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OFFICE OF SALINE WATER

EVAPORATIVE HEAT TRANSFER IN VERTICAL TUBES AT GEOTHERMAL BRINE CONDITIONS — A PRELIMINARY INVESTIGATION

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OAK RIDGE NATIONAL LABORATORY
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NUCLEAR DESALINATION PROGRAM
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ABSTRACT

The objective of these tests was to obtain overall heat transfer coefficients in a single tube loop for a smooth tube and two fluted tubes proposed for use in a geothermal brine upflow VTE pilot plant. Tests were run at steam temperatures from 250°F to 390°F, flow rates of 0.5 to 2.5 gpm, and steam to brine ΔTs of 10-30°F using demineralized water and 3% NaCl solutions. In each case the liquid entering the tube flashed through a ΔT equal to the steam-brine ΔT. The tubes tested were a 3/4 in. smooth stainless steel tube, a 1 in. double fluted CuNi tube, and a 7/8 in. double fluted Al-Brass tube.

Average heat transfer coefficients using 3% NaCl were as follows: for the stainless steel tube, 550 Btu/hr/°F/ft^2 at 250°F to 765 at 390°F; for the CuNi tube, 2000 at 250°F to 2600 at 390°F; for the aluminum brass tube, 1750 at 250°F to about 2650 at 390°F. Flow rate and ΔT, in general, had only small effects on the coefficients.

Keywords: Geothermal brine + heat transfer coefficient + enhanced heat transfer + vertical tube evaporation + design data + distillation processes + OSW sponsored + flash evaporation + pilot plant operation + parametric studies

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OBJECTIVE

The objective of the investigation was to establish the range of heat transfer coefficients at the high temperatures (250-400°F) proposed for use in the desalting of goethermal brines. The objective was limited to providing guidelines for extrapolating existing vertical tube evaporator (VTE) correlations to the temperature of a proposed pilot plant.

SCOPE

A test loop was designed, constructed and operated at 250°-400°F with small diameter VTE tubes in upflow. Parameters to be investigated included brine feed rate, evaporative ΔT, and the effect of enhanced surface. (See Table 1 for a more complete set of parameters.) The range of parameters was intended to cover a region useful for the design of water desalting plants using geothermal brine feeds.

The initial runs were made using demineralized water and a stainless steel tube in order to provide baseline data with which to compare to literature values for similar systems. Later runs were extended to fluted tubes and salt solutions. While all the runs were made in upflow, the facility could be converted to falling film operation for future tests.

Since the composition of geothermal brines vary widely, a 3% NaCl solution was used in these tests as an approximate simulation.

LOOP DESCRIPTION

Criteria

The loop was designed specifically to carry out the program described in the Scope. The features of the facility include:

1. Maximum design operating temperature of 487°F (600 psi).

2. Tube sizes from 3/4 in. OD to 1 1/2 in. OD with an effective heated length of 7.7 ft. Larger or smaller OD tubes or longer tubes can be handled with minor loop modifications.

3. Brine flow in the range of 0.5 to 2.7 gpm.

4. Vapor condenser for handling condensate loads of from 20 to 300 lb/hr, while permitting control of the evaporation temperature over the entire range.

5. Variable orifice at the evaporator tube inlet so that the pressure drop can be controlled over the range of temperatures and flow rates to prevent flashdown upstream of the tube entrance.

Flowsheet

The process flowsheet is shown in Figure 1. The brine system consists of a total recycle closed loop. Brine is pumped from an 8 gallon capacity head tank using a 2.7 gpm triplex feed pump past a pulsation damping standing leg, through two flow measuring orifices to the brine heater. Building steam (250 psi or 150 psi), reduced to low pressure as required is condensed in the brine heater, heating the brine to the desired feed temperature, which for the geothermal steam process is set equal to the shellside (condensing steam) temperature.

TABLE 1

PARAMETERS TO BE TESTED IN THE GEOTHERMAL TEST LOOP

1.	Steam Chest Temperature:	400°F, 350°F, 300°F, 250°F
2.	Brine Feed Temperature:	Equal to steam chest temperature plus boiling point elevation (BPE)
3.	Evaporation ΔT:	10°F, 20°F, 30°F
4.	Tubes:	3/4 in. OD smooth stainless steel 1 in. OD fluted cupronickel (French tube) 7/8 in. OD fluted aluminum brass (Phelps-Dodge tube)
5.	Tube Length:	8 ft
6.	Brine Composition:	0%, 3% NaCl. In addition, sodium sulfite added to protect against corrosion
7.	Brine Flow Rate:	0.5, 1.5, 2.5 gpm.

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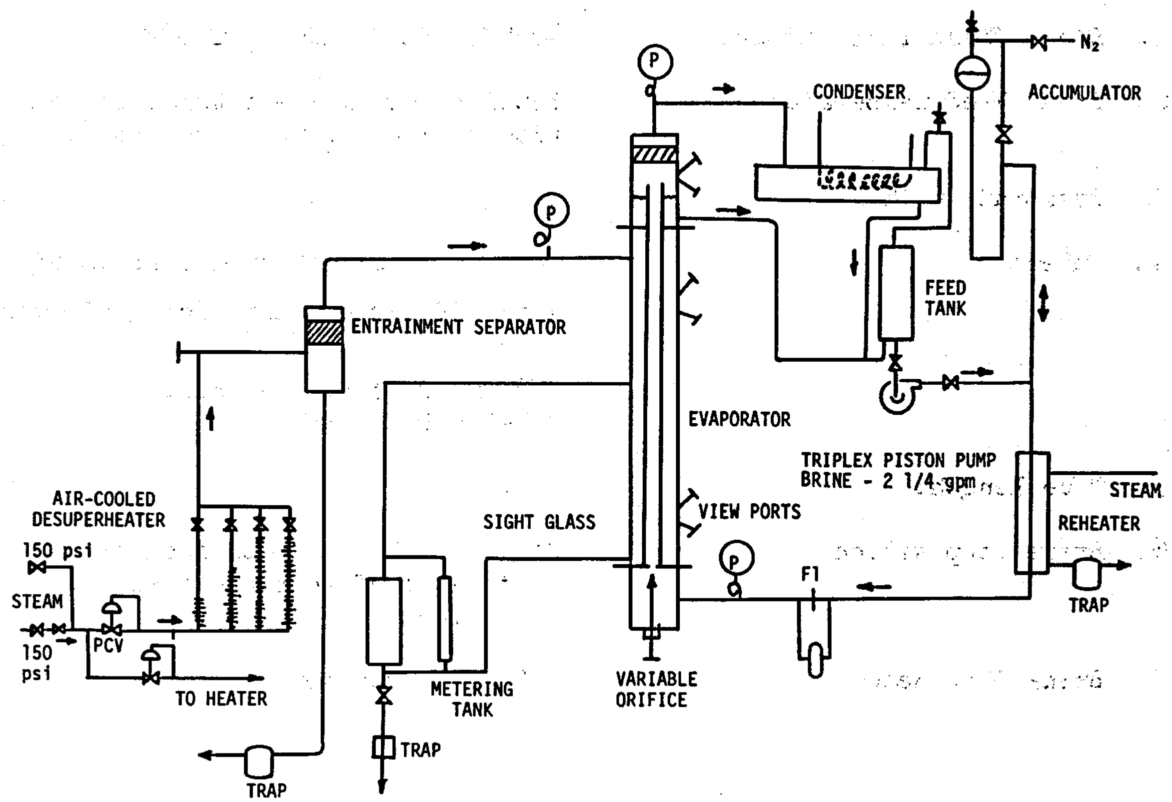

FIGURE 1. GEOTHERMAL BRINE EVAPORATOR LOOP

The brine is prevented from boiling in the heater and in the piping to the evaporator by maintaining its pressure above saturation. The brine then flashes on entering the evaporator tube by throttling through a variable area annular orifice. The two phase mixture is carried up the tube by the pressure drop of the rising vapor produced by flashdown at the entrance and by evaporation of the rising liquid film.

On leaving the tube, the two phase stream is separated in the vapor disengagement section and the unevaporated brine is returned by gravity to the head tank. The vapor flows through an entrainment separator to the vapor condenser where it is condensed and returned to the brine head tank.

The steam for evaporation is supplied from the building 150 psi or 250 psi system through a regulating valve, a desuperheater, and an entrainment separator. The steam condensate produced in the evaporator shell flows through a volumetric measuring tank to the building drain through a steam trap. A small vent at both top and bottom of the evaporator purges the shell of non-condensable gases.

Cooling water for the vapor condenser tubes is maintained at temperatures between ambient and 212°F by recirculation from the condenser to a 35 gallon head tank. The temperature of the coolant in the head tank is controlled by adding cold building process water and overflowing the heated coolant to drain. At the lowest desired evaporation and flashing rates, where the area of the cooler tubes is too large for stable operation below an inlet temperature of 212°F and the coolant pump cavitates, a once-through stream of cold demineralized water is used as a coolant. This is permitted to boil, and no measurements are made for this mode of operation of the heat removal rate of the vapor condenser.

Component Descriptions

Figures 2 to 4 are photographs of the completed loop before being insulated.

