DOE/SF/00962--T4

MASTER

LMFBR DEMONSTRATION PLANT
STEAM GENERATOR

PRELIMINARY THERMAL/HYDRAULIC SIZING CALCULATIONS FOR DUPLEX
TUBE EVAPORATOR/SUPERHEATER
(INTERCHANGEABLE UNITS)

REVISION 1

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1.0 Thermal/Hydraulic Analysis Results

1.1 Introduction

This is a preliminary thermal/hydraulic report reflecting work under Subtask 6.2 of Ref. 1.1. This report is an extension of the previous thermal/hydraulic design report, Ref. 1.2. Parts of this report have been transmitted to GE in References 1.3 and 1.4 (filled in Ref. 1.5). The three most important references used in arriving at an updated design basis are as follows:

- (1) Steam Generator Specification, Ref. 1.6.
- (2) Bench Test Results, Ref. 1.7.
- (3) GE Review, Refs. 1.8 and 1.9.

1.2 Thermal/Hydraulic Design Basis

The detailed design basis, listed by source, is given in Table 1.1. Additional details are discussed in Section 2.0 of this report, Thermal Sizing Methods. Specific items which reflect Task 6 analysis are as follows:

- . Sodium Side Pressure Drop and Bypass (Section 1.3)
- . Water and Sodium Side Heat Transfer Correlation Uncertainty Analysis
- . DNB Study (Section 2.2.2.2)
- . Bench Test Results (Section 2.3.1)
- . U-Bend Effectiveness and Tube Length Variation Study (Section 2.4.1)
- . Inlet and Outlet Plenum Performance (Section 2.4.2.)
- . Non-Uniform Tube Heating Due to Flow Distribution Uncertainties (Section 2.6.2.)
- . Heat Loss Estimate (Section 2.10)
- . Stability Analysis (Section 2.8)
- . Natural Circulation Capability (Section 2.9)

Table 1.1
Thermal/Hydraulic Design Basis

Sodium Heated Steam Generator
Specification Data

Total plant duty, MWt (three loops).....	975
Number of steam generator loops in plant.....	3
Duty per loop, MWt.....	325
Flow per loop, lb/hr	
Sodium.....	12.75×10^6
Feedwater/steam.....	1.11×10^6
Feedwater inlet to steam drum temperature, °F.....	450
Superheater outlet steam temperature, °F.....	905
Superheater outlet steam pressure, psig.....	1525
Pressure drop, steam drum to superheater inlet, psig..	26
Pressure drop, evaporator outlet to steam drum, psig..	29
Superheater sodium inlet pressure.....	160
Superheater sodium inlet temperature, °F.....	936
Evaporator sodium outlet temperature, °F.....	651
Recirculation ratio (maximum).....	2:1
Thermal conductivity (2½Cr-1Mo), Btu/hr-ft-°F.....	26-0.0055T(°F)
Maximum water/steam pressure drops	
Evaporator, psi.....	110
Superheater, psi.....	200
Maximum sodium pressure drop for combined evaporator and superheater, psi.....	50
Tubes plugged during fabrication, %.....	1
Sodium side fouling, hr-ft ² -°F/Btu.....	0.0

Table 1.1 (Cont.)

Bench Test Results

Uniform gap thickness, in.....	0.00025
Uniform thermal resistance of as-built annealed duplex tube interface, $\text{hr-ft}^2\text{-}^\circ\text{F/Btu}$	0.0005
Long-term thermal degradation of duplex tube interface factor, applied to overall wall thermal resistance.....	1.15

GE Review

Water/steam side fouling, $\text{hr-ft}^2\text{-}^\circ\text{F/Btu}$	
based on inside tube surface.....	0.000300
based on outside tube surface.....	0.000483

Task 6 Analysis

Tube O.D., in.....	0.875
Tube I.D., in.....	0.543
Maximum tube length, ft.....	86.1
Minimum tube bend radius, in.....	36
Tubes plugged during operation, %.....	2
U-Bend active area, %.....	50
Overall contingency factors:	
Water/steam and sodium side heat transfer correlation uncertainties, %.....	5
Non-Uniform tube heating, water/steam and sodium side flow distribution uncertainties.....	10
DNB exfoliation fouling allowance (evaporator only),%..	15
Water/steam pressure loss contingency factors:	
Evaporator.....	1.50
Superheater.....	1.25

1.3 Thermal/Hydraulic Analysis Results

The analysis results are summarized in Table 1.2. Detailed computer printouts are also given as follows:

Figure or Table Title	Evaporator	Superheater
Temperatures and Water/Steam Pressure Profiles	Figure 1.1	Figure 1.3
Pressure and Heat Flux Profiles	Figure 1.2	Figure 1.4
Summary Data	Table 1.3	Table 1.6
Heat Transfer Data	Table 1.4	Table 1.7
Film Coefficients and Resistances	Table 1.5	Table 1.8

Results are summarized as follows:

Two recirculating evaporator units each rated at 119 MWt are required for each of three Demonstration Plant heat transport loops. At full power 6,375,000 lbs/hr of sodium at 859°F enters the inlet nozzle located near the top of the long leg. It is then uniformly/distributed over the tube bundle by the inlet cylindrical baffle, flows downward through flow holes in the tube support plates, turns 180° in the U-shell and exits the unit at 651°F. On the tube side, 1,110,000 lbs/hr of subcooled recirculating water at 540°F and 1750 psia enters the tube bundle at the top of the short leg. It then flows down the short leg and up the long leg where it is heated to 50.0 quality steam at 615.7°F and 1730 psia. Static/intermittent flow helium is maintained in the intratubesheet plena and duplex tube interface/groove region at approximately 100 psi above the sodium pressure for the purpose of providing a leak detection capability.

One superheater unit rated at 87 MWt is required for each of the three Demonstration Plant heat transport loops. At full power 12,750,000 lbs/hr of sodium at 936°F enters the inlet nozzle located near the top

of the long leg. Following the same flow path described for the evaporator it exits at 859°F. On the tubeside, 1,110,000 lbs/hr of dry steam (provided by the moisture separator) at 609.2°F and 1650 psia enters the tube bundle at the top of the short leg where it is heated to 905°F and 1540 psia during its flow through the unit. The helium third fluid leak detection system is maintained at approximately 100 psi above sodium pressure in the same manner described for the evaporator.

The sodium side pressure drop allowances are 10/40 psi for evaporator/superheater respectively. The baffle spacing has not been determined but is expected to be in the 25" - 40" range. Sodium side pressure loss estimates show the sodium ΔP to be 10 psi/40 psi for 40" baffle spacing (17 baffles) and 14 psi/60 psi for a 25" baffle spacing (27 baffles). Pressure drop data in Table 1.2 supersedes pressure drop curves in Figures 1.2 and 1.4. Baffle-plate-to-shell-clearance flow is estimated to be 2% of the total flow.

Table 1.2
Thermal/Hydraulic Analysis Results

	<u>Evaporator</u>	<u>Superheater</u>
Number of Units per Loop	2	1
MWt Rating per Unit	119	87
Tube Diameter		
O.D., in.	0.875	0.875
I.D., in.	0.543	0.543
Number of Tubes per Unit	715	715
Maximum OAL, ft.	86.1	86.1
Central Tube OAL, ft.	80.45	80.45
Central Tube Under-Sodium Length, ft.	72.45	72.45
Sodium Side Parameters		
Sodium Flow Rate per Loop, #/hr.	12.75×10^6	12.75×10^6
Sodium Inlet Temperature, °F	859	936
Sodium Outlet Temperature, °F	651	859
Sodium Pressure Drop Allowance, psi	10	40
Water/Steam Side Parameters		
Water/Steam Flow Rate per Loop, #/hr.	2.22×10^6	1.11×10^6
Water/Steam Inlet Temperature, °F	540	609.2
Water/Steam Inlet Pressure, psia	1750	1650
Water/Steam Outlet Temperature, °F	615.7	905
Water/Steam Outlet Pressure, psia	1730	1540
Water/Steam Outlet Quality, %	50	-
Water/Steam Pressure Drop, psi	20	105

Table 1.2 (Cont.) Sodium Side Pressure Loss Calculations

Shell Side Pressure Loss	Flow Area Basis for Mass Velocity	Flow Area, In^2	k_t or $\lambda L/d_e$	Evaporator loss, psi	Superheater loss, psi
Inlet Nozzle Expansion (Sudden Expansion)	Inlet Nozzle Area	905	1	0.165	0.7
Entrance Flow Reversal	Bundle Free Flow Area	1083	2	.224	0.95
Baffle Loss	" "	"	4.2	12.73	54
Parallel Flow Loss	" "	"	5.5/4.7	0.62	2.25
Shell to U-Bend Sudden Expansion	" "	"	1	.224	0.95
U-Bend to Shell Sudden Contraction	" "	"	.5	.112	0.475
Shell to Outlet Plenum Sudden Expansion	" "	"	1.	.112	0.475
Outlet Plenum to Outlet Nozzle Sudden Contraction	Outlet Nozzle Area	905	.5	.082	0.35
Total Pressure Drops	For 27 Baffles:			14.27 psi	60.15 psi
	For 17 Baffles:			9.56 psi	40.15 psi

