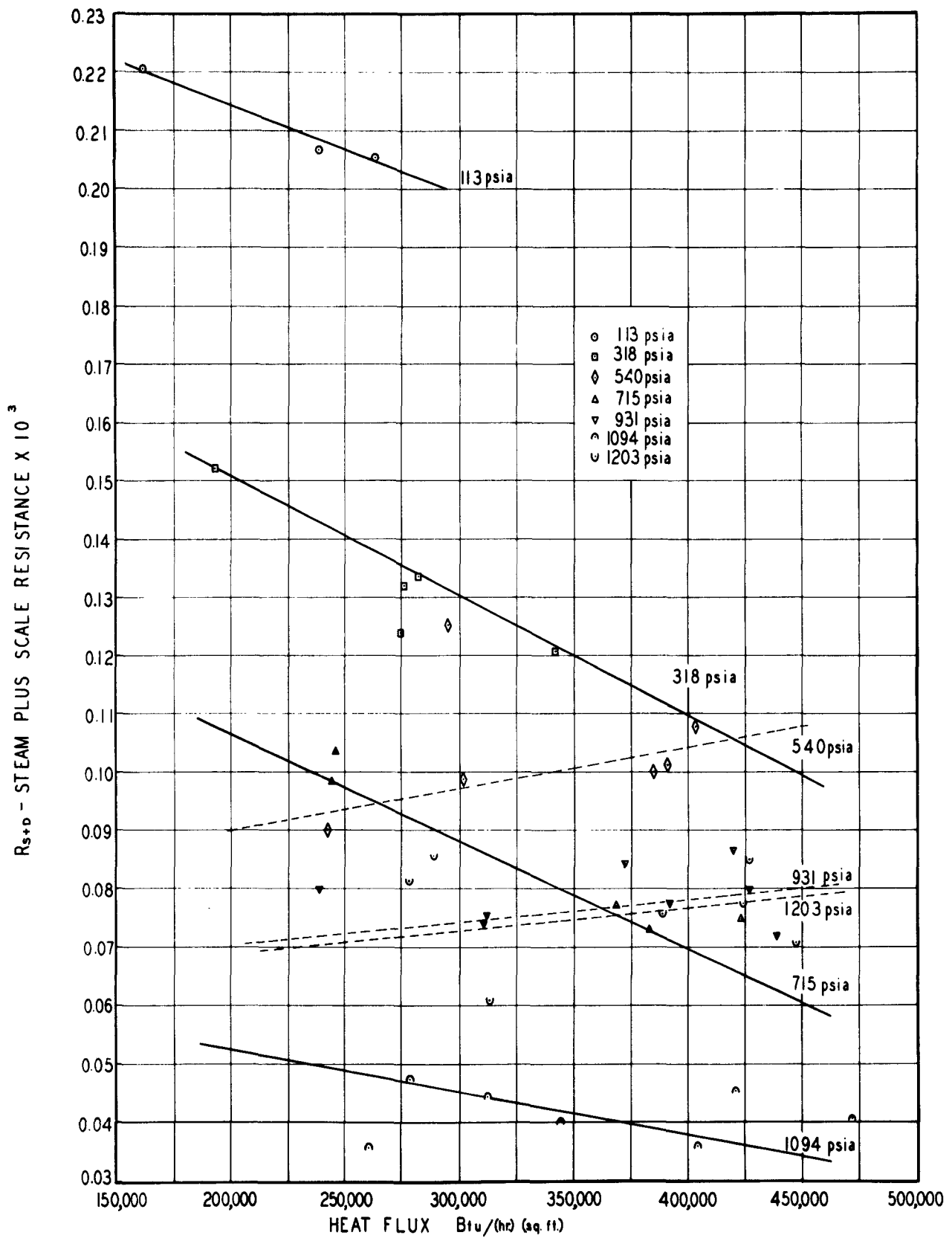


FIG. 8 PLOT OF THE OUTSIDE STEAM FILM PLUS SCALE RESISTANCE vs THE HEAT FLUX FOR THE SINGLE WALL TUBE

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The temperature at the inside and outside of the double wall tube was calculated as follows:

$$T_{wm} \text{ (inside)} = T_{NaK} - R_{NaK} \times \Delta T_m \times U \quad (18)$$

$$T_{wm} \text{ (outside)} = T_{H_2O} + R_{s+d} \times \Delta T_m \times U \quad (19)$$