Shell

The evaporator shell is 6 in. Schedule 40 pipe of 347 stainless steel, which material minimizes thermal expansion effects with the 316 stainless steel and the cupronickel tubes to be tesed. The lower head of the shell

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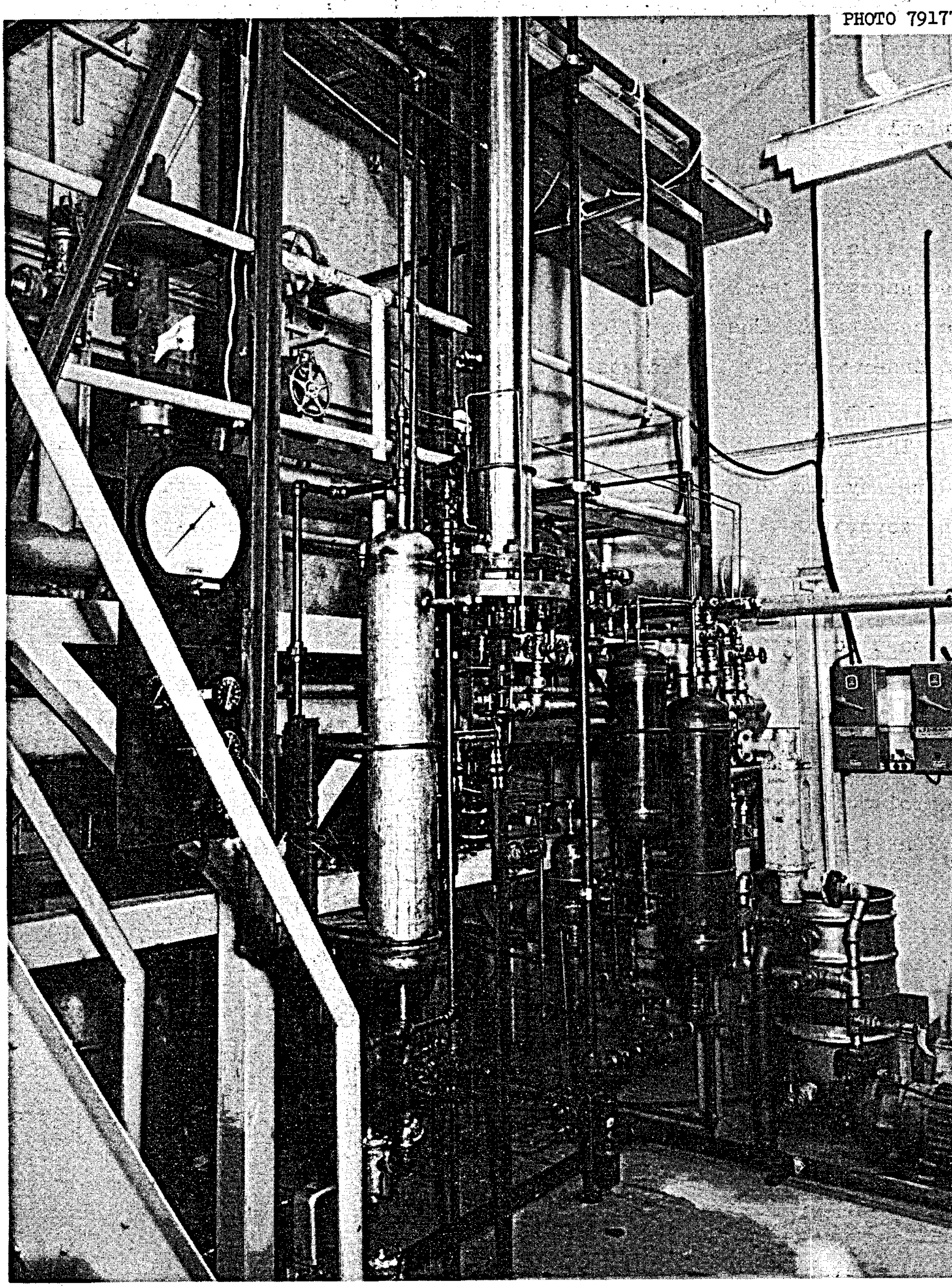

FIGURE 2. COMPLETED LOOP BEFORE BEING INSULATED

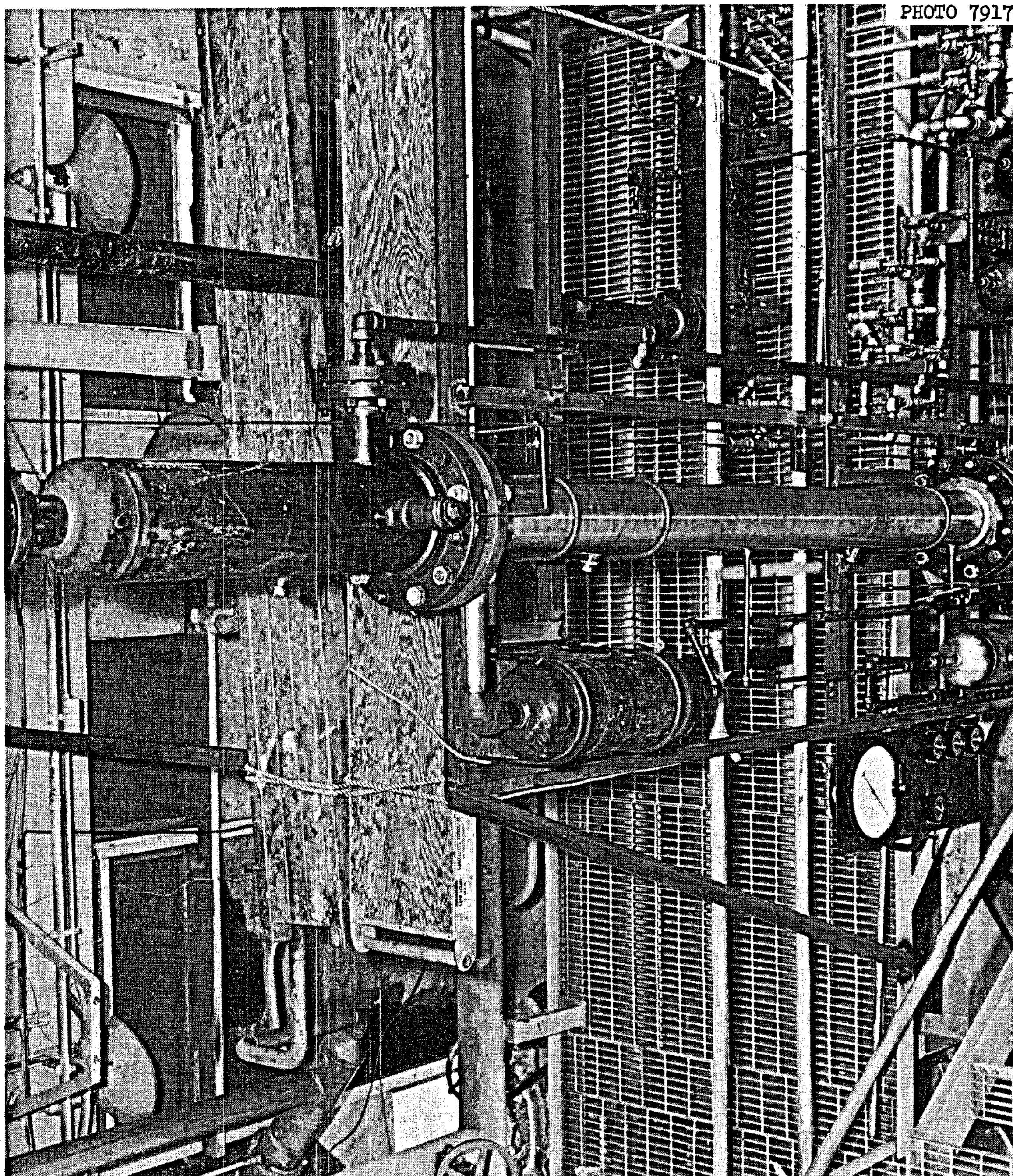

FIGURE 3. COMPLETED LOOP BEFORE BEING INSULATED

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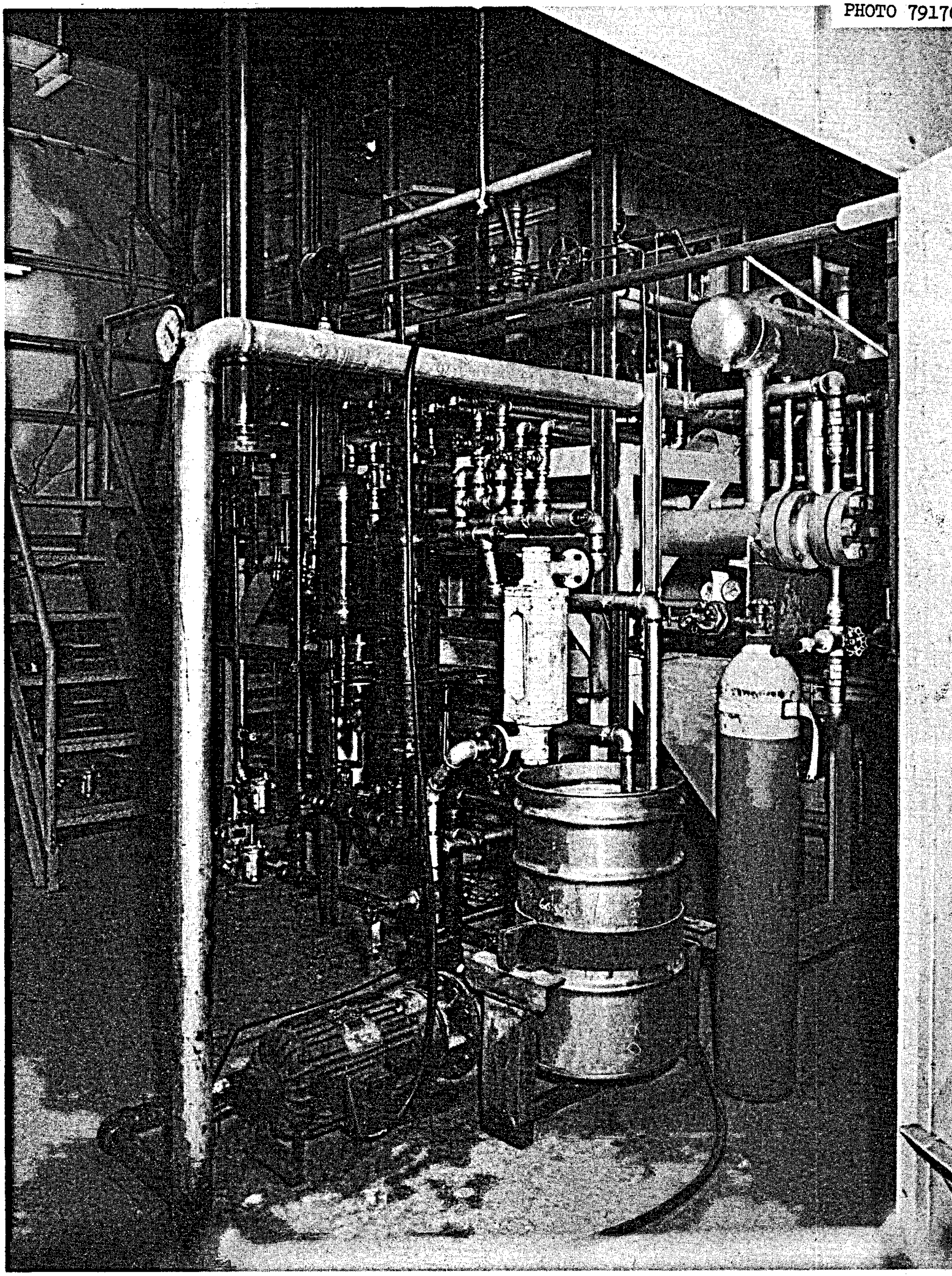