SSS TASK 6 EVAPORATOR

Figure 1.1

SSS TASK 6 EVAPORATOR

Figure 1.2

Table 1.3

TASK 6 EVAPORATOR

1

PHYSICAL DESCRIPTION

UNITS PER LOOP

TUBES PER UNIT, INCL. 42 TUBES FOR PLUGGING

1430

TUBE OD	0.8750		(IN)
TUBE ID	0.7150		(IN)
TUBE WALL THICKNESS	0.0800		(IN)
INNER TUBE OD	0.7145		(IN)
ID	0.5425		(IN)
WALL + INSUL. THK.	0.0860		(IN)
TOTAL TUBE LENGTH	78,450	941,399	(FT,IN)
ACTIVE TUBE LENGTH	72,450	869,399	(FT,IN)
TUBE MATERIAL			
SHELL MATERIAL			

OPERATING CONDITIONS

HEAT TRANSFER	240.73		(MWT)
ACTIVE HEAT TRANSFER AREA	20487.08		(FT ²)
WATER/STEAM FLOW	2220000.0		(LB/HR)
SODIUM FLOW	12750000.0		(LB/HR)
SODIUM INLET TEMP	859.29		(F)
SODIUM OUTLET TEMP	648.37		(F)
SODIUM PRESS DROP	2.42		(PSI)
WATER/STEAM INLET TEMP	540.00		(F)
STEAM OUTLET TEMP	615.74		(F)
STEAM INLET PRESSURE	1750.00		(PSIA)
STEAM OUTLET PRESSURE	1729.35		(PSIA)
STEAM PRESS DROP	20.65		(PSI)
ENTHALPY IN	535.496		(BTU/LB)
ENTHALPY OUT	905.597		(BTU/LB)

EVAPORATOR DATA

DNB	0.360		
PREHEAT LENGTH	34.78	417.31	(FT,IN)
BOILING LENGTH	37.67	452.09	(FT,IN)
SUPERHEAT LENGTH	0.0	0.0	(FT,IN)
SATURATION TEMP	615.90		(F)
LMTD (AVG)	97.22	157.41	(F)
U (AVG)	281.01	314.03	0.0 (BTU/HR*FT ² *F)

Table 1.3 (Cont.)

TASK 6 EVAPORATOR

SUBCASE	1	SODIUM		WATER		240,73 MWT	
FLOW		12750000,0	2220000,0			(LB/HR)	
TEMP IN		859,29	540,00			(F)	
TEMP OUT		648,37	615,74			(F)	
FLOW AREA		2357,61	320,60			(SQ IN)	
EQUIVALENT FLOW DIA		2,282	0,542			(IN)	
INLET ENTHALPY			535,496			(BTU/LB)	
INLET PRESSURE			1750,00			(PSIA)	
PRESS DROP		2,42	20,65			(PSI)	
Q		821623040,00				(BTU/HR)	
TOTAL NO. OF 180 DEG BENDS			0				
PRESSURE DROP LENGTH			941,40			(IN)	
NUMBER TUBES AFTER PLUGGING			1387				
TUBES AVAILABLE FOR PLUGGING			42				
HEAT TRANSFER AREA		20487,08				(SQ FT)	
DNB		0,360					
		PREHEAT	BOILING	SUPERHEAT			
Q	(SUM)	233576240,00	588046848,00	0,0	(BTU/HR)		
LMTD	(AVG)	97,22	157,41	0,0	(F)		
HEAT TRANSFER AREA		8517,11	11969,98	0,0	(SQ FT)		
U	(AVG)	281,01	314,03	0,0	(BTU/HR*FT2*F)		
HEAT TRANSFER LENGTH, IN.		417,31	452,09	0,0	(IN)		
NUMBER OF 180 DEG BENDS		0,	0,	0,			
RESISTANCE (TOTAL)		0,002737	0,002467	0,0	(HR*FT2*F/BTU)		
AVERAGES (STEAM)		0,000553	0,000265	0,0	(HR*FT2*F/BTU)		
(FOULING)		0,000483	0,000483	0,0	(HR*FT2*F/BTU)		
(WALL)		0,001466	0,001478	0,0	(HR*FT2*F/BTU)		
(SODIUM)		0,000236	0,000241	0,0	(HR*FT2*F/BTU)		
--- WATER/STEAM ---							
TEMP OUT		615,90	615,74	0,0	(F)		
PRESSURE DROP, TOTAL		1,16	16,72	0,0	(PSI)		
HEAD		2,09	4,69	0,0			
ACCELERATION		0,05	1,75	0,0			
PRESSURE OUT		1749,37	1732,64	0,0	(PSI)		
ENTHALPY OUT		640,710	905,597	0,0	(BTU/LB)		
REYNOLDS NUMBER OUT		226684,06	363906,19	0,0			
VELOCITY OUT		6,76	36,04	0,0	(FT/SEC)		
DENSITY		40,94	7,69	0,0	(LB/FT3)		
--- SODIUM ---							
TEMPERATURE IN		707,90	859,29	0,0	(F)		
REYNOLDS NUMBER IN		209682,06	243157,06	0,0			
VELOCITY IN		4,02	4,11	0,0	(FT/SEC)		
DENSITY		53,83	52,59	0,0	(LB/FT3)		

Table 1.4

TASK 6 EVAPORATOR				HEAT TRANSFER DATA		AREA	Q	ENTHALPY	QUALITY
SECTION	WATER	WALL	SODIUM	LMTD	OVERALL U				
--- PREHEAT ---									
0	540.00		648.37					535.496	
1	545.07	588.72	651.84	107.63	282.00	460.39	13658203.	541.648	
2	549.89	593.08	655.35	106.11	281.89	460.39	13815380.	547.871	
3	554.73	597.27	658.73	104.79	281.78	460.39	13315664.	553.869	
4	559.33	601.45	662.15	103.42	281.68	460.39	13436528.	559.921	
5	563.94	605.49	665.46	102.22	281.57	460.39	13014858.	565.784	
6	568.34	609.50	668.79	101.00	281.47	460.39	13063637.	571.668	
7	572.71	613.40	672.04	99.93	281.37	460.39	12763374.	577.418	
8	576.93	617.24	675.27	98.87	281.27	460.39	12679365.	583.129	
9	581.07	620.97	678.42	97.91	281.18	460.39	12337910.	588.687	
10	585.04	624.67	681.60	96.98	281.08	460.39	12490751.	594.313	
11	589.01	628.27	684.72	96.18	280.98	460.39	12230053.	599.822	
12	590.90	631.01	686.38	95.56	280.91	230.19	6487646.	602.745	
13	592.93	632.75	687.87	95.26	280.87	230.19	5873027.	605.390	
14	594.76	634.59	689.54	94.81	280.82	230.19	6540219.	608.336	
15	596.77	636.29	691.01	94.58	280.77	230.19	5738613.	610.921	
16	598.52	638.09	692.65	94.14	280.72	230.19	6437241.	613.821	
17	600.47	639.75	694.10	93.94	280.67	230.19	5670864.	616.375	
18	602.17	641.51	695.73	93.55	280.62	230.19	6374912.	619.247	
19	604.07	643.13	697.16	93.39	280.57	230.19	5624794.	621.781	
20	605.73	644.86	698.78	93.03	280.53	230.19	6325590.	624.630	
21	607.58	646.45	700.20	92.91	280.48	230.19	5586313.	627.146	
22	609.19	648.15	701.81	92.59	280.43	230.19	6282231.	629.976	
23	612.68	650.53	704.76	92.41	280.36	460.39	11560693.	635.184	
24	615.90	653.81	707.90	91.99	280.27	460.39	12268535.	640.710	
(AVG/TOTAL)	586.57A	1268.25A	683.43A	97.22A	281.01A	8517.11T	233576240.T	597.515A	
--- BOILING ---									
25	617.02	643.12	711.56	93.26	326.71	460.39	14310635.	647.156	0.009
26	616.98	644.57	715.20	96.37	326.54	460.39	14229757.	653.566	0.022
27	616.94	645.43	719.02	100.14	327.00	460.39	14938409.	660.295	0.035
28	616.90	646.32	723.05	104.11	327.47	460.39	15713489.	667.373	0.049
29	616.86	647.26	727.28	108.27	327.92	460.39	16523182.	674.816	0.064
30	616.82	648.25	731.72	112.65	328.33	460.39	17338656.	682.626	0.079
31	616.78	649.33	736.33	117.21	328.61	460.39	17988400.	690.729	0.095
32	616.73	650.40	741.18	121.98	329.00	460.39	18886768.	699.237	0.112
33	616.69	651.58	746.19	126.96	329.23	460.39	19557024.	708.046	0.129
34	616.65	652.79	751.40	132.11	329.48	460.39	20291952.	717.187	0.147
35	616.61	654.03	756.82	137.47	329.73	460.39	21105856.	726.694	0.165
36	616.56	655.28	762.52	143.07	330.07	460.39	22158144.	736.675	0.185
37	616.51	656.64	768.42	148.91	330.27	460.39	22975280.	747.024	0.205