If the tube were assumed to be a solid wall tube of the same dimensions as the double wall tube and the inside and outside wall temperatures of this solid wall tube were to be the same as those found for the double wall tube, the resistance of the solid wall tube could be calculated by

$$R_{wa} = \frac{D_o - D_i}{2 k_w} \times \left(\frac{D_o}{D_i} \right) \quad (20)$$

The difference between the calculated resistance of the double wall tube and the similar single wall tube would then be the combined resistance of the bond and the grooves.

$$R_{B+G} = R_w - R_{wa} \quad (21)$$

The primary factor relating one resistance to another throughout the test has been the temperature drop through the wall. This will be discussed later. A plot of the bond and groove resistance vs. the temperature drop through the wall for both the first and second tubes can be seen in Figure 9.

CALCULATIONS OF THE RESISTANCE TO HEAT TRANSFER DUE TO THE EFFECT OF THE MECHANICAL BOND

A method for calculating the wall resistance for a grooved tube was suggested by R. O. Parker of the Griscom-Russell Company. The method, which has been modified slightly, is described on page 10.

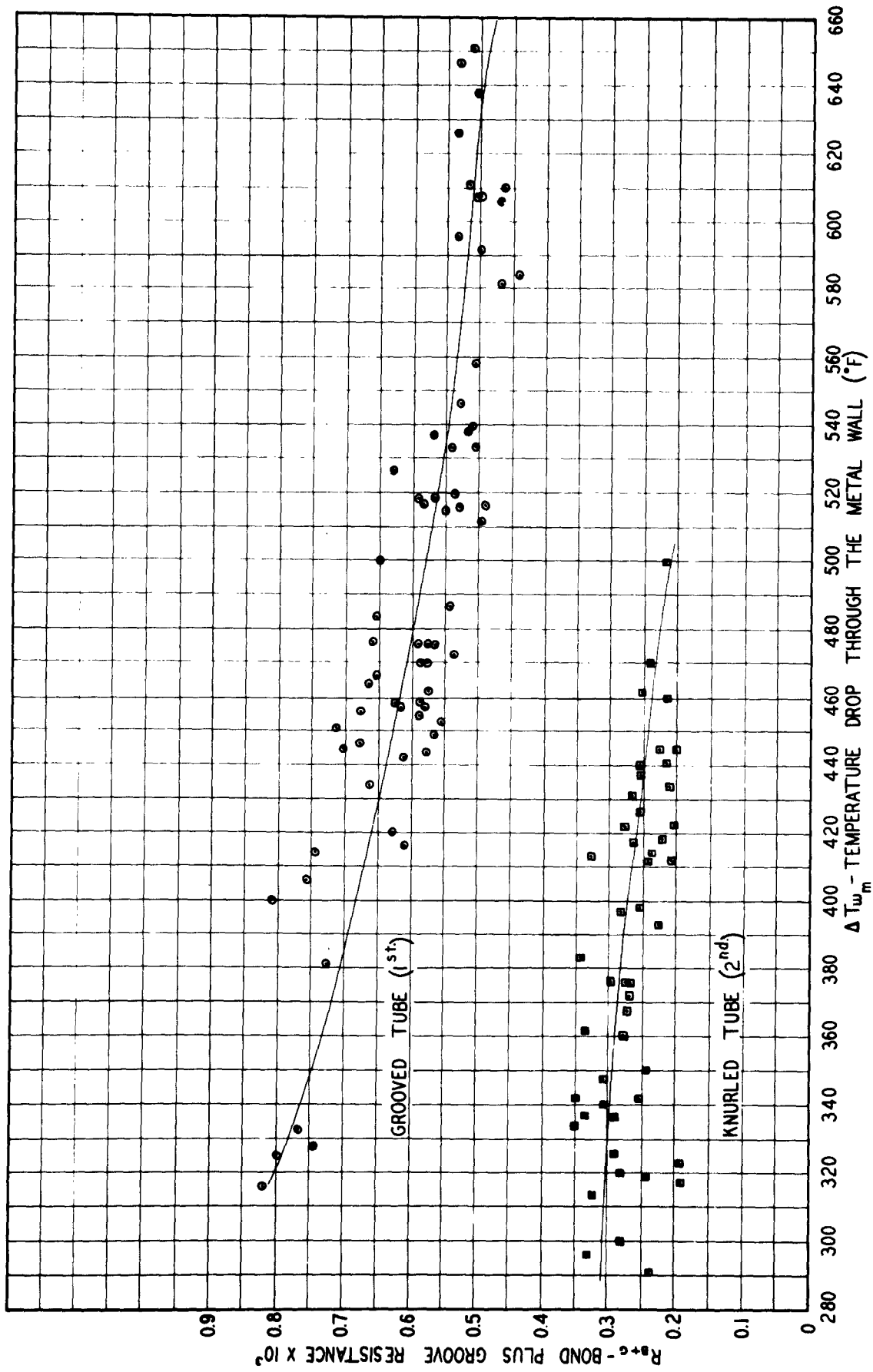
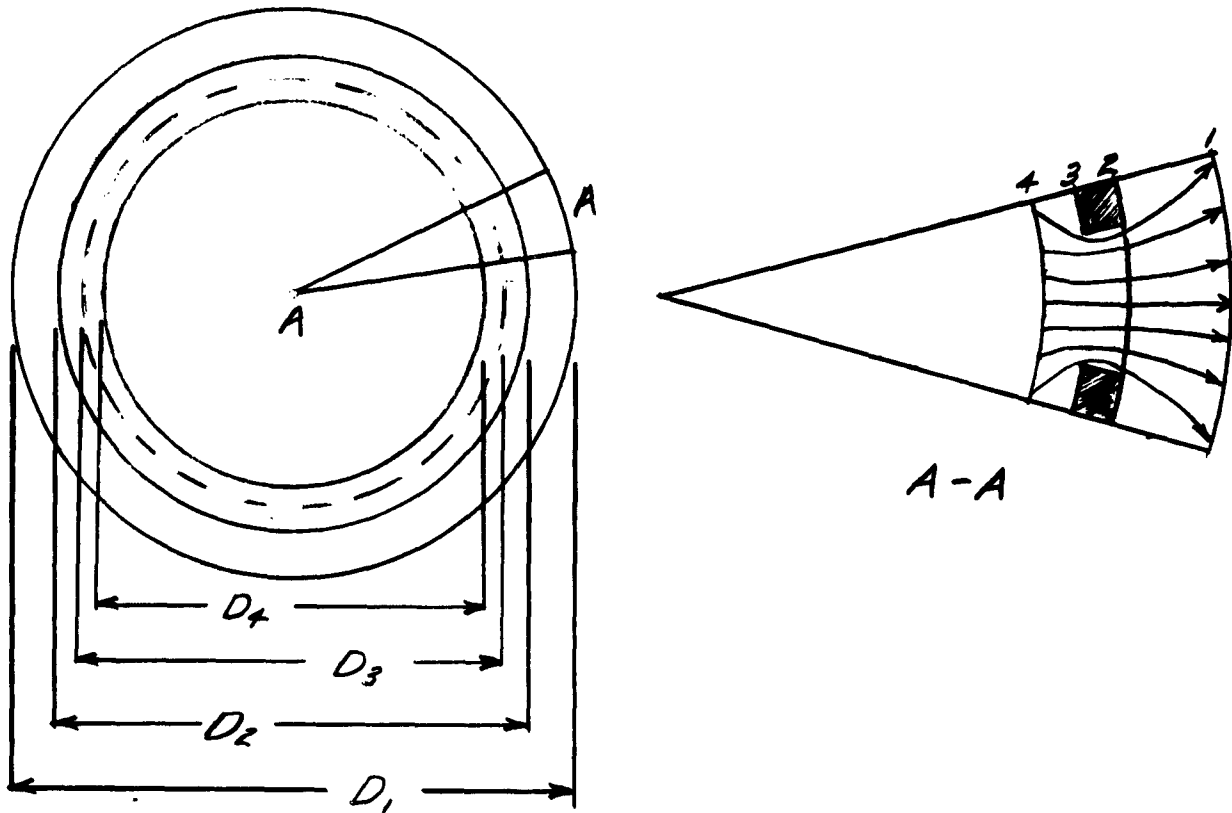