FIGURE 4. COMPLETED LOOP BEFORE BEING INSULATED

is an 8 in. 300 psi steel flange and the upper head is a 3 ft length of 8 in. Schedule 40 carbon steel pipe. Two pair of 1 in. diameter glass viewports are installed in the shell for visual observation of the mode of condensation. A pair of 1 in. diam. glass viewports is located in the upper head to observe the brine-vapor discharge jet.

The upper head contains a diagonal baffle to deflect the brine vapor discharge jet. A 6 in. depth of York wire mesh above the baffle provides for separation of entrainment from the vapor which discharges from the top of the vapor head.

The steam enters the shell near the upper end of the evaporator tube after passing through the external entrainment separator. Wall condensate is collected in a separate annular trough located near the bottom of the shell and is drained through a steam trap separate from the tube condensate.

Shell penetrations are provided for draining condensate ,for two vents (one at top and one at bottom) and for shell temperature sensors.

Brine Heater

The brine heater is a horizontal shell and tube steam condenser 4 inches in diameter and 6 ft long containing 20 1/4 in. OD tubes with a total heat transfer surface of 6 ft^2. The heater is fabricated of Inconel, including both shell and tubes. The steam is condensed in the shell of the exchanger and the condensate is drained through a steam trap.

Vapor Condenser

The vapor condenser consists of an 8 in. diameter carbon steel shell 3 ft long containing four horizontal bayonet coolers. Each bayonet is a 1 1/2 in. Schedule 40 carbon steel pipe containing a concentric 1 in. Schedule 40 carbon steel pipe extending to 2 in. from the opposite end. Water is circulated in through the inner pipe and out through the annulus. Three of the bayonets have 1.5 ft^2 area and one was 0.73 ft^2. The bayonets are connected in parallel such that any combination can be in service at a time.

Brine Pump

The pump is a triplex boiler feed pump consisting of three pistons in parallel with separate inlet and discharge ball check valves. The pump is belt driven by a 440 v, 3 phase, 3 horsepower motor and has a normal capacity of 2.5 GPM. The brine flow is regulated by varying the frequency to the pump motor, using a 25 hp variable frequency motor-generator manufactured by Louis Allis Company. The M-G set has an output frequency range from 12 to 70 cycles per second.

Piping

The material for the piping, volumetric tanks and other equipment is carbon steel. All pipe over 2 in. is seamless Schedule 40 with welded or flanged fittings. All piping less than 2 in. is Schedule 80 with threaded fittings. The steam piping is 1 1/2 and 2 in. diameter, the brine vapor piping is 3 in. and the brine and condensate piping is 1/2 and 1 in.

Adjustable Orifice

A right angle valve was modified to provide an adjustable orifice for flashing the brine entering the evaporator tube. The modification consisted of removing the valve seat to provide flow area and adding a valve stem extension with a 30° tapered titanium tip. The tip was aligned with and could pass through the tube inlet orifice located at the valve discharge to permit varying the flow area. The range of annular area was chosen to provide a range of pressure drop to prevent flashing upstream of the valve under all operating conditions.

Pulsation Damper

A standing leg with a 2 in. diameter by 6 in. long upper chamber is located immediately downstream of the pump discharge to damp the pump pulsations. A viewport in the chamber provides a means of insuring a gas interface. The chamber gas volume is connected to a N_2 cylinder for pressurization. The N_2 supply also is used to provide an inert gas blanket in both brine and steam systems to prevent corrosion during shutdowns.

Instrumentation

The brine flow is measured by the pressure drop across orifices. Two sharp edged orifices with flange taps are installed in series downstream of the pulsation damper. They are cross-connected to a common 100 in. of water d/p cell. The orifices are sized to provide full scale readings of 0.81 gpm and 2.7 gpm so that accurate readings can be obtained over the entire expected flow range.

The steam condensate and vapor condensate flow rates are measured by the rise time in calibrated tanks. The time of rise of the fluids in armored sightglasses is measured by closing the tank drain valves since in each case the normal flow of condensate is diverted into the bottom of the metering tank.

Flow rate of coolant to the bayonets of the vapor condenser and of makeup water to the coolant system are measured with variable orifice meters.

The steam and vapor pressures are measured with a 600 psi range calibrated Heise gage which has 1 psi subdivisions. The two phase fluid pressure drop across the evaporator tube and across the variable orifice is measured with pneumatic-operated d/p cells.

Eight calibrated stainless steel clad chromel-alumel thermocouples are located in the system as indicated in Figure 1. The thermocouples are read with an L and N null balance potentiometer with an ice bath for temperature compensation.

DATA REDUCTION

A sample data sheet is shown in Figure 5. The thermocouple emf's are converted to temperatures using calibration charts prepared by the ORNL Calibration Laboratory from individual calibration data obtained for each thermocouple. The temperatures and the flow readings are then combined in a computer data reduction program to yield the following parameters:

a. Brine flow (lb/hr)

b. Steam temperature (°F)

c. Brine outlet temperature (°F)

d. Flashdown (°F)

e. Steam-brine vapor ΔT (°F)

f. Tube average temperature (°F)

g. U, overall heat transfer coefficient (Btu/hr-ft^2-°F)

h. Residual U (Btu/hr-ft^2-°F)

i. Condensation group (X1)

j. Ratio of residual U to condensation group

k. Heat added by condensing steam, Btu/hr

l. Heat liberated by flashdown of vapor, Btu/hr

m. Heat removed by condenser water, Btu/hr

n. Heat removed from vapor condensate, Btu/hr

o. Calculated heat loss of vapor-brine separator, Btu/hr

Date ____________________ Run No. ____________________

Tube ____________________

Geothermal Brine Loop Data Sheet

Tube __________ Length __________ Wall

Brine Conc. __________ wt %

Spec.	Description	Reading	Value	R	V	
T1	Brine into Evaporator	mv	Temp.			
T2	Brine Out of Evap. Tube	"	"			
T3	Vapor Out of Evap. Tube	"	"			
T4	Bldg. Steam to Shell	"	"			
T5	Condensate from Shell	"	"			
T6	Condenser Water In	"	"			
T7	Condenser Water Out	"	"			
T8	Vapor Condensate					
P1	Brine Evap. - Inlet	psig				
P2	Steam, Evap. Shell	psig				
P3	Brine Vapor, Evap. Out	psig				
P4	Barometric Press.	mm Hg				
ΔP1	Evap. Tube ΔP FS=14.44	% FS	psi			
ΔP2	Feed Pump ΔP FS=50 in.	% FS	in H_2O			
ΔP3	Flashdown ΔP					
F1	Brine Flow FS=1500 lb/hr	% FS	lb/hr			
F2	Shell Condensate .029 ft^3/in.	in./sec	lb/hr	/		
F3	Cooling Water Flow	% FS	lb/hr			
F4	Vapor Condensate	in./sec	lb/hr	/		
A1	Condenser Sections	A+B+C+D	ft^2			
A2	Tube Area		ft^2			
L	Var. Orifice Stem Position	in.				

FIGURE 5. SAMPLE DATA SHEET

The computer program calculated parameters to assist in finding correlations. These calculations included:

1. Simplified average two phase pressure drop (ΔP_{TP}) using the Martinelli-Lockhart correlation.

2. The overall HTC based on the mean vapor temperature as derived from the calculated tube ΔP_{TP}.

3. The reduced overall HTC (ratio of the residual overall HTC to the condensation group).

Heat Balance

The latent heat given up by steam condensing on the tube is all utilized as latent heat in evaporating brine. Additional vapor is produced from the brine as a result of its flashdown from the temperature at the upstream side of the brine orifice to the temperature at the discharge end of the tube. Thus, except for heat losses, the sum of the steam condensate rate plus the brine flashdown rate will equal the vapor condensate rate.

Heat losses from the shell result in additional steam condensate forming on the shell wall, which is collected separately from the tube condensate and thus does not affect the above heat balance. Heat losses from the brine chest above the tube will result in condensation of a small portion of the vapor. This condensate will mix with the unevaporated brine and will not be measured as vapor condensate, nor will it be measured as temperature rise of the vapor condenser coolant. In order to account for this loss, the loop heat balance is written:

$$Q_{sc} + Q_{bf} = Q_{vc} + Q_{loss}$$

The magnitude of Q_{loss} was estimated from preliminary heat balances taken at several loop operating temperatures. An approximate equation describing the loss was derived:

$$Q_{lc} = 23\ (T_v - 80)$$

for use in calculating overall heat balances. For the purpose of determining the precision of measurement of a run, the following ratio was then calculated:

$$\frac{Q_{sc} + Q_{bf}}{Q_{vc} + Q_{lc}}$$

Calculation of Parameters

The following equations were used in calculating run parameters.