38	616,46	658,04	774,56	154,98	330,48	460,39	23857088,	757,771	0,226
39	616,42	659,49	780,95	161,29	330,69	460,39	24822048,	768,952	0,248
40	616,36	660,98	787,60	167,86	330,89	460,39	25822144,	780,583	0,270
41	616,32	662,53	794,53	174,70	331,08	460,39	26890544,	792,696	0,294
42	616,26	664,14	801,74	181,82	331,26	460,39	27987808,	805,303	0,319
43	616,21	665,81	809,26	189,24	331,43	460,39	29152192,	818,435	0,344
44	616,14	705,61	815,63	196,25	268,45	460,39	24674496,	829,550	0,366
45	616,09	707,56	822,24	202,80	270,00	460,39	25575600,	841,070	0,388
46	616,02	709,60	829,09	209,59	271,46	460,39	26530224,	853,021	0,412
47	615,96	711,73	836,21	216,64	272,84	460,39	27546480,	865,429	0,436
48	615,89	713,96	843,61	223,97	274,14	460,39	28607664,	878,315	0,461
49	615,82	716,30	851,30	231,58	275,36	460,39	29710688,	891,698	0,487
50	615,74	718,75	859,29	239,49	276,49	460,39	30854048,	905,597	0,514
(AVG/TOTAL)	616,45A	1366,26A	776,79A	157,41A	314,03A	11969,98T	588046848,T	761,531A	
(TOTAL)						20487,08	821623040,		

Table 1.4 (Cont.)

Table 1.5

TASK 6 EVAPORATOR

1

SECTION	FILM COEFFICIENTS		FILM COEFFICIENTS AND RESISTANCES				TOTAL
	WATER	SODIUM	WATER	WALL	SODIUM	FOULING	
--- PREHEAT ---							
1	2916,3	4275,7	0,00055	0,00146	0,00023	0,00048	0,00273
2	2916,4	4272,2	0,00055	0,00146	0,00023	0,00048	0,00273
3	2916,5	4268,8	0,00055	0,00146	0,00023	0,00048	0,00273
4	2916,6	4265,4	0,00055	0,00146	0,00023	0,00048	0,00273
5	2916,7	4262,0	0,00055	0,00146	0,00023	0,00048	0,00273
6	2916,8	4258,6	0,00055	0,00146	0,00023	0,00048	0,00273
7	2916,9	4255,3	0,00055	0,00146	0,00023	0,00048	0,00273
8	2917,0	4252,1	0,00055	0,00146	0,00024	0,00048	0,00273
9	2917,1	4248,9	0,00055	0,00146	0,00024	0,00048	0,00274
10	2917,2	4245,7	0,00055	0,00147	0,00024	0,00048	0,00274
11	2917,2	4242,5	0,00055	0,00147	0,00024	0,00048	0,00274
12	2917,3	4240,1	0,00055	0,00147	0,00024	0,00048	0,00274
13	2917,4	4238,5	0,00055	0,00147	0,00024	0,00048	0,00274
14	2917,5	4237,0	0,00055	0,00147	0,00024	0,00048	0,00274
15	2917,4	4235,4	0,00055	0,00147	0,00024	0,00048	0,00274
16	2917,3	4233,8	0,00055	0,00147	0,00024	0,00048	0,00274
17	2917,1	4232,3	0,00055	0,00147	0,00024	0,00048	0,00274
18	2916,9	4230,7	0,00055	0,00147	0,00024	0,00048	0,00274
19	2916,7	4229,2	0,00055	0,00147	0,00024	0,00048	0,00274
20	2916,6	4227,6	0,00055	0,00147	0,00024	0,00048	0,00274
21	2916,4	4226,1	0,00055	0,00147	0,00024	0,00048	0,00274
22	2916,3	4224,6	0,00055	0,00147	0,00024	0,00048	0,00274
23	2916,1	4222,3	0,00055	0,00147	0,00024	0,00048	0,00274
24	2916,0	4219,2	0,00055	0,00147	0,00024	0,00048	0,00274
(AVG)	2916,8A	4243,5A	0,00055A	0,00147A	0,00024A	0,00048A	0,00274A
--- BOILING ---							
25	9813,1	4215,8	0,00016	0,00147	0,00024	0,00048	0,00235
26	9781,2	4212,2	0,00016	0,00147	0,00024	0,00048	0,00236
27	10017,5	4208,4	0,00016	0,00147	0,00024	0,00048	0,00235
28	10269,7	4204,5	0,00016	0,00147	0,00024	0,00048	0,00235
29	10526,9	4200,3	0,00015	0,00147	0,00024	0,00048	0,00235
30	10779,2	4196,0	0,00015	0,00147	0,00024	0,00048	0,00234
31	10974,7	4191,4	0,00015	0,00147	0,00024	0,00048	0,00234
32	11240,7	4186,7	0,00014	0,00147	0,00024	0,00048	0,00234
33	11433,6	4181,7	0,00014	0,00147	0,00024	0,00048	0,00234
34	11641,4	4176,6	0,00014	0,00147	0,00024	0,00048	0,00233
35	11867,4	4171,3	0,00014	0,00147	0,00024	0,00048	0,00233
36	12154,2	4165,7	0,00013	0,00147	0,00024	0,00048	0,00233
37	12370,7	4159,9	0,00013	0,00148	0,00024	0,00048	0,00233

38	12599,9	4153,8	0,00013	0,00148	0,00024	0,00048	0,00233
39	12846,0	4147,6	0,00013	0,00148	0,00024	0,00048	0,00233
40	13095,7	4141,0	0,00012	0,00148	0,00024	0,00048	0,00232
41	13357,0	4134,3	0,00012	0,00148	0,00024	0,00048	0,00232
42	13619,5	4127,2	0,00012	0,00148	0,00024	0,00048	0,00232
43	13892,3	4119,8	0,00012	0,00148	0,00024	0,00048	0,00232
44	2469,8	4112,9	0,00065	0,00149	0,00024	0,00048	0,00287
45	2537,9	4106,4	0,00064	0,00149	0,00024	0,00048	0,00285
46	2605,5	4099,8	0,00062	0,00149	0,00024	0,00048	0,00283
47	2672,5	4092,8	0,00060	0,00149	0,00024	0,00048	0,00282
48	2738,7	4085,6	0,00059	0,00149	0,00024	0,00048	0,00281
49	2803,7	4078,1	0,00058	0,00149	0,00025	0,00048	0,00279
50	2867,3	4070,4	0,00056	0,00149	0,00025	0,00048	0,00278
(AVG)	9268,3A	4151,5A	0,00026A	0,00148A	0,00024A	0,00048A	0,00247A

Table 15 (Cont.)

SSS TASK 6 SUPERHEATER

Figure 1.3

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SSS TASK 6 SUPERHEATER

Figure 1.4

Table 1.6

TASK 6 SUPERHEATER

1

PHYSICAL DESCRIPTION

UNITS PER LOOP

TUBES PER UNIT, INCL. 21 TUBES FOR PLUGGING

715

TUBE OD 0.8750 (IN)

TUBE ID 0.7150 (IN)

TUBE WALL THICKNESS 0.0800 (IN)

INNER TUBE OD 0.7145 (IN)

ID 0.5425 (IN)

WALL + INSUL. THK. 0.0860 (IN)

TOTAL TUBE LENGTH 78.450 941.399 (FT, IN)

ACTIVE TUBE LENGTH 72.450 869.399 (FT, IN)

TUBE MATERIAL

SHELL MATERIAL

OPERATING CONDITIONS

HEAT TRANSFER 87.86 (MWT)

ACTIVE HEAT TRANSFER AREA 10236.11 (FT²)

WATER/STEAM FLOW 1110000.0 (LB/HR)

SODIUM FLOW 12750000.0 (LB/HR)

SODIUM INLET TEMP 936.85 (F)

SODIUM OUTLET TEMP 859.00 (F)

SODIUM PRESS DROP 26.41 (PSI)

WATER/STEAM INLET TEMP 609.20 (F)

STEAM OUTLET TEMP 908.76 (F)

STEAM INLET PRESSURE 1650.00 (PSIA)

STEAM OUTLET PRESSURE 1545.26 (PSIA)

STEAM PRESS DROP 104.74 (PSI)

ENTHALPY IN 1161.907 (BTU/LB)

ENTHALPY OUT 1432.914 (BTU/LB)

EVAPORATOR DATA

DNB 0.0

PREHEAT LENGTH 0.0 0.0 (FT, IN)

BOILING LENGTH 0.0 0.0 (FT, IN)

SUPERHEAT LENGTH 72.45 869.40 (FT, IN)

SATURATION TEMP 608.78 (F)

LMTD (AVG) 0.0 0.0 122.43 (F)

U (AVG) 0.0 0.0 244.41 (BTU/HR*FT²*F)

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CONFIDENCE IN OVERALL U
FOULING F DISTANCE

86.96
0.000483 0.000483 0.000483 0.000483 (0/0)
(HR*FT2F/BTU)

Table 1.6 (Cont.)