FIG.9-PLOT OF THE BOND PLUS GROOVE RESISTANCE FOR THE GROOVED AND KNURLED TUBES
v.s. THE TEMPERATURE DROP THROUGH THE METAL WALL

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C O N F I D E N T I A L

Assume the dimensions of the tube to be as shown



Assuming the flow of heat through the tube follows a log mean path around the grooves and assuming the path to be that shown by

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the arrows in the sketch above, then the boundaries or circumferences are:

$$C_1 = \pi \times D_1 \quad (22)$$

$$C_2 = \pi \times D_2 - n \times l \quad (23)$$

$$C_3 = \pi \times D_3 - n \times l \quad (24)$$

$$C_4 = \pi \times D_4 \quad (25)$$

then the log mean circumference through which the heat passes is:

$$C_m (3-4) = \frac{C_3 - C_4}{\ln \frac{C_3}{C_4}} \quad (26)$$

$$C_m (2-3) = \frac{C_3 - C_2}{\ln \frac{C_3}{C_2}} \quad (27)$$

$$C_m (1-2) = \frac{C_1 - C_2}{\ln \frac{C_1}{C_2}} \quad (28)$$

The values of the heat transfer resistance for each section based on the outside area will then be

$$R_{4-3} = \frac{D_3 - D_4}{2 k_w} \times \frac{C_1}{C_m (3-4)} \quad (29)$$

$$R_{3-2} = \frac{D_2 - D_3}{2 k_w} \times \frac{C_1}{C_m (2-3)} \quad (30)$$

$$R_{2-1} = \frac{D_1 - D_2}{2 k_w} \times \frac{C_1}{C_m (1-2)} \quad (31)$$

C O N F I D E N T I A L

The total wall resistance will then be the sum of the individual resistances. The thermal conductivity of each section will in the summation be approximately the value obtained using the log mean temperature. The total resistance is then:

$$R_{wt} = \frac{C_1}{2 k_w} \left[\frac{D_3 - D_4}{C_m(3-4)} + \frac{D_2 - D_3}{C_m(2-3)} + \frac{D_1 - D_2}{C_m(1-2)} \right] \quad (32)$$

Since resistances of a solid wall tube have been calculated previously in equation 20, the factor relating the solid wall tube calculated to the grooved tube calculation will then be:

$$f = \frac{R_{wt}}{R_{wa}} \quad (33)$$

The resistance of the mechanical bond will be the difference between the actual resistance and the calculated grooved tube resistance which is

$$R_B = R_w - f \times R_{wa} \quad (34)$$

A plot of the bond resistance for both the grooved and knurled tube vs. the temperature drop through the metal wall can be seen in Figure 10.

DESCRIPTION OF THE LEAK IN THE STEAM GENERATOR BETWEEN THE NAK AND WATER SYSTEM

A leak developed at the tube joint of the single wall tube between the NaK and water system. Since this was a single wall tube and did not include a helium leak detecting system the exact time the leak developed was not known, but was discovered during draining operations.

The system had remained charged and idle for a period of four months with the NaK system under nitrogen pressure and the water system under vacuum before being put back into operation seven days before the leak was discovered. The system was run eight hours a day for two days at various flow rates, and at a steam pressure of 500 psi.