1. Evaporator shell heat load

$$Q_{sc} = W_s \left(h_{lg} + c_p \left(T_s - T_{sc}\right)\right)$$

2. Flashdown heat load

$$Q_{bf} = W_b \times cp_{(ave.)} \times (T_{Bi} - T_{Bo})$$

3. Vapor condensate heat load

$$Q_{vc} = W_{vc} \times h_{lg}$$

4. Heat removed by cooling water minus vapor condensate subcooling

$$Q_{cw} = W_{cw} \times c_p \left(T_{cw_o} - T_{cw_i}\right) - W_{vc}\, c_p \left(T_v - T_{vc}\right)$$

5. Overall heat transfer coefficient

$$U_1 = Q_{sc} / [A_T \times (T_s - T_v)]$$

6. Residual heat transfer coefficient

$$U_2 = 1/(1/U_1 - R_w) \qquad \text{where } R_w = \frac{do \ln \frac{do}{di}}{2K}$$

7. Calculated tube frictional pressure drop

$$\frac{\Delta P}{\Delta L}_{TP} = \phi^2_{tt} \left(\frac{\Delta P}{\Delta L}\right)_{\ell} \quad \text{for isothermal flow}$$

$$\phi_{tt} = \text{exponential}\ (1.478 - (.5403 \ln \frac{Wl}{Wv}) + .0519 \times (\ln \frac{Wl}{Wv})^2 + 6.98 \times 10^{-4} (\ln \frac{Wl}{Wv})^3$$

$$\frac{\Delta P}{\Delta L} = \frac{32\ f\ w^2}{\pi^2 \rho^2 g_c D^5} \times \rho_L / 62.4 \times .4332$$

$\Delta P_{calculated}$ (ΔP inlet cond. + ΔP outlet condition)/2

8. Tube average temperature

$T_{T\ in} = 1.8 \exp [4.61 + .2503 (\ln P - 2.686)] + 32$

$P = P_v \text{ (absol.)} + L \left(\frac{\Delta P}{\Delta L}\right)_{TP}$

$T_{T\ ave} = (T_{T\ in} + T_v)/2$

9. Overall heat transfer coefficient for tube ave temperature

$U_{T\ ave} = Q_{sc}/[A_T x (T_s - T_{T\ ave})]$

Nomenclature

Q	heat flow, Btu/hr
W	mass flow, lb/hr
T	temperature, °F
U	heat transfer coefficient, Btu/hr-ft^2-°F
A	area, ft^2
P	pressure, psi
L	length, ft
D	diameter, ft
h_{1g}	heat of vaporization, Btu/lb
cp	heat capacity, Btu/lb
k	thermal conductivity, Btu/hr-ft^2-°F/ft
f	Fanning friction factor
ρ_g	density, lb/ft^3
gc	conversion factor, 32.2

subscripts

sc	steam condensate
s	steam
bf	brine flashdown
b	brine
bi	brine in
bo	brine out
vc	vapor condensate
cw	cooling water
ϕ_{tt}	function
v	brine vapor
T	tube
tp	two phase
ℓ	liquid
tt	vapor phase turbulent, liquid phase turbulent
ave	average
absol	absolute
lc	heat loss, calculated

HEAT TRANSFER RESULTS

The following tubes were tested:

1. A smooth, 316 ss tube, 3/4 in. OD by 0.035 in. wall.

2. A double fluted, 90-10 CuNi tube, 1.01 in. nominal OD by 0.025 in. wall. The tube had 36 flutes with a depth of about 0.017 in. (Tube A in Figure 6) and was manufactured by French Tube Division of Noranda Metal Industries.

3. A double-fluted, Al-Brass tube, 0.875 in. nominal OD by 0.041 in. wall. This tube had 20 flutes with a depth of about 0.05 in. (Tube B in Figure 6) and was manufactured by Phelps-Dodge Copper Products Corporation.

The first two tubes were tested with demineralized water and ∿3% NaCl solution. The Al-Brass tube was tested with ∿3% NaCl solution. All tests were with liquid flow in the up direction with the liquid entering the tube with a 10-30°F total flashdown.

Table 2 shows the range of overall heat transfer coefficients (HTC) obtained at each temperature level. In Figures 7 through 12, the individual run HTC are plotted versus steam temperature with the liquid flow rate and steam exit vapor ΔT as parameters.

Tables 3 through 7 summarizes the heat transfer results for the different tests.

DISCUSSION OF RESULTS

Stainless Steel Smooth Tube

The results of both water and brine tests gave heat transfer coefficients which increased from 550 (±10%) at 250°F steam temperature to 765 (±10%) Btu/hr,sq.ft., °F at 350°-390°F. There was no significant difference between the water and brine tests, and no pronounced effect of either liquid flow or steam-vapor ΔT.

These results are consistent with upflow observations at the VTE Pilot Plant with smooth copper tubes evaporating seawater, where heat transfer coefficients of 450-675 were reported at 240-250°F evaporating temperature.[1]

Figure 9 is a graph of the ratio of the reduced overall HTC plotted vs. ΔT. This ratio was in the range 0.13 ± without significant trends as a function of T or ΔT.

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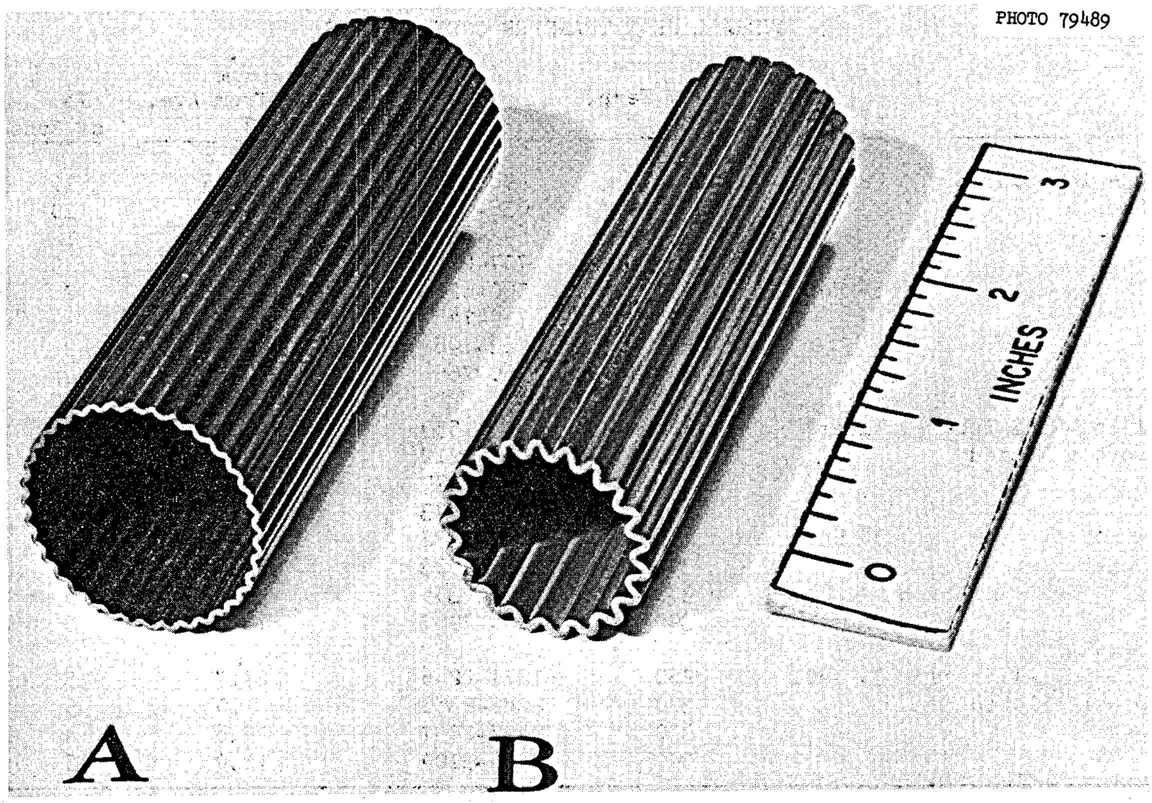

FIGURE 6. DOUBLE-FLUTED TUBES

TABLE 2

OVERALL HEAT TRANSFER COEFFICIENTS

Tube	Liquid	Steam Temp. °F	HTC Btu/hr/ft^2/°F	Maximum Dev. from Ave. %	No. of Runs
3/4 in. 314 SS Smooth	Water	250	498-602	9.45	10
		300	636-678	3.20	10
		350	693-889	12.9	12
		390	707-838	8.4	9
	3% NaCl	250	560-610	4.2	2
		300	719-748	1.6	2
		350	762-798	2.0	2
		390	760-765	0.4	2
1 in. CuNi Tube Double Fluted	Water*	250	1076-1553	16.5	6
		300	1664-2212	14.1	6
		350	1605-2377	19.4	6
		390	2126-2673	11.4	5
	3% NaCl	250	1825-2332	12	2
		300	2009-2523	11.3	5
		350	1950-2355	9.4	5
		390	2266-2967	13.4	5
7/8 in. Al Brass Double Fluted	3% NaCl	250	1271-2246	27.7	5
		300	2282-2386	1.9	5
		350	2437-2737	5.8	4
		390	2446-3109	11.9	5

*Does not include low value water runs made after the brine runs.