TASK 6 SUPERHEATER

SUBCASE 1		SODIUM		WATER		87.86 MWT	
FLOW		12750000.0		1110000.0		(LB/HR)	
TEMP IN		936.85		609.20		(F)	
TEMP OUT		859.00		908.76		(F)	
FLOW AREA		1178.81		160.19		(SQ IN)	
EQUIVALENT FLOW DIA		2.237		0.542		(IN)	
INLET ENTHALPY				1161.907		(BTU/LB)	
INLET PRESSURE				1650.00		(PSIA)	
PRESS DROP		26.41		104.74		(PSI)	
Q		299879936.00				(BTU/HR)	
TOTAL NO. OF 180 DEG BENDS				0			
PRESSURE DROP LENGTH				941.40		(IN)	
NUMBER TUBES AFTER PLUGGING				693			
TUBES AVAILABLE FOR PLUGGING				21			
HEAT TRANSFER AREA		10236.11				(SQ FT)	
DNB		0.0					
		PREHEAT		BOILING		SUPERHEAT	
Q	(SUM)	0.0		0.0		299879936.00	(BTU/HR)
LMTD	(AVG)	0.0		0.0		122.43	(F)
HEAT TRANSFER AREA		0.0		0.0		10236.11	(SQ FT)
U	(AVG)	0.0		0.0		244.41	(BTU/HR*FT2*F)
HEAT TRANSFER LENGTH, IN.		0.0		0.0		869.40	(IN)
NUMBER OF 180 DEG BENDS		0.0		0.0		0.0	
RESISTANCE (TOTAL)		0.0		0.0		0.003564	(HR*FT2*F/BTU)
AVERAGES (STEAM)		0.0		0.0		0.001374	(HR*FT2*F/BTU)
(FOULING)		0.0		0.0		0.000483	(HR*FT2*F/BTU)
(WALL)		0.0		0.0		0.001520	(HR*FT2*F/BTU)
(SODIUM)		0.0		0.0		0.000187	(HR*FT2*F/BTU)
--- WATER/STEAM ---							
TEMP OUT		0.0		0.0		908.76	(F)
PRESSURE DROP, TOTAL		0.0		0.0		93.33	(PSI)
HEAD		0.0		0.0		0.40	
ACCELERATION		0.0		0.0		3.77	
PRESSURE OUT		0.0		0.0		1553.47	(PSI)
ENTHALPY OUT		0.0		0.0		1432.746	(BTU/LB)
REYNOLDS NUMBER OUT		0.0		0.0		692123.69	
VELOCITY OUT		0.0		0.0		131.70	(FT/SEC)
DENSITY		0.0		0.0		2.10	(LB/FT3)
--- SODIUM ---							
TEMPERATURE IN		0.0		0.0		936.85	(F)
REYNOLDS NUMBER IN		0.0		0.0		511320.19	
VELOCITY IN		0.0		0.0		8.33	(FT/SEC)
DENSITY		0.0		0.0		51.92	(LB/FT3)

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Table 1.7

TASK 6 SUPERHEATER				HEAT TRANSFER DATA					1
SECTION	WATER	WALL	SODIUM	LMTD	OVERALL U	AREA	Q	ENTHALPY	QUALITY
--- SUPERHEAT ---									
0	609.20		859.00					1161.907	
1	617.08	751.31	862.96	247.86	270.37	230.03	15298813.	1176.365	
2	625.57	758.12	866.81	243.61	268.31	230.03	14836765.	1189.731	
3	634.54	765.09	870.55	238.67	266.22	230.03	14448969.	1202.748	
4	643.97	772.15	874.18	233.16	264.15	230.03	14012666.	1215.372	
5	653.79	779.27	877.70	227.10	262.11	230.03	13572297.	1227.600	
6	663.92	786.38	881.09	220.58	260.12	230.03	13069870.	1239.374	
7	674.27	793.44	884.35	213.66	258.21	230.03	12553894.	1250.684	
8	684.79	800.39	887.46	206.44	256.39	230.03	11993203.	1261.489	
9	695.32	807.20	890.45	198.95	254.71	230.03	11518146.	1271.865	
10	705.85	813.85	893.30	191.34	253.12	230.03	10968024.	1281.747	
11	716.32	820.33	896.03	183.60	251.62	230.03	10517358.	1291.222	
12	721.39	825.13	897.39	177.77	250.53	115.01	5258950.	1295.959	
13	726.69	828.18	898.66	174.04	249.83	115.01	4889853.	1300.365	
14	731.67	831.27	899.94	170.09	249.14	115.01	4914785.	1304.792	
15	736.77	834.20	901.13	166.39	248.49	115.01	4594467.	1308.932	
16	741.57	837.14	902.34	162.54	247.84	115.01	4655441.	1313.126	
17	746.53	839.92	903.46	158.94	247.25	115.01	4338918.	1317.035	
18	751.19	842.74	904.62	155.15	246.65	115.01	4437832.	1321.033	
19	756.03	845.40	905.69	151.64	246.09	115.01	4112636.	1324.738	
20	760.54	848.12	906.79	147.90	245.53	115.01	4244069.	1328.561	
21	765.27	850.66	907.80	144.48	245.02	115.01	3888251.	1332.064	
22	769.62	853.28	908.86	140.80	244.50	115.01	4076865.	1335.737	
23	778.81	856.97	910.80	135.65	243.80	230.03	7493583.	1342.488	
24	787.35	861.88	912.71	128.56	242.91	230.03	7328818.	1349.091	
25	795.87	866.41	914.43	122.03	242.12	230.03	6642927.	1355.075	
26	803.64	870.84	916.13	115.42	241.35	230.03	6533173.	1360.961	
27	811.42	874.90	917.67	109.44	240.68	230.03	5910424.	1366.286	
28	818.49	878.88	919.18	103.36	240.03	230.03	5831564.	1371.539	
29	825.57	882.52	920.55	97.90	239.45	230.03	5254885.	1376.273	
30	831.95	886.09	921.90	92.36	238.89	230.03	5200144.	1380.958	
31	838.36	889.33	923.11	87.41	238.39	230.03	4663842.	1385.160	
32	844.11	892.53	924.32	82.37	237.90	230.03	4631323.	1389.332	
33	849.89	895.42	925.39	77.92	237.47	230.03	4132419.	1393.055	
34	855.02	898.27	926.46	73.37	237.05	230.03	4121037.	1396.768	
35	860.22	900.83	927.41	69.38	236.68	230.03	3656550.	1400.062	
36	864.80	903.37	928.37	65.28	236.32	230.03	3664951.	1403.364	
37	869.45	905.64	929.21	61.72	235.99	230.03	3232170.	1406.276	
38	873.52	907.89	930.06	58.05	235.67	230.03	3258457.	1409.211	

39	877.68	909.90	930.80	54.89	235.39	230.03	2854672.	1411.783
40	881.29	911.91	931.55	51.59	235.11	230.03	2897219.	1414.393
41	885.00	913.64	932.18	48.85	234.87	230.03	2421079.	1416.574
42	888.05	915.43	932.86	45.87	234.62	230.03	2628933.	1418.943
43	891.44	916.95	933.43	43.51	234.40	230.03	2154960.	1420.884
44	894.15	918.56	934.04	40.80	234.18	230.03	2359020.	1423.009
45	897.20	919.90	934.53	38.72	233.99	230.03	1900495.	1424.721
46	899.60	921.35	935.09	36.28	233.79	230.03	2122983.	1426.634
47	902.35	922.54	935.52	34.44	233.62	230.03	1688847.	1428.156
48	904.46	923.83	936.02	32.24	233.43	230.03	1903205.	1429.870
49	906.92	924.88	936.41	30.63	233.28	230.03	1485871.	1431.209
50	908.76	926.03	936.85	28.66	233.12	230.03	1706191.	1432.746
(AVG/TOTAL)	791.36A	1736.95A	911.57A	122.43A	244.41A	10236.11T	299879936.T	1345.104A
(TOTAL)						10236.11	299879936.	