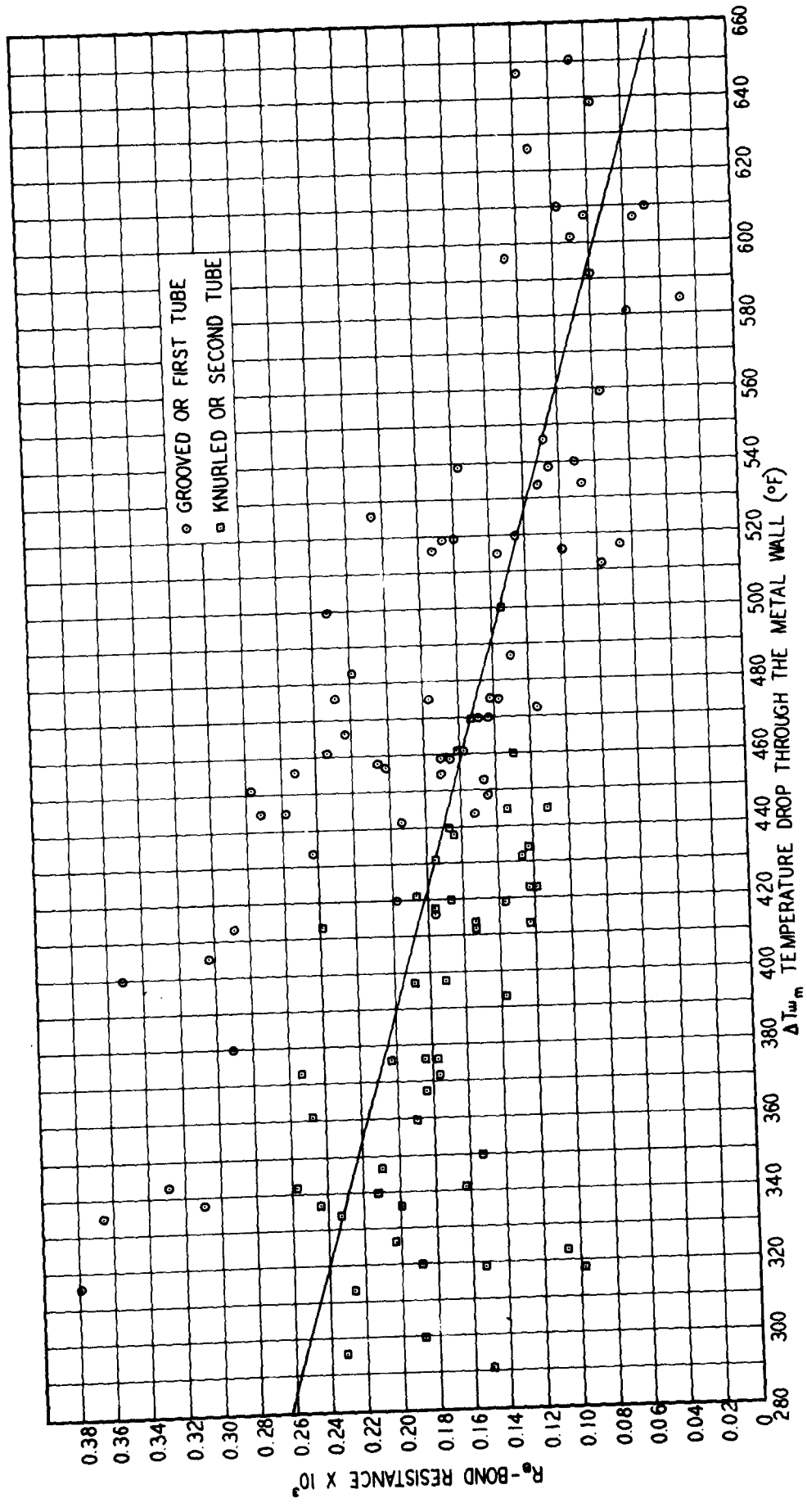


FIG.10 - PLOT OF THE BOND RESISTANCE FOR BOTH THE GROOVED AND KNURLED TUBES
vs THE TEMPERATURE DROP THROUGH THE METAL WALL

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The maximum NaK inlet temperature reached was 1300°F. The system was then run 36 hours continuously at a constant flow rate and various steam pressures up to 1200 psi.

During these operations considerable initial difficulty was encountered in getting the NaK flow to start. After two days of being idle it became necessary to fire the NaK furnace to heat the NaK before normal circulation was reached for the last day of operation. The system was operated at pressures from 300 to 600 psi.

During the cooling down operations on the last day the NaK circulation stopped because of plugging and it became impossible to condense any more steam below 20 psi even though there was no NaK circulation. The possibility of a leak was discounted since the NaK system showed the usual 50 psi and the steam gage showed 20 psi which corresponded to the water temperature for a time. The system was allowed to cool over night.