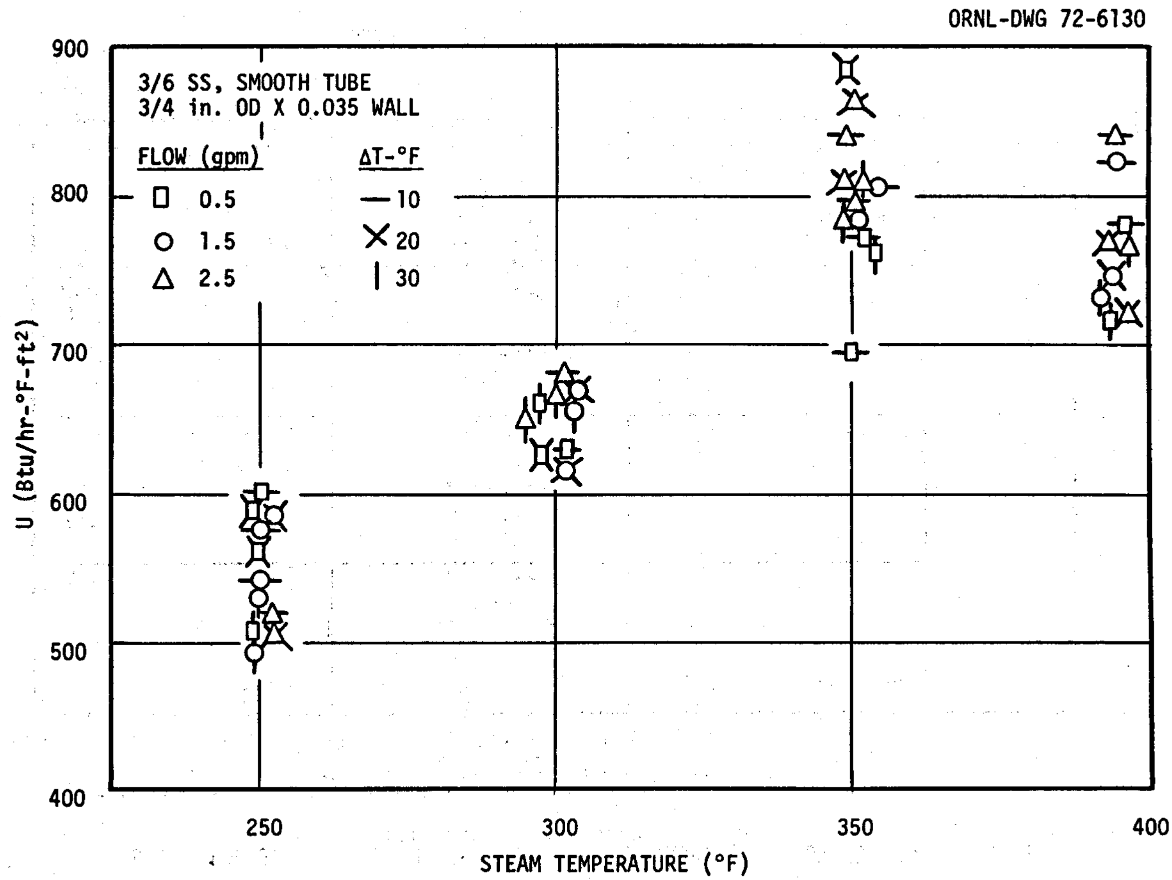

FIGURE 7. HEAT TRANSFER COEFFICIENT VS STEAM TEMPERATURE FOR WATER RUNS

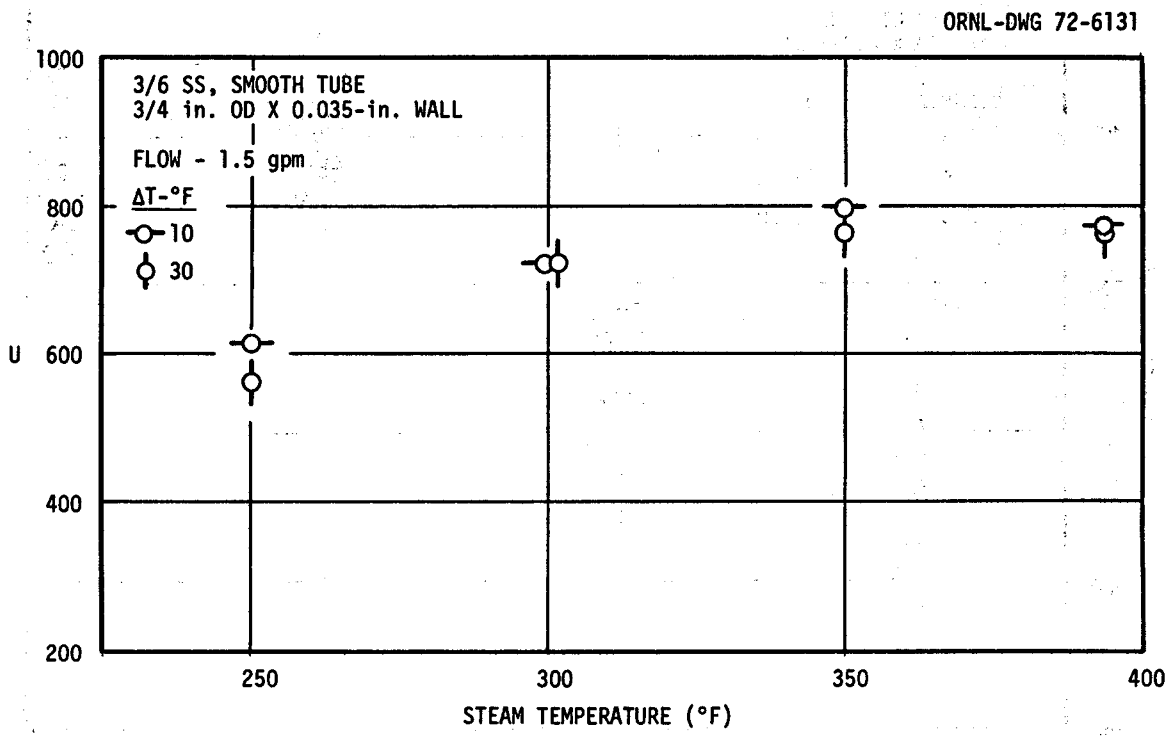

FIGURE 8. HEAT TRANSFER VS TEMPERATURE FOR 3% BRINE RUNS

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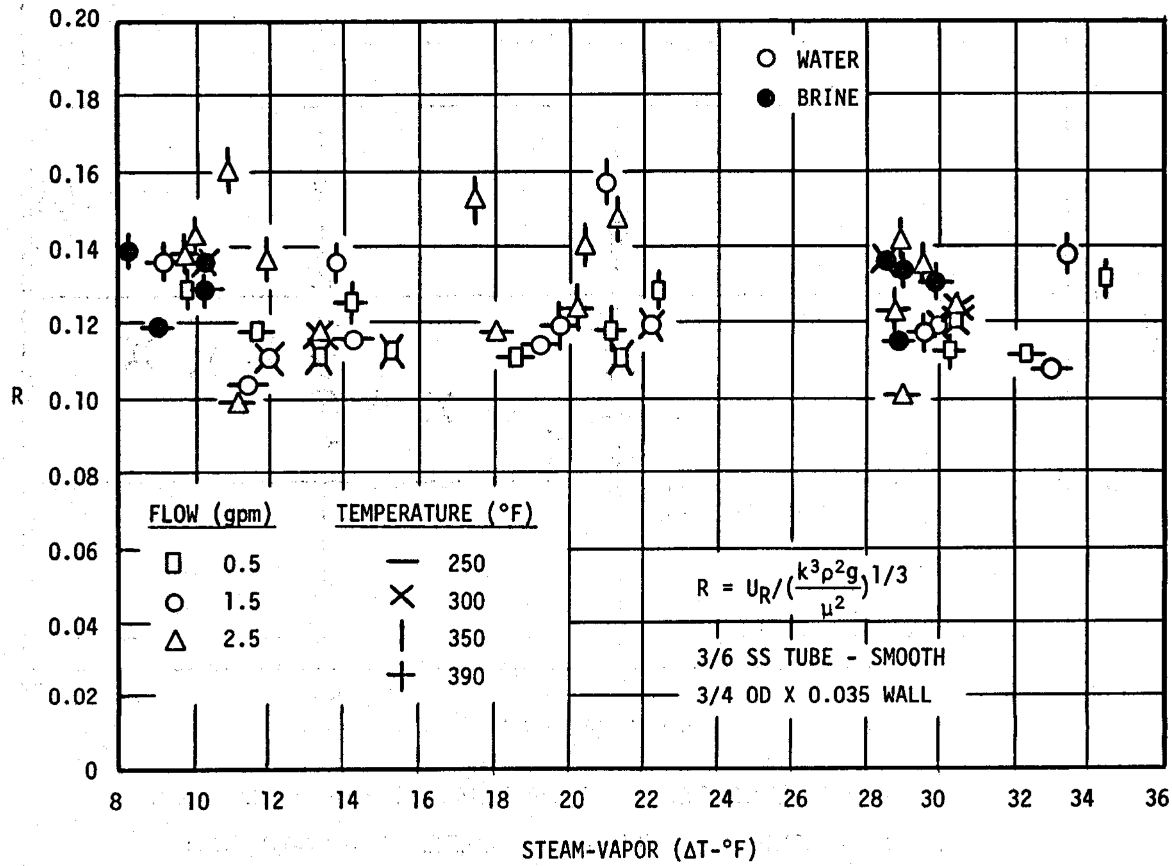