Table 17 (Cont.)

Table 1.8

1

TASK 6 SUPERHEATER

SECTION	FILM COEFFICIENTS		FILM COEFFICIENTS AND RESISTANCES				
	WATER	SODIUM	RESISTANCES				TOTAL
			WATER	WALL	SODIUM	FOULING	
--- SUPERHEAT ---							
1	1534.9	5402.6	0.00105	0.00150	0.00019	0.00048	0.00322
2	1501.9	5397.8	0.00107	0.00150	0.00019	0.00048	0.00324
3	1469.3	5393.1	0.00110	0.00150	0.00019	0.00048	0.00327
4	1437.8	5388.5	0.00112	0.00150	0.00019	0.00048	0.00329
5	1407.6	5384.1	0.00115	0.00150	0.00019	0.00048	0.00332
6	1379.0	5379.8	0.00117	0.00150	0.00019	0.00048	0.00334
7	1352.2	5375.7	0.00119	0.00151	0.00019	0.00048	0.00337
8	1327.5	5371.8	0.00122	0.00151	0.00019	0.00048	0.00339
9	1305.0	5368.0	0.00124	0.00151	0.00019	0.00048	0.00341
10	1284.3	5364.5	0.00126	0.00151	0.00019	0.00048	0.00344
11	1265.1	5361.0	0.00127	0.00151	0.00019	0.00048	0.00346
12	1251.4	5358.5	0.00129	0.00151	0.00019	0.00048	0.00347
13	1242.7	5356.9	0.00130	0.00151	0.00019	0.00048	0.00348
14	1234.1	5355.4	0.00131	0.00151	0.00019	0.00048	0.00349
15	1226.2	5353.8	0.00132	0.00151	0.00019	0.00048	0.00350
16	1218.3	5352.4	0.00132	0.00151	0.00019	0.00048	0.00351
17	1211.2	5350.9	0.00133	0.00152	0.00019	0.00048	0.00352
18	1204.0	5349.6	0.00134	0.00152	0.00019	0.00048	0.00353
19	1197.4	5348.2	0.00135	0.00152	0.00019	0.00048	0.00353
20	1190.8	5346.9	0.00135	0.00152	0.00019	0.00048	0.00354
21	1184.8	5345.6	0.00136	0.00152	0.00019	0.00048	0.00355
22	1178.7	5344.3	0.00137	0.00152	0.00019	0.00048	0.00356
23	1170.8	5342.5	0.00138	0.00152	0.00019	0.00048	0.00357
24	1160.7	5340.2	0.00139	0.00152	0.00019	0.00048	0.00358
25	1151.8	5337.9	0.00140	0.00152	0.00019	0.00048	0.00359
26	1143.3	5335.9	0.00141	0.00152	0.00019	0.00048	0.00360
27	1135.9	5333.9	0.00142	0.00152	0.00019	0.00048	0.00361
28	1128.8	5332.0	0.00143	0.00152	0.00019	0.00048	0.00362
29	1122.6	5330.3	0.00144	0.00152	0.00019	0.00048	0.00363
30	1116.5	5328.6	0.00144	0.00152	0.00019	0.00048	0.00364
31	1111.3	5327.1	0.00145	0.00153	0.00019	0.00048	0.00365
32	1106.1	5325.6	0.00146	0.00153	0.00019	0.00048	0.00366
33	1101.6	5324.2	0.00146	0.00153	0.00019	0.00048	0.00366
34	1097.3	5322.9	0.00147	0.00153	0.00019	0.00048	0.00367
35	1093.4	5321.7	0.00148	0.00153	0.00019	0.00048	0.00367
36	1089.6	5320.6	0.00148	0.00153	0.00019	0.00048	0.00368
37	1086.3	5319.5	0.00148	0.00153	0.00019	0.00048	0.00368
38	1083.0	5318.5	0.00149	0.00153	0.00019	0.00048	0.00369
39	1080.2	5317.5	0.00149	0.00153	0.00019	0.00048	0.00369

40	1077.3	5316.6	0.00150	0.00153	0.00019	0.00048	0.00370
41	1074.8	5315.8	0.00150	0.00153	0.00019	0.00048	0.00370
42	1072.3	5315.0	0.00150	0.00153	0.00019	0.00048	0.00371
43	1070.1	5314.2	0.00151	0.00153	0.00019	0.00048	0.00371
44	1067.9	5313.5	0.00151	0.00153	0.00019	0.00048	0.00371
45	1066.0	5312.8	0.00151	0.00153	0.00019	0.00048	0.00372
46	1063.9	5312.2	0.00152	0.00153	0.00019	0.00048	0.00372
47	1062.2	5311.6	0.00152	0.00153	0.00019	0.00048	0.00372
48	1060.4	5311.1	0.00152	0.00153	0.00019	0.00048	0.00373
49	1058.9	5310.5	0.00152	0.00153	0.00019	0.00048	0.00373
50	1057.2	5310.0	0.00153	0.00153	0.00019	0.00048	0.00373
(AVG)	1186.3A	5341.4A	0.00137A	0.00152A	0.00019A	0.00048A	0.00356A

Table 1.8 (Cont.)

2.0 Thermal Sizing Methods

2.1 Nomenclature for Sections 2.0 and 3.0

- A = outside tube surface area in ft^2 , corrected for inactive area
- c_p = constant pressure specific heat, $\text{Btu/lb-}^\circ\text{F}$
- d_i = tube inside diameter, ft.
- d_o = tube outside diameter, ft.
- D_e = equivalent diameter = $4 (\text{Flow Area})/(\text{Wetted Perimeter})$, ft.
- f = friction factor = 0.25λ , dimensionless
- G = mass velocity (lbm/hr-ft^2)
- g = local gravitational constant (ft/hr^2)
- g_c = gravitational conversion factor (ft-lbm/lbf-hr^2)
- Δh = change in water/steam enthalpy for the given increment, Btu/lb
- h_i = water/steam side film coefficient, $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$
- h_o = sodium side film coefficient, $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$
- k = molecular thermal conductivity, $\text{Btu/hr-ft-}^\circ\text{F}$
- k_t = form loss coefficient, dimensionless
- l = length of channel increment (ft)
- LMTD = local log mean temperature difference between the sodium and water/steam temperature, $^\circ\text{F}$
- $\dot{m}$ = $\dot{m}_{\text{water}}$ and $\dot{m}_{\text{sodium}}$ are flow rates in lb/hr
- Nu = $h D_e/k$ = Nusselt number, dimensionless
- P = tube pitch, ft.
- p = system pressure, psia
- Pr = $\mu c_p/k$ = Prandtl number, dimensionless
- Q = heat transfer in Btu/hr for any given increment

q = radial heat flux through tube wall, Btu/hr-ft²
 Re = $G D_e / \mu$ = Reynolds number, dimensionless
 Δt = change in sodium temperature per increment, °F
 T = temperature, °F
 U = overall heat transfer coefficient, Btu/hr-ft²-°F
 v = "homogeneous" specific volume (ft³/lbm)
 v_{fg} = change in specific volume between saturated water and steam, ft³/lb
 v_f = specific volume of saturated water, ft³/lb
 Δv = change in specific volume over the length increment, ft³/lb
 $\bar{x}$ = average steam quality over the length increment
 (mass flow steam/total mass flow), dimensionless
 $\sin\theta$ = Sine of the channel inclination angle from the horizontal
 ϵ = equivalent Nikuradse sand grain dimension, ft.
 λ = Darcy friction factor, dimensionless
 μ = absolute, lb/hr-ft
 ρ = density, lb/ft³

2.2 Water/Steam Side Film Coefficients

2.2.1 Single Phase Water (Ref. 2.1)

$$\frac{h_i D_e}{k} = Nu_i = 0.023 Re_i^{0.8} Pr_i^{1/3} \quad (1)$$

This correlation is believed to be accurate within a few percent.
(Ref. 2.10, Page 7-32).

Properties are evaluated at the bulk water temperature. The inside resistance is corrected to the outer tube surface area as follows:

$$R_{io} = d_o / (h_i d_i) \quad (2)$$

2.2.2 Boiling Region

2.2.2.1 Nucleate Boiling Regime (Ref. 2.2)

$$h = \frac{e P/1260}{0.072} (q)^{0.5} \quad (3)$$

Agreement with experimental data is $\pm 20\%$ (Ref. 2.10, Page 13-37).

2.2.2 DNB Study

The bulk boiling region is divided into two major heat transfer mechanisms: nucleate and film boiling. This transition is labeled "Departure from Nucleate Boiling" (DNB).