The following day draining operations began. Attempts were made to start the NaK pump, but only a spasmodic flow was indicated.

After 16 of about 23 total pounds of NaK had been forced out of the system by 50 psi nitrogen pressure, the system was left unattended for about 1 hour. At the end of this time it was noticed that the steam gage showed a 50 psi pressure which indicated a leak between the NaK and water system. Upon cutting the steam generator out NaK was found in the exit NaK pipe and water was found in the inlet NaK pipe. The boiler water was tested for alkalinity and it was found that only 0.02 pounds of NaK had leaked through.

In cleaning the NaK system it was estimated from the amount of water found in the NaK piping that between 2 to 4 quarts of water had leaked into the NaK pipes.

An inspection of the leak by the Griscom-Russell Company showed the leak to be in the rolled tube joint on the NaK inlet side. It would appear that the path of the leak as observed from the outside made a 90° turn through the rolled joint.

C O N F I D E N T I A L

It is thought that the following sequence of events took place.

1. The leak had been present in the system almost from the beginning of operation but was too small to be located during the initial test of the system.
2. Upon charging the NaK system NaK found its way into the leak and formed a caustic plug when steam was brought up to pressure.
3. The difficulty in starting the NaK to flow was the result of a very slight amount of water leaking into the NaK stream and manifesting itself in the form of oxide causing a partial plug in the NaK stream. During shut down any NaK attempting to go through the wet hole would seal itself off. However, during the final shut down a small quantity of NaK must have succeeded in getting into the water system and formed hydrogen which vapor locked the condenser. When the NaK was drained away from the leak area nitrogen flowed through the leak and when the pressure on the NaK side went below the pressure on the steam side water was forced into the NaK piping. It has been demonstrated in the water-NaK hazard work (8) that water and NaK can exist as such in the same section of pipe because a caustic interface is formed which keeps the two liquids separated.

DISCUSSION

The results of the tests have been very encouraging in that they have shown that a tube with a safety feature built into it will still give a good performance without very much increase in weight and volume of the steam generating equipment. This is not only a saving in space but in cost as well.

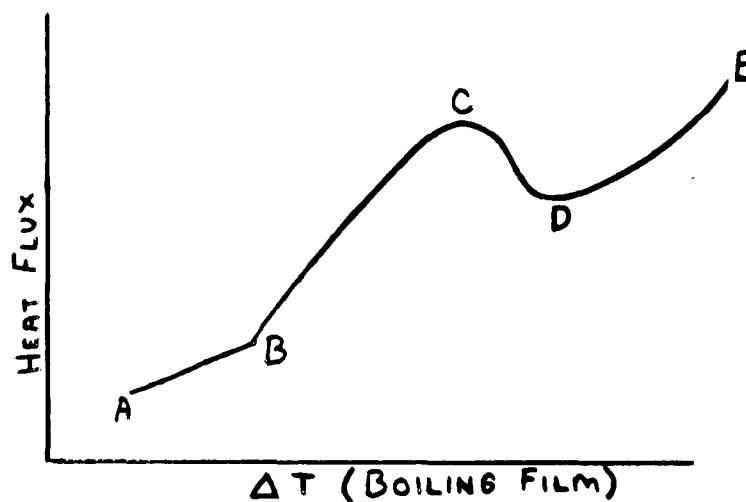
The plot of the heat fluxes in Figure 5 shows the performance of the three tubes as they were tested. To the casual observer this comparison would leave the false impression that the grouping of the three sets of data is due to the bond and groove resistance alone but in reality it is also due to the thickness of the wall. The tube with the greatest bond and groove resistance also had the thickest tube wall, two 16 B. W G tube walls for a total thickness of 0.130 in.

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The second tube that had the intermediate bond and groove resistance also had the intermediate thickness which was two 18 B. W. G. tube walls for a total of 0.098 in. The third tube was just half the wall thickness of the first since it was a single 16 B. W. G. tube wall of 0.065 in. thickness.

A number of investigations (3) (4) (5) (6) and (7) have been made to determine boiling film coefficients, a few of which include water. Almost all the work with water, especially that at high pressures, was made using resistance wire as the heat source as well as the boiling surface.