FIGURE 9. CONDENSATE GROUP CORRELATION OF HEAT TRANSFER

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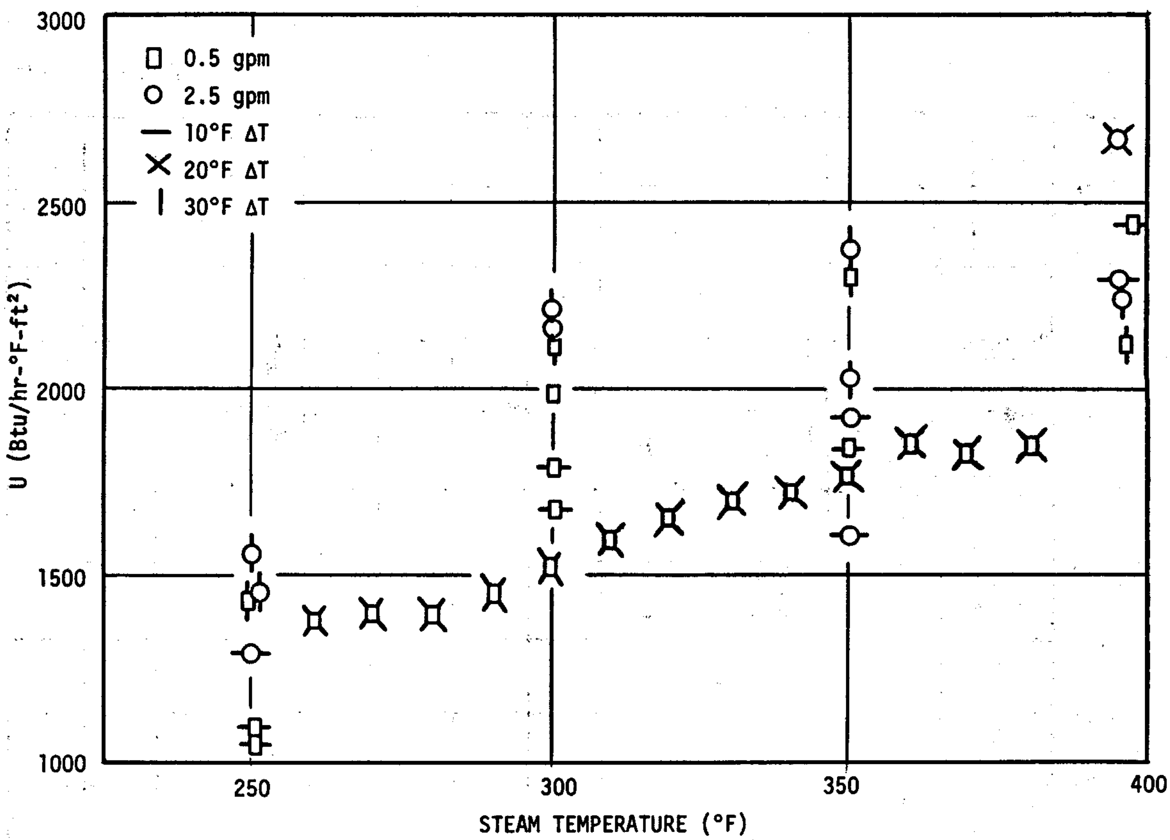