According to the operating condition of steam generator ($p=1700$ psia, $G = 1.0 \times 10^6$ lb/hr-ft²), the relationship between critical heat flux and steam quality is obtained by referring to the available electrically heated dryout data in the previous works. It is shown in Figure 2.1 that the liquid film dryout mechanisms occurs at an essentially constant steam quality of 36% for a heat flux of 145,000 Btu/hr-ft² for the clean tube and at a steam quality of 38% for the design heat flux of 107,000 Btu/hr-ft² for the fouled tube in the present steam generator design. The DNB mechanism predicted by the W-3 correlation does not occur upstream of film dryout location.

Figure 2.1 Critical Heat Flux Versus Steam Quality

2.2.2.3 Film Boiling Regime (Ref. 2.6)

The following correlation is for high pressure steam:

$$\frac{h_i D_e}{k} = Nu_f = 0.0073 (Re)_f^{0.886} (Pr)_f^{0.61} \quad (4)$$

where subscript f denotes evaluation of the steam properties at the film temperature.

This relation correlates data from five independent investigations with an uncertainty of 11.7% at the 95% confidence level.

2.2.3 Superheated Steam (Ref. 2.6)

Equation 4 is used for superheated steam.

2.3 Duplex Tube Wall Heat Transfer

2.3.1 Bench Test Results

Extensive empirical data on duplex tube wall heat transfer has become available and is reported on in Ref. 1.7. The results of these tests are included in the present Demonstration Plant Evaporator/Superheater design. Bench Test results showed that for the tube wall heat flux range for full load conditions the gap resistance is uniform and is approximately 5×10^{-4} hr-ft²-°F/Btu. This gap resistance value includes the groove effects. The approximate gap width was 0.00025 inch for an annealed tube. Bench Test gap oxidation/contamination tests showed the overall increase in wall resistance due to oxidation/contamination to be 15%.

These test results have been incorporated into the Demonstration Plant evaporator/superheater thermal/hydraulic calculations.

2.3.2 Overall Resistance

The duplex tube diameters are defined as follows:

$$d_1 = \text{inner tube I.D., in.} = 0.5425$$

$$d_2 = \text{inner tube O.D., in.} = 0.7145$$

$$d_3 = \text{outer tube I.D., in.} = 0.7150$$

$$d_4 = \text{outer tube O.D., in.} = 0.8750$$

The outer tube wall resistance is defined as:

$$R_{\text{outer tube}} = \frac{\ln \frac{d_4}{d_3} d_4}{24 k_{\text{wall}}} \quad (5)$$

$$\text{where } k_{\text{wall}} = 26.0 - .0055(T) \quad \text{Btu/hr-ft}^2\text{-}^\circ\text{F from Ref. 1.6.} \quad (6)$$

The helium gap resistance is:

$$R_{\text{He}} = \frac{\ln \frac{d_3}{d_2} d_4}{24 k_{\text{He}}} = 5 \times 10^{-4} \quad \text{hr-ft}^2\text{-}^\circ\text{F/Btu} \quad (7)$$

$$k_{\text{He}} = 0.051 \quad \text{Btu/hr-ft}^2\text{-}^\circ\text{F}$$

The inner tube wall resistance is:

$$R_{\text{inner tube}} = \frac{\ln \frac{d_2}{d_1} d_4}{24 k_{\text{wall}}} \quad (8)$$

The above equations are combined as follows:

$$R_{\text{wo}} = (R_{\text{outer tube}} + R_{\text{He}} + R_{\text{inner tube}})(\text{CFR}) \quad (9)$$

where CFR=1.15 for oxidation/contamination of gap.

2.4 Sodium Shell-Side Film Coefficients

2.4.1 U-Bend Effectiveness and Tube Length Variation Study

The design basis for the evaporators and superheater is 50% U-bend effectiveness for the central heat exchanger tube. A sensitivity study has been performed as to the effects of U-bend effectiveness upon performance for the shortest, central and longest tube for both evaporator and superheater.

The performance of the evaporator and of the superheater has been calculated for 10%, 50%, and 90% U-bend effectiveness. The 10% and 90% U-bend effectiveness are taken as the plausible extremes in U-bend performance. The shortest, central and longest tube parameters used for this study are given in Table 2.1. Performance results are summarized in Tables 2.2 and 2.3 for the evaporator and superheater respectively.

The conclusion from this study is that the overall performance changes are small compared to performance contingency factors used in the design basis predictions. The design basis contingency factors are 30% for the evaporator and 15% for the superheater. The corresponding performance degradation assuming 10% U-bend effectiveness is 4.3% for the evaporator and 2.3% for the superheater. The 50% U-bend effectiveness and central tube are therefore still used as a design basis.

2.4.2 Inlet and Outlet Plenum Performance

For conservatism inlet and outlet plenum sodium side cross-flow regions are assumed to be in-line flow. Cross-flow film coefficients are approximately twice as high as in-line coefficients. For completeness, correlations for both in-line (Section 2.4.3) and cross-flow (Section 2.4.4) are given.

Table 2.1
Shortest Versus Central Versus Longest Tube Length Data

Tube Length	Straight Under-Sodium Length, ft.	Tube Bend Radius, in.	Tube Bend Length, ft.	Total Under-Sodium Tube Length, ft.	Computer Node Length (50 nodes), in.	No. of Nodes in U-Bend	No. of Nodes in U-Bend Used in Code
Shortest Tube	57.4	36.0	9.43	66.83	16.038	7.05	7
Central Tube	57.4	57.5	15.05	72.45	17.388	10.39	11
Longest Tube	57.4	79.0	20.68	78.08	18.738	13.25	13

Table 2.2
Evaporator U-Bend Performance Effects

	Under Sodium Tube Length, ft.	U-Bend Effectiveness	MWt Rating per Loop	Exit Quality	Steam ΔP	% Diff. in MWt from Design Basis
Shortest Tube	66.83	10%	230.89	0.484	9.905	-3.6
	66.83	50%	236.31	0.500	10.306	-1.34
	66.83	90%	242.42	0.519	10.75	+1.21
Central Tube	72.45	10%	229.30	0.480	10.26	-4.26
	72.45	50%	239.50	0.510	10.96	0.00
	72.45	90%	246.79	0.532	11.58	+3.04
Longest Tube	78.08	10%	232.45	0.489	10.87	-2.95
	78.08	50%	245.51	0.528	11.78	+2.50
	78.08	90%	259.76	0.570	12.81	+8.45

Table 2.3
Superheater U-Bend Performance Effects

	Under Sodium Tube Length, ft.	U-Bend Effectiveness	MWt Rating per Loop	Exit Quality	Steam ΔP	% Diff. in MWt from Design Basis
Shortest Tube	66.83	10%	85.81	899.30	70.61	-2.34
	66.83	50%	87.02	905.24	71.86	-0.96
	66.83	90%	87.91	909.49	72.90	0.00
Central Tube	72.45	10%	85.83	899.0	75.98	-2.32
	72.45	50%	87.86	908.8	78.13	0.00
	72.45	90%	89.00	914.3	79.68	+1.29
Longest Tube	78.08	10%	86.52	901.8	82.05	-1.53
	78.08	50%	88.56	911.6	84.66	+0.79
	78.08	90%	89.93	918.4	86.59	+2.35

Further studies under Task 6 on inlet plenum cross-flow and heat transfer edge-to-center differences are discussed below.

2.4.2.1 Inlet Manifold Design

Uniform cross-flow into the tube bundle in the inlet plenum can be obtained by controlling the width of the discharge slot in the distribution shroud. This width of discharge slot variation can be determined by employing the manifold theory by determining the static pressure recovery and friction pressure drop effects along the manifold path.

Based on present steam generator design and the operation conditions (100% load), the analytical results of manifold theory indicates that the present uniform slot width design provides uniform cross flow into the inlet plenum.

2.4.2.2 Heat Transfer Edge-to-Center Difference

In defining the heat transfer edge-to-center difference, the temperature difference across the tube bundle in the cross flow zone of the inlet plenum is also determined simultaneously. It is evaluated based on the following assumptions:

- (1) Fluid is uniformly flowing into the tube bundle from the inlet manifold.
- (2) Sodium is perpendicular to the tubes in whole cross-flow zone in the inlet plenum, before entering the in-line region.
- (3) The axial sodium flow rates for each tube are equal.
- (4) Heat transfer coefficients on steam side are equal for all tubes in the sodium cross flow zone.
- (5) Thermal conductivity of tube wall is constant and does not vary with temperature.

The 60° segment of the tube bundle is chosen as the analytical model for the evaluation. The process of the evaluation is described as follows:

- (a) Determine the axial flow rate per each tube (W_n) according to assumption (3), it can be written as $W_n = \frac{W_t}{N}$

Where W_t and N are the total sodium flow rate and the number in the 60° segment of the tube bundle, respectively.

- (b) Determine the overall heat transfer coefficient, U including sodium side, tube wall and steam/water side heat transfer coefficients. It can be determined by using the cross-flow correlation equation for sodium side, pipe flow correlation for steam/water side and the conventional cylindrical heat conduction equation for tube wall.