A typical curve to show the temperature through the boiling film vs. the heat flux is shown below.



Heat is transferred from point A to B by conduction with evaporation at the surface of the water. At point B steam bubbles begin to form on the tube or wire on certain active nuclei (called nucleate boiling). With increased ΔT the boiling rate becomes

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more vigorous to the point C where the steam bubbles cannot break away as fast as they are formed and the tube or wire becomes steam blanketed. At point D all the tube is blanketed with steam and from that point to point E heat is transferred by natural convection and radiation (called film boiling).

With change in pressure the shape of the curve remains essentially the same but the values of the corresponding points change slightly to the left and up with increased pressure. The value for the heat flux for point C changes from about 400,000 Btu/(hr) (sq. ft.) at atmospheric pressure to about 2,000,000 Btu/(hr) (sq. ft.) at 1200 psi while the temperature drop through the steam film changes from about 30°F to 20°F through the same increase in pressure.

The values obtained and plotted in Figure 7 show the same general shift as predicted by previous investigators. The values do not match those obtained from the wire data; however, it has been shown that the values of ΔT change with the degree of scale on the surface and the material of construction of the wire (7).

The change in slope of curves in Figure 7 and 8 is rather difficult to explain other than by the fact that the runs at the pressures 931 and 1203 psia were made two days after the runs at the other pressures which were made over a 30 hour period and this change in slope could be the result of some scaling of the tube which should not affect the heat transfer by over 2 or 3%. At the completion of the test when the steam generator was dismantled, a film of rust was noted on the outside surface of the tube.

A better method of plotting Figure 8 might have been to cross plot the data and adjust the 931 and 1203 psia curves into the pattern.

Attempts to isolate the bond and groove resistance are rather difficult since the resistances in question are the difference between rather large numbers. Both the combined bond and groove resistance as seen in Figure 9 and the isolated bond resistance in Figure 10 decrease with increased temperature drop through the metal wall. This decrease in resistance is probably due to the increased pressure on the bond due to the expansion of the inner tube into the outer tube at higher temperatures. The bond resistance as plotted in Figure 10 may

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well be in error; however, it is a means of making an intelligent guess as to the value of such a resistance. A 1% error in the heat flux could result in an error in the bond resistance as high as 10%.

CONCLUSIONS

The performance of double wall tubes as described in this report has proven that for only a slight cost in added surface a safety feature can be had that could save considerable trouble should a leak develop in a tube in a steam generator using an alkali metal as the heat transfer fluid.

By using the method presented here for calculating the bond resistance and by using the values of the bond resistance and outside resistance, one should be able to estimate with a fair degree of accuracy the performance of any tube of similar design.

ACKNOWLEDGEMENTS

The work presented here was made under the direction of Mine Safety Appliances Company under Contract No. N9onr- 85801 sponsored by the Bureau of Ships and has been released by the Naval Reactor Branch of the A. E. C. The authors wish to thank the above mentioned organizations and also the Griscom-Russell Company for their cooperation for preparing this data for publication. The authors are also indebted to R. C. Werner and R. A. Tidball for their help in designing the original equipment.

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NOTATION

Symbols

- A - Area, sq. ft.
- C - Circumference, ft.
- C_p - Specific heat, Btu/(lb)(°F)
- D - Diameter, ft.
- f - factor
- h - heat transfer coefficient, Btu/(hr) (sq. ft.) (°F)
- k - Thermal conductivity, Btu/ (hr)(sq. ft.) (°F/ft.)
- l - width of grooves or knurls ft.
- n - number of grooves or knurls
- P_e - Peclet number
- q - quantity of heat, Btu/hr.
- R - Resistance to Heat Transfer, (hr) (sq. ft.) (°F) /Btu
- T - Temperature in °F
- U - Overall heat transfer coefficient, Btu/ (hr) (sq. ft.) (°F)
- w - weight of fluid flowing, lbs. /hr.

Subscripts

- a - solid wall
- B - Mechanical bond
- G - Groove or knurl in tube
- H₂O - water
- i - inlet or inside
- m - mean
- NaK - NaK
- o - outlet or outside
- s - steam film
- s + d - steam film plus scale
- t - total
- w - tube wall

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