FIGURE 10. HEAT TRANSFER VS TEMPERATURE FOR WATER RUNS
1-IN. - DOUBLE FLUTED TUBE; MATERIAL -90-10 CUNI

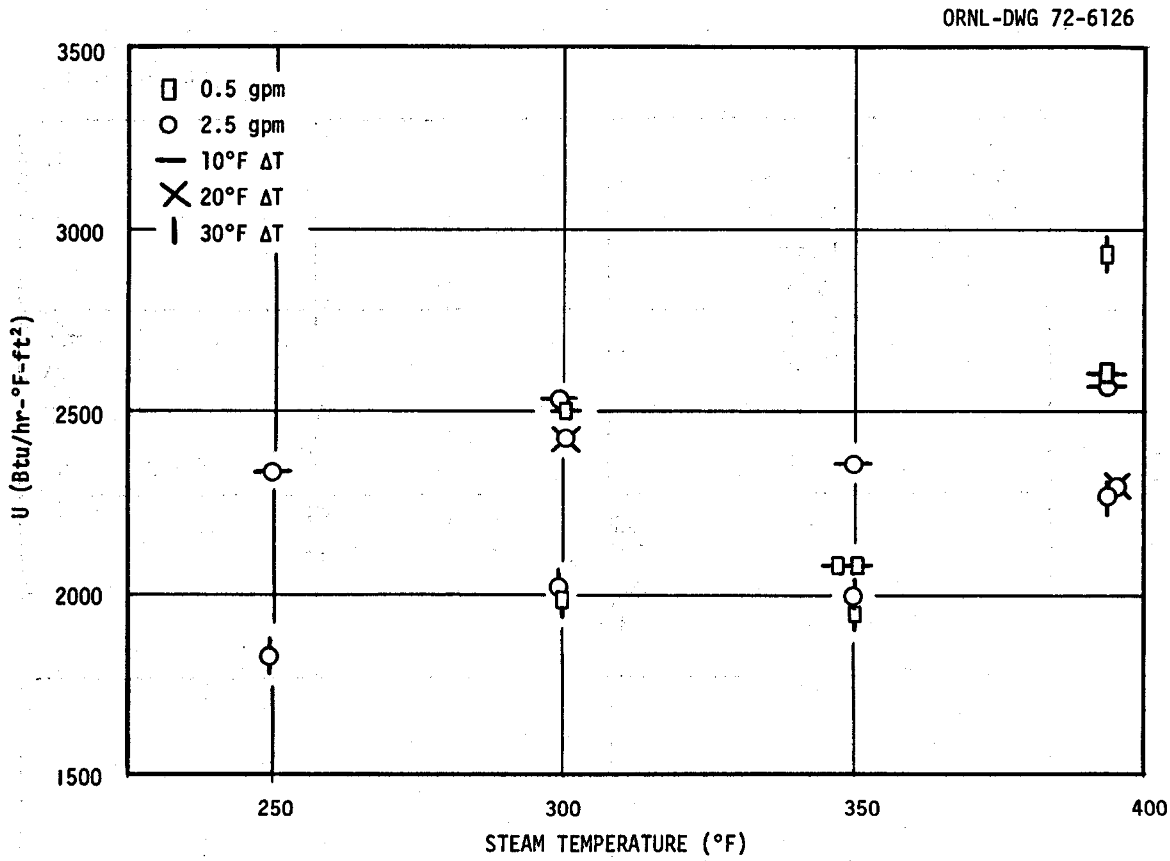

FIGURE 11. HEAT TRANSFER VS TEMPERATURE FOR 3% BRINE SOLUTION 1-IN. - DOUBLE-FLUTED TUBE; MATERIAL - 90-10 CUNI

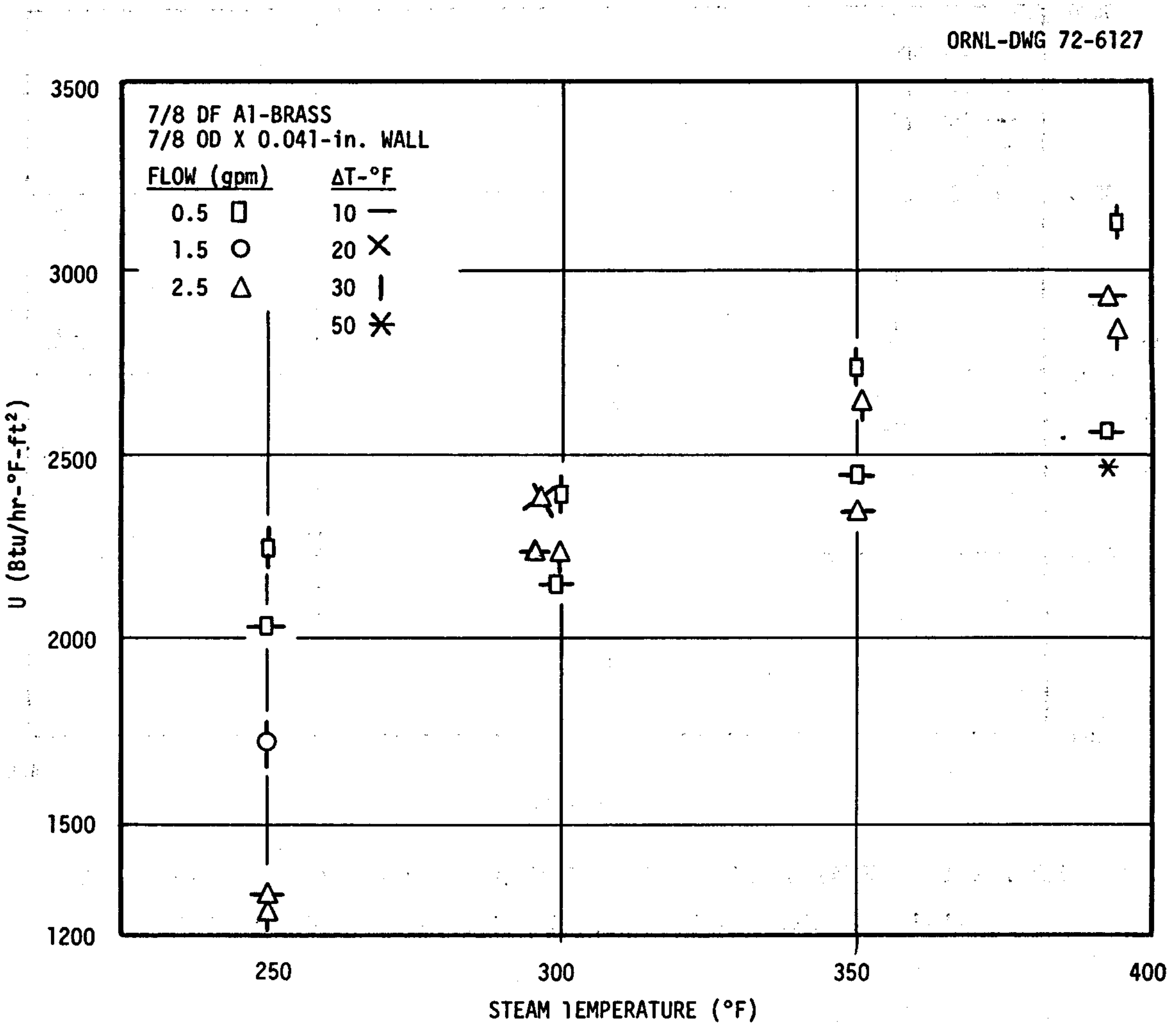

FIGURE 12. HEAT TRANSFER VS STEAM TEMPERATURE FOR 3% BRINE TESTS

TABLE 3

RUN RESULTS FOR 3/4 IN. SS TUBE WATER TESTS

Run No.	Flow lb/hr	Temperature: Steam °F	Temperature: Liquid Out °F	Temperature: ΔT Flashdown °F	Temperature: Steam-Vapor ΔT °F	U Overall Btu/hr/°F/ft²	Heat Load (Btu/hr): Steam Condensate	Heat Load (Btu/hr): Flashdown	Heat Load (Btu/hr): Vapor Condensate	Heat Loss Calculated	Heat Balance Ratio
1	1226	249.4	237.4	10.4	11.7	528	9303	13010	17554	3620	1.054
2	790	249.8	238	10.1	11.4	519	9381	8166	13218	3634	1.041
3	777	248.5	233.9	11.4	14.4	590	12841	9065	16918	3540	1.071
4	250	249.4	236.6	13.4	11.7	602	10632	3408	10542	3602	0.993
5	251	249.4	230.4	18.3	18.6	566	15903	4677	17588	3459	0.978
6	758	249.4	229.6	20.4	19.4	581	17046	15716	27241	3441	1.068
7	1242	249.7	230.9	16.5	18.1	596	16342	20923	32812	3471	1.027
8	1251	249.9	220.4	27.5	29	505	22124	35080	53674	3229	1.005
9	781	249.4	211.3	34.2	37.7	498	28335	27182	51882	3020	1.011
10	780	250.2	216.7	30.6	33.2	532	26665	24266	45639	3144	1.044
11	257	251.1	218.4	31.1	32.3	550	26874	8139	33652	3183	0.951
12	246	299.1	268.2	29.4	30.5	669	30881	7457	33332	4329	1.018
13	771	299.5	269.2	27.2	30.0	655	29672	21547	44333	4352	1.052
14	1234	297.0	259.3	33.8	37.0	652	36488	42914	66989	4133	1.116
15	1231	298.9	268.0	28.7	30.5	672	31007	36268	58234	4324	1.075
16											
17	256	299.3	276.7	20.5	22.4	669	22578	15965	35902	4524	0.953
18	1211	301.1	287.4	11.3	13.4	678	12776	14120	21432	4770	1.065
19	768	297.8	285.6	11.7	12.1	645	11749	9284	16217	4733	1.004
20	258	299.7	278.1	18.7	21.5	636	20635	9458	20612	4560	1.195
21	251	298.6	283	13.4	15.4	645	14993	3465	12880	4673	1.052
22	257	299	285.5	11.8	13.4	638	12951	3120	10257	4729	1.072
23	239	353.9	319.4	30.6	34.4	767	39864	7595	44047	5509	0.958
24	234	353.4	331	19.9	22.5	771	26221	4855	26269	5771	0.970
26	755	353.7	340	10.8	13.9	805	16915	8497	18213	5975	1.05
27	765	351.6	330.3	21.6	21.1	889	28376	17157	40133	5760	0.992
28	761	351.7	318.1	31.3	33.4	795	40133	24735	59950	5479	0.991
29	1186	351.7	323.9	24.8	29.2	811	35763	30539	60110	5578	1.009
30	1208	351.7	334.2	16.5	17.5	869	23032	20738	35378	5845	1.062
31	1190	352.3	330.7	18.7	21.4	844	27315	23182	44364	5771	1.007
33	1187	349.9	337.8	9.6	11.9	803	14441	11861	19731	5934	1.025
42	286	349.0	338.7	12.0	10.8	693	11340	3573	7113	5937	1.108
45	776	299.1	279.7	19.5	19.3	618	117980	15557	30751	4593	0.949
46	1201	391.4	362.1	28.2	28.7	752	32621	35496	63821	6488	0.969
47	1193	392.2	371.6	19.1	20.3	768	23557	23907	40530	6704	1.005
48	1189	392.6	382.5	8.2	9.6	838	12150	10235	13616	6958	1.088
49	718	393.1	383.5	7.7	9.2	822	11324	5807	10776	6980	0.965
50	721	393.2	373.0	18.7	19.8	745	22280	14143	30770	6739	0.971
51	724	392.2	361.7	29.3	30.0	733	33246	22221	51159	6479	0.962
52	257	393.4	362.7	28.3	30.2	707	32254	7618	36605	6502	0.925
53	260	394.1	372.5	19.1	21.1	733	23398	5205	22890	6728	0.966
54	265	394.9	380.3	11.4	14.2	777	16666	3169	14051	6907	0.946
57	1197	349.7	329.0	20.6	20.5	811	25126	25648	40865	5727	1.090
58	1189	350.7	340.7	9.1	9.9	836	12510	11264	16354	5998	1.064
59	235	350.1	339.9	9.6	10.0	775	11713	2355	8472	5982	0.973

TABLE 4

RUN RESULTS FOR 3/4 IN. SS TUBE WITH 3% BRINE

		Temperature					Heat Load (Btu/hr)				
Run No.	Flow lb/hr	Steam °F	Liquid Out °F	ΔT Flashdown °F	Steam-Vapor ΔT °F	U Overall Btu/hr/°F/ft^2	Steam Condensate	Flashdown	Vapor Condensate	Heat Loss Calculated	Heat Balance Ratio
300	771	250.4	241.7	10	9.3	610	8574	7598	12472	3703	1.00
301	798	249.4	220.6	30.4	28.9	560	24438	23842	44353	3232	1.015
302	765	300	271.8	29.7	28.6	719	31094	22553	47464	4402	1.034
303	771	299.8	290.8	10.5	9.8	748	11078	8054	14504	4830	0.990
304	751	347.5	340.7	10.7	8.0	798	9650	8064	12042	5969	0.984
305	742	349.8	321.7	30.1	29.4	762	33849	22345	52872	5529	0.962
306	760	387.5	359.3	28	29.6	765	34218	21434	51460	6392	0.962
307	761	387.5	378.7	10.1	10.1	760	11596	7771	12819	6840	0.985

TABLE 5

RUN RESULTS FOR DOUBLE FLUTED CUNI TUBE WATER TESTS

Run No.	Flow lb/hr	Temperature: Steam °F	Temperature: Liquid Out °F	Temperature: ΔT Flashdown °F	Temperature: Steam-Vapor ΔT °F	U Overall Btu/hr/°F/ft²	Heat Load (Btu/hr): Steam Condensate	Heat Load (Btu/hr): Flashdown	Heat Load (Btu/hr): Vapor Condensate	Heat Loss Calculated	Heat Balance Ratio
101	1257	249.5	239.5	10.3	9.7	1296	25578	13213	35335	3675	0.994
102	1267	249.4	222.4	27.2	26.5	1553	83740	35113	116231	3287	0.994
103	259	247.7	217.8	30.9	29.7	1439	86985	8154	93769	3174	0.981
104	1292	250.4	221	28.9	29.1	1456	86273	38038	123041	3250	0.984
105	261	250	239.9	11.4	9.9	1084	21834	3034	21628	3682	0.983
106	261	249.6	240	9.9	9.5	1076	20809	2638	20119	3682	0.985
107	251	300.4	289.4	10.6	10.9	1664	36905	2742	35736	4818	0.978
108	252	299.9	269.8	30.1	29.9	2130	129586	7810	135308	4370	0.984
109	254	300	279.4	20.7	20.5	1990	83012	5405	85936	4588	0.977
110	1258	300.1	269.7	29.9	30.3	2171	133887	38684	164601	4365	1.021
111	1220	300.2	289.6	10.5	10.5	1782	38067	13207	47770	4823	0.975
112	255	299.8	269	30.5	30.6	2212	137738	8013	143153	4352	0.988
113	239	349.9	320.3	27.3	29.5	2307	138511	7278	140138	5529	1.001
114	245	349.9	339.2	10.1	10.1	1840	37826	2576	35911	5975	0.964
115	1233	349.8	340	10.1	9.7	1605	31674	12964	37507	5982	1.026
116	1244	349.9	321	28.9	28.7	2831	118593	37364	138621	5548	1.082
117	1241	350.1	319.4	30.9	30.6	2377	148009	39835	178162	5508	1.023
118	1246	349.7	339.7	10.4	9.9	1926	38848	13429	46279	5974	1.000
119	1215	391.4	381.9	9.5	9	2300	42127	12146	45795	6954	1.029
120	1219	390.5	372.8	18	17.5	2673	95066	23057	114856	6739	0.971
121	1191	391.7	361	31.4	30.4	2254	139397	39196	170943	6469	1.007
122	222	372	361	30.1	31.1	2126	134708	7024	135670	6461	0.997
123	219	394.7	382.1	11.7	12.1	2443	59899	2690	57992	6961	0.964
200	254	260	239.1	20.3	20.6	1386	58098	5268	61661	3666	0.970
201	253	269.3	249.1	21.1	20	1398	56893	5457	60987	3894	0.961
202	250	279.1	260.8	19	18.1	1398	51476	4873	54586	4163	0.959
203	248	289.2	270.7	19.3	18.5	1445	54402	4924	56522	4386	0.974
204	251	299.4	280.1	19.2	19.1	1517	58959	4966	60263	4607	0.985
205	242	310.3	289.9	20.9	20.3	1600	66109	5225	68754	4830	0.969
206	240	319.9	299.9	19.8	20	1650	67134	4922	68386	5058	0.981
207	237	330.1	310.6	19.2	19.5	1700	67478	4714	67094	5304	0.997
208	233	339.6	319.9	20	19.6	1720	68591	4842	68745	5520	0.989
209	233	349.5	330	19.8	19.5	1774	70384	4789	71541	5750	0.973
210	224	360.2	340.3	19.1	19.8	1849	74501	4460	73376	5989	0.995
211	229	369.5	349.3	19.9	20.1	1829	74792	4761	74983	6196	0.980
212	226	380.6	360.4	19.4	20	1856	75549	4596	74899	6454	0.985