- (c) Determine LMTD

It is obtained from equation

$$LMTD = \frac{(\Delta T)_{\max} - (\Delta T)_{\min}}{\ln \frac{(\Delta T)_{\max}}{(\Delta T)_{\min}}}$$

- (d) Determine sodium temperature drop across one row of tubes in the 60° segment ΔT_{ri}

It can be calculated by equation

$$T_{ri} = \frac{U_i A_{ri} (LMTD)_i}{W_i C_p} \quad i = 1, 2, 3 \dots M$$

Where A_{ri} = total heat transfer area of one row of tubes.

W_i = Total flow rate across one row of tubes. For the first tube row from the edge of tube bundle W_i is W_t . For the remaining rows, W_i is $W_t - W_n$ where n is the number of tube rows crossed.

The cross-flow LMTD variation is as follows:

$$(LMTD)_{i+1} = (LMTD)_i - T_{ri}$$

The U_i variation is determined based on the local condition as described in process (b). By following above procedure, the temperature difference across the tube bundle in the cross flow zone of the evaporator inlet plenum is approximately 35°F . The temperature distribution is shown in Fig. 2.2.

Also shown in Figure 2.2 is the effect of sodium inlet temperature on overall (evaporator) counterflow LMTD, in percent of the nominal LMTD (859°F sodium inlet temperature). Averaging the counterflow LMTD distribution from the

Radial NA Temperature Distribution
at Inlet Plenum of

Temperature Drop Across the Tube
Bundle at Cross-Flow Zone in the
Inlet Plenum of

Figure 2.2 Sodium Inlet Radial Temperature Distribution and Overall Counterflow LMTD Distribution from Outer Edge to Center of Tube Bundle

edge of the tube bundle to the center of the tube bundle gives an overall degradation in LMTD of 2.95%.

2.4.3 In-Line Flow Through Tube Bundles

The design correlation employed by Westinghouse Tampa Division is one favored by Dwyer^[2.7] and is the Maresca-Dwyer correlation^[2.8]

The Maresca-Dwyer correlation covers two regions. One expression covers the region of turbulent flow molecular conduction ($Pe < 700$),

$$Nu_{mc} = -2.79 + 3.97 (P/d_o) + 1.025 (P/d_o)^2 + 3.12 \log_{10} Re - 0.265 (\log_{10} Re)^2 \quad (10)$$

The other expression covers the region of combined molecular and eddy diffusion that is valid for the ranges of Peclet number from 700 to 10^4 and P/d_o from 1.3 to 3.0,

$$Nu = 6.666 + 3.126 (P/d_o) + 1.184 (P/d_o)^2 + 0.0155 (\bar{\Psi} Pe)^{0.86} \quad (11)$$

where

$$\bar{\Psi} = 1 - \frac{1.82}{Pr \left(\frac{\epsilon_m}{\nu} \right)_{max}^{1.4}} \quad (12)$$

$\frac{\epsilon_m}{\nu}$ = ratio of momentum eddy diffusivity to kinematic viscosity

and the expression $\frac{\epsilon_m}{\nu}_{max}$ may be taken from a graph in

Reference 2.9. The approximation for tube bundles is used:

$$\frac{\epsilon_m}{\nu}_{max} = (\exp -2.95 + 0.311 \ln Re + 0.0257 (\ln Re)^2 \frac{d_o}{P}) \times 1.70 \quad (13)$$

Once the Nusselt number is determined,

$$h_o = (k)(Nu)/D_e \quad (14)$$

and

$$R_o = 1/h_o \quad (15)$$

The Maresca-Dwyer correlation agrees with experimental data within +15% as was shown in Figure 2.4 in Ref. 1.2

2.4.4 Cross-Flow Through Staggered and Rectangular Tube Bundles

A comparison of experimental results for cross-flow through staggered and rectangular lattice tube bundles is shown in Ref. 1.2. The following is the recommended correlation:

$$Nu = 0.633 (Pe)_{V,max}^{0.56} \quad (16)$$

The above correlation is valid for $(Pe)_{V,max} > 10^2$ for a staggered lattice and the range 10^2 to 10^3 for a rectangular lattice. Equations 14 and 15 are then used to calculate the cross-flow sodium side heat transfer resistance.

2.5 Water/Steam and Sodium Side Fouling

Fouling resistance is incorporated in a heat transfer calculation to account for an increase in heat transfer resistance with time as caused by a combination of solids deposition on the tube surface and by oxidation of the tube metal surface.

Water/steam side fouling, corrected to outside surface, is taken as

$$R_{fo} = \frac{d_o}{d_i} R_{fi} = 0.000483 \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$$

where $R_{fi} = 0.0003 \text{ hr-ft}^2 \text{ }^\circ\text{F/Btu}$ from Ref. 1.8.

Sodium side fouling is considered negligible in the design of the steam generator as per Ref. 1.6.

2.6 Overall Contingency Factors

2.6.1 Water and Sodium Side Heat Transfer Correlation Uncertainties

The design basis overall contingency factor for heat transfer correlation uncertainties is 5%.

When considering relative thermal resistances, this contingency factor is equivalent to a 25% factor on evaporator correlations and 15% on superheater correlations. Predicted correlation uncertainties have been given for individual correlations in Sections 2.2 and 2.4 and are well within the above allowances.

2.6.2 Non-Uniform Tube Heating Due to Flow Distribution Uncertainties

The overall contingency factor applied to the design for flow distribution uncertainties is 10%. Flow distribution is being studied under Task 6. One such study has been completed and is reported here. The study basis is as follows:

- 50% U-Bend Effectiveness for Shortest versus Central versus Longest Tube.
- All inlet conditions held constant except water/steam flow.
- Water/Steam side ΔP for all cases equal to central tube ΔP .
- Water/Steam flow rate is allowed to float to achieve water/steam side ΔP above.
- The sodium temperature profile (sodium exit temperature) is allowed to float, i.e., no sodium inter-channel heat exchange.
- The steam exit quality and/or temperature is allowed to float.

Results of the present study are given in Table 2.4. From this study maximum performance uncertainties are $\pm 3\%$, considerably less than the 10% allowance.

2.7 Heat Transfer Area Determination

Computer sizing codes are used to size the evaporator and the superheater. The code divides the active tube length under consideration into 50 increments. Sodium side, tube wall, and water/steam side resistances are evaluated at appropriate average temperatures and pressures for each of the 50 increments.

The overall heat transfer coefficient for each increment is calculated as follows:

$$U = 1 / (R_o + R_{wo} + R_{io} + R_{fo}) \quad (\text{sizing margin}) \quad (17)$$

Table 2.4
Tube Side Flow Distribution Study

		MWt Rating per Loop	% Flow Maldistribution	EV Exit Quality, %	Superheater Outlet Temperature, °F	% Difference in MWt Rating
Evaporator	Shortest Tube	238.0	+6%	46.5		-0.63
	Central Tube	239.5	Nom.	51		±0.0
	Longest Tube	242.7	-6.7%	57.2		+1.33
Superheater	Shortest Tube	90.46	+5%		901.6	+2.96
	Central Tube	87.86	Nom.		908.8	±0.0
	Longest Tube	85.15	-4.2%		914.3	-3.08

By iterative methods the final sodium and water/steam temperature versus area profiles are established which satisfy the following equations:

$$Q = UA \text{ (LMTD)} \quad (18)$$

$$Q = \dot{m}_{\text{water}} (\Delta h) \quad (19)$$

$$Q = \dot{m}_{\text{sodium}} (c_p) (\Delta t) \quad (20)$$

Detailed incremental printouts were given in Section 1.0.

2.8 Stability Analysis

2.8.1 Static Stability Analysis

Static sensitivity is a characteristic inherent in the performance of a boiling channel which can be interpreted as an amplification of steady state disturbances. Such disturbances encompass tube circuit configurations, heating imbalances, fabrication uncertainties, etc. The magnitude of this sensitivity is required for use in predictions of performance imbalances between circuits.

Various boiling static stability indices have been proposed to define circuit stability [2.12,2.13]. The index employed here represents the normalized slope at any point on the steady state pressure drop versus flow rate characteristic curve for a heated channel. The index is written in the form,

$$-I = \frac{\delta \Delta P / \Delta P}{\delta W / W}$$

When the index is less than or equal to zero, it becomes an indication of static instability of the flow excursion class. When greater than zero, the index is a qualitative indicator of a flow maldistribution tendency. It becomes necessary then that the index be >0 to avoid an excursion instability and, furthermore, that it be of a large enough magnitude that an acceptable flow distribution is realized under the worst conditions of heating imbalance, dimensional tolerances, etc. The upper bound of the index is ~ 2 , representing a nonboiling flow condition.