TABLE 6

RUN RESULTS FOR DOUBLE FLUTED CUNI TUBE 3% BRINE TESTS

Run No.	Flow lb/hr	Temperature: Steam °F	Temperature: Liquid Out °F	Temperature: ΔT Flashdown °F	Temperature: Steam-Vapor ΔT °F	U Overall Btu/hr/°F/ft^2	Heat Load (Btu/hr): Steam Condensate	Heat Load (Btu/hr): Flashdown	Heat Load (Btu/hr): Vapor Condensate	Heat Load (Btu/hr): Heat Loss Calculated	Heat Balance Ratio
125	246	300.3	292.2	9.3	8.8	2508	44867	2274	42088	4866	1.004
126	247	299.6	269	33.8	31.0	2000	125975	8126	134421	4339	0.966
127	1238	299.4	290.5	11.8	9.2	2523	47346	14498	52294	4834	1.083
128	1265	299.6	269.9	31.8	30.0	2009	122476	39837	152044	4361	1.038
129	1255	299.9	279.9	22.6	20.3	2424	99970	28172	105129	4592	1.168
130	1274	249.7	239.3	11.2	10.5	2332	49738	14454	60157	3661	1.006
131	1279	249.2	219.7	30.3	29.3	1825	108838	38054	143253	3218	1.003
132	242	349.4	338.4	13.3	12.7	2067	53428	3223	43535	5904	1.146
133	240	350.1	339.2	12.5	12.6	2068	53028	3002	49790	5923	1.006
134	244	350.3	320.8	31.3	30.4	1950	120660	7505	120402	5518	1.018
135	1259	349.8	320.2	31.8	29.9	1983	120677	40017	148278	5518	1.045
136	1247	349.6	340.4	11.6	9.7	2355	46495	14512	54737	5978	1.005
137	1205	389.8	379.9	11.2	10.8	2573	56550	13626	62334	6877	1.014
138	1227	387	358.6	29.5	28.7	2262	132127	36404	156766	6401	1.033
139	1222	389.2	370.4	21.2	19.6	2289	91287	26119	107822	6661	1.026
140	228	387.8	377.1	12.4	12	2598	63454	2834	60235	6803	0.989
141	233	387.4	360.8	27.5	29.7	2927	176884	6159	173091	6387	1.020

TABLE 7

RUN RESULTS FOR 7/8 IN. DOUBLE FLUTED AL-BRASS TUBE - 3% BRINE TESTS

Run No.	Flow lb/hr	Temperature: Steam °F	Brine Out °F	ΔT Flashdown °F	Steam-Vapor ΔT °F	U Overall Btu/hr/°F/ft^2	Heat Load (Btu/hr): Steam Condensate	Flashdown	Vapor Condensate	Heat Loss Calculated	Heat Balance Ratio	Tube ΔP psi
400	247	298.6	289	11.8	10.6	2144	40065	2889	42067	4784	0.917	--
401	248	350.0	271.1	30.6	29.6	2386	124533	7401	128155	4379	0.995	--
402	1299	300.1	271.8	30.4	28.4	2226	111238	39116	134820	15534	1.080	--
403	1309	300.2	281.1	21.4	19.5	2380	81832	27810	98784	4616	1.060	--
404	1306	299.7	291.3	10.5	9.1	2222	35655	13632	45568	4844	0.978	--
405	1287	350.5	342.4	10.3	9.4	2437	40382	13171	38459	6005	1.204	--
406	1275	351	321.4	31.3	29.9	2635	138900	39868	173704	5545	0.997	--
407	234	350.8	320.4	30.5	32.8	2737	158268	6856	162787	5434	0.981	1.656
408	227	350.7	341.4	11.6	10.6	2537	47415	2626	47021	5982	0.944	0.792
409	224	383.4	373.5	10.0	11.5	2547	51647	2252	49527	6714	0.958	1.152
410	1264	382.3	373.1	10.9	10.3	2903	52727	13906	57096	6716	1.044	2.52
411	1286	384.4	334	51.0	50.7	2446	218590	65670	268398	5835	1.037	3.6
412	1271	250.3	241.5	9.2	9.6	1302	22043	11520	25956	3696	1.132	2.232
413	1293	250.5	220.7	30.6	29.6	1271	66345	38872	102234	3241	0.988	>7.2
414	293	250.2	241.6	11.5	9.1	2025	32492	3314	33181	3705	0.971	1.656
415	295	250	221.2	30.0	29.0	2246	114844	8629	112499	3243	1.067	4.032
416	830	250.4	221.9	29.7	28.6	1722	86831	24189	97863	3261	1.098	6.408
417	252	388.3	359.7	29.7	32.8	3109	179772	7224	181291	6337	0.997	3.96
418	1234	387.4	356.6	29.9	31.7	2830	158174	37091	181778	6341	1.038	4.03

Copper-Nickel Fluted Tube

The overall heat transfer coefficients are plotted in Figures 10 and 11 for water and brine, respectively. The following generalizations appear justified.

Water Runs

At each steam temperature, the heat transfer coefficient increased with increased liquid flow and also with increased steam-vapor ΔT; the only exceptions were the 20°F ΔT point at 390°F and the low 10°F point at 350°F.

A series of measurements of HTC at 10°F increments were run with plain water, following the brine tests. The results of these tests (Figure 10) indicated the expected steady increase in HTC with increased temperature. The general reduction in overall coefficients from values in the earlier runs indicated fouling of the tube surface. A fouling resistance was calculated for runs at 2.5 gpm and a 20° ΔT for plain water tests before and after the brine runs. At 300°F the fouling factor was 0.000157, while at 350°F the fouling factor was .000064. An inspection of the tube after its removal indicated a thin film on the outside of the tube which gave a dull, light purplish cast to the metal, and some black streaks in a few of the external grooves. The inside of the tube had a generally darker coloring which appeared smooth when a light shined through the tube.

Brine Runs

The plot of overall HTCs for the brine tests versus temperature appears to reflect the buildup of fouling noted above. At 250°F the HTC was more than 50% greater than for plain water runs, while at 390°F, there was only a 2% increase, with a drop in the coefficient being observed between the 300°F and the 350°F tests. In addition, the brine runs showed the opposite effect of flow and steam-vapor ΔT compared to the water runs; with lower HTCs as the ΔT and/or flow increased for a given steam temperature.

The reduced overall HTC varied in the range .29 - .49 reflecting the flow rate and ΔT effects. This variation would be expected if the major heat transfer resistance were the liquid-vapor film, which is the expected situation in double fluted tubes.

TABLE 8

PRESSURE DROP IN 7/8 IN. OD, DOUBLE FLUTED AL-BRASS TUBE

Run No.	Flow lb/hr	Vapor Flashed lb/hr	Total lb/hr	Vapor Flash ft3/hr	Volume Total ft^3/hr	ΔP Measured	Calc. ΔP (min. ID)	Steam Temp. °F	ΔT Flashed
412	1270	12.1	35	195	484	2.232	1.508	250	9.2
413	1293	40.3	109	933	2521	>7.22	5.867	250	30.6
414	293	3.5	38	57	620	1.656	0.431	250	11.5
415	295	8.9	128	207	2959	4.032	2.517	250	30.0
416	830	25.0	115	579	2661	6.408	4.222	250	29.7
407	234	7.6	184	39	904	1.656	0.929	351	30.5
408	226	3.0	57	11	190	0.792	0.209	351	11.6
409	225	2.6	63.3	7	159	1.152	0.176	383	10.0
410	124	16.3	78.2	42	200	2.52	1.100	382	10.9
411	1286	74.3	660	303	2703	3.6	5.634	284	51.0
417	252	8.3	216	26	667	3.96	0.775	388	29.7
418	1234	42.8	225	132	694	4.032	3.162	387	29.9

The HTCs at 250°F appear to be consistent with results reported by L. G. Alexander and H. W. Hoffman for fluted tube heat transfer surfaces with liquid flow in the down mode,[2,3] as well as upflow VTE data of H. H. Sephton[4] and of the VTE Pilot Plant.[1]

Aluminum-Brass Fluted Tube

This tube was tested with brine only. The HTC versus steam temperature are shown in Figure 12. The results were consistent with results obtained with the CuNi tube. The average HTC at 300°F was about the same for the two tubes, while at 350°F and 390°F, the HTC for this tube was somewhat higher than the CuNi tube. This could have been due to the buildup of fouling on the latter tube.

At 250°F the tube showed a large change in coefficient with flow rate. At 0.5 gpm brine flow, the HTC was about the same as the CuNi tube (2025-2246), but it dropped drastically at 2.5 gpm brine flow, suggesting profound change in flow characteristics. This was not entirely a pressure drop effect since the measured pressure drop at high flow and low ΔT was less than that for the low flow and high ΔT case.

Pressure Drop Measurements

Although concentrating on heat transfer measurements, pressure drop measurements were also obtained for all three tubes using a differential pressure transmitter which sensed the pressure drop between the entrance of the tube and the vapor disengagement volume at the discharge of the tube. The measured value thus included the tube friction pressure drop, accelerational loss and the static head of the two phase system.

Due to instrumentation difficulties, no reliable measurements were obtained on the smooth stainless steel tube or on the CuNi tube. A few reliable pressure drop measurements were obtained on the deep fluted Al-Brass tube and these are presented in Table 8, along with the weight of liquid flashed and total liquid vaporized. Calculated tube frictional pressure drop using the minimum inside tube diameter are also shown, but are generally much below the observed total ΔP, since they do not include either the static head or the exit head losses.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from this series of experiments are in general agreement with results obtained for smooth and double fluted tubes at lower temperatures, in both upflow and downflow. The trend of increasing evaporative heat transfer coefficients with temperature is maintained in the temperature range 250-400°F.

The heat transfer coefficients for the double fluted tubes indicate an improvement over the smooth tube by a factor of 2-2.5, with salt solutions giving higher values than plain water.

More effort than expended in this preliminary investigation would be required to get definitive correlations for the effect of discrete parameters such as brine concentration, ΔT, feed rate and type of nozzle. The pressure drop data were also too limited for correlation, although no unusual response to any of these variables was observed.

In the interim, it is recommended that the values of overall HTC obtained in this study be used as a basis for design of pilot plant scale evaporators operating in the temperature range 250-400°F.

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4. H. H. Sephton (U. of Calif.), Monthly Report for January 1971, OSW Contract No. 14-30-2559 (February 19, 1971).

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