The inverse of the static stability index for once-through boiling operation referred to the inverse index for nonboiling operation can be interpreted as an amplification of a nonboiling circuit flow deviation resulting from a disturbance in circuit hydraulic resistance. Thus, we can write the inverse index as a flow sensitivity S

$$S = \frac{1}{I} = \frac{\delta W / \delta \Delta P}{W / \Delta P}$$

and an amplification factor F as a ratio of the boiling flow sensitivity (S_b) and the nonboiling flow sensitivity (S_{nb}).

$$F = \frac{S_b}{S_{nb}}$$

Since the nonboiling flow sensitivity obeys a square-law relationship (at large values of Reynolds number) we have

$$S_{nb} \approx 0.5$$

The following tabulation describes a range of representative static stability indices (I) and the associated values of amplification factor (F). Since steam temperature and wall temperature deviations are closely related to the flow deviation in a circuit, the amplification factor also approximately represents temperature deviations in a boiling circuit referred to those which occur in a nonboiling circuit due to a given disturbance.

Static Stability Index I	Flow Sensitivity Amplification Factor F
2.0	1.0 (nonboiling)
	(boiling)
0.8	2.5
0.2	10
0.0	∞
< 0	excursion

Negative values of the index indicate that the circuit being examined is statically unstable when operating in a matrix of manifolded tube circuits, i.e., a flow excursion is predicted. Small positive values of the index imply static stability but are undesirable since a large amplification of a given disturbance occurs which can result in an unacceptable maldistribution in performance within the ensemble of tube circuits.

Static stability results for full load conditions are as follows, indicating a very stable unit when compared to the I and F values above:

Static Stability Index I	Flow Sensitivity Amplification Factor F
Evaporator 1.77	1.14
Superheater 1.93	1.04

2.8.2 Shotkin's Crucial Boiling Length

There are six effects of parameters on the density wave instability most often observed. Besides effects of inlet restriction, exit restriction, pressure, mass velocity and power, and heat flux delay, inlet subcooling is another parameter^[2.14]. Subcooling may be stabilizing or destabilizing as there is an unstable subcooling range. The heating rate, mass flow rate, and degree of subcooling determine the location of the boiling boundary. A boiling channel will tend to become more stable as the boiling boundary approaches either end of the heated channel and reach a most unstable subcooling at some intermediate location.

In his analysis^[2.12], Shotkin defined the crucial boiling length at which the system is least stable. The crucial boiling length is related to the important parameters including the heat flux to mass velocity ratio and the degree of inlet subcooling.

It is defined where the ratio of heat input to mass flow rate is a minimum. The equation of the crucial boiling length is,

$$L(0) = 1 - \frac{\delta H/L}{\frac{Q_o}{G_o(0)} + v}$$

where

$$L = \left[\frac{dH_{so}(0)}{dp_o} \right] \left[\frac{\partial P}{\partial Z} \right]_{sub} > 0$$

$$H_{so}(0) = 100 P_o^{1/4}$$

δH = degree of subcooling [BTU/lb]

$$\frac{Q_o}{G_o(0)} = \text{ratio of heat input to mass flow rate} \left[\frac{\text{Btu}}{\text{lb-ft}} \right]$$

L = channel (tube) length [ft]

The theoretical results only had reasonable agreement with few test results obtained from cases of electrically heated pipe under pressures less than 1000 psia and high ratio of heat input to mass flow

rate [2.16]. For a system such as a sodium heated steam generator with the pressure greater than 1000 psia and relatively low ratio of heat input to mass flow rate, the accuracy of the prediction from Shotkin's model was not demonstrated physically. For a system of higher system pressure and low ratio of heat input to mass flow rate, the effect of inlet subcooling on the flow instability could be a minimal factor. To prove this fact, the analysis based on the concept of Shotkin's model and the present evaporator design was performed at WTD according to the present evaporator design and assuming the present boiling length to be equal to the Shotkin's crucial boiling length. The minimum ratio of heat input to mass flow rate is calculated to be 2.761 Btu/lb-ft. It is much greater than 0.06 Btu/lb-ft of the present designed value. Referring to the figure presented in the Shotkin's paper the present design system is very stable. The effect of inlet subcooling on flow instability of the present designed evaporator is negligible.

2.8.3 Dynamic Stability Analysis

Dynamic instability reflects the tendency of a once-through boiling channel to develop self-excited fluctuations in flow and temperature which result from the density change in the direction of flow and involve the unstable feedback between flow and void formation. The resulting instability is commonly called a "density-wave" oscillation to reflect the physical mechanism involved.

The study of the boiling flow oscillation phenomenon requires a dynamic description encompassing two phase slip flow, subcooled boiling non-equilibrium thermodynamic flow conditions, transient response of the tube wall, spatial variation of mass flow rate, and a non-uniform axial heating distribution. The dynamic analysis solves the linearized partial differential conservation equations using Laplace transformation of the temporal terms and integration of the spatial variations. The resulting equations represent the transfer functions for each spatial node. The computer code is then written in complex variable notation and employs frequency response

techniques to develop the system transfer function. Stability criteria used in control system theory may then be applied to determine if the boiling channel is unstable (i.e., if flow oscillations will appear).

The analysis is intended for use as a design tool to avoid the inception of oscillations and is not capable of predicting the severity of oscillations in an unstable design. These self-sustained oscillations occur without the influence of any periodic external forces but arise entirely from the internal structure of the system and the manner in which energy is transferred from one state to another.

Since the analytical solution describing the system dynamics is built into the program, the code is not subject to numerical instabilities and does not require time-consuming iterations.

When ascending values of positive frequencies are used in the analysis, the polar frequency response plot may have three possible general forms with reference to the complex point $-1 + 0j$:

1. Clockwise encirclement
2. No encirclement
3. Counterclockwise encirclement

Only the first case is a sufficient condition for instability. Case 2 is stable while Case 3 is unstable except in special situations.

Preliminary output from the dynamic stability computer code results in a Nyquist diagram indicating no encirclement of the $-1 + 0j$ point which indicates the unit is predicted to be dynamically stable.

2.9 Natural Circulation Capability

Table 2.5 shows the Ref. 1.6 natural circulation requirements. All input parameters are TBD so that actual evaluation of the natural circulation capability of the concept is also TBD.

The J concept is inherently flexible as far as providing for natural circulation. The following are three options for increasing natural circulation capability if required, listed in order of decreasing preference:

Table 2.5

Ref. 1.6 Natural Circulation Requirements

3.2.2.2 Natural Circulation

The evaporators shall be used to remove decay and sensible (residual) heat from the reactor and sodium systems during the period immediately following a scram and during subsequent shutdown periods. The heat removal duty represented by decay and sensible heat will vary from approximately 14% of full load 30 seconds after a scram to 0.2% at the end of ten days. The evaporators shall be designed to remove this heat under the following conditions:

<u>Flow Conditions</u>	<u>Parameters</u>
a. Sodium side flow @ 10% rated and water flow at 100% rated	Na temperatures as a function of time TBD
b. Sodium side flow @ 10% rated and natural circulation on water side	Na temp. vs. time TBD; water side ΔP and head TBD
c. Sodium side under natural circulation and water side 100% rated	Na temp. vs. time TBD; Na flow vs. time TBD
d. Both sodium and water sides on natural circulation	Na temp. & flow vs. time TBD; water side ΔP and head TBD

- (1) Switch sodium outlet flow from normal outlet nozzle to drain nozzle during natural circulation operation only.
- (2) Shorten the length of the short leg (and lengthen long leg proportionally) of the evaporator as required for natural circulation capability.
- (3) Place the sodium outlet nozzle at the bottom of the U-shell where the 16 in. drain is at present. The short leg is shortened to zero in this case.

Option (1) gives a minimum sodium side ΔP and maximum natural circulation capability without changing the short leg/long leg length ratio of the evaporator.

The present short leg/long leg length ratio is used to minimize overall unit height. Only if for some reason Option (1) is not feasible, and a natural circulation analysis shows an increase in capability is required, would Option (2) or (3) be considered.

2.10 Heat Loss Estimate

Ref. 1.6 gives the following insulation requirements:

The supplier shall establish the requirements for insulation based on the following criteria:

1. Operating conditions as specified in Paragraph 3.6
2. Insulation materials and configuration specified TBD
3. Maximum insulation surface temperature to be 140°F
4. Environmental conditions in steam generator equipment rooms as specified in 3.1.11

Since no insulation material is specified, the insulation material used for the SSGM was assumed. Four inches of J. M. Thermobestos (Ref. 2.11) insulation met the requirement for the maximum insulation surface temperature of 140°F. Heat losses from a 900°F, 100 ft. long unit were 130,000 Btu/hr or 0.038 Mwt which is equivalent to a loss of 0.05% of the superheater full load rating. Heat losses are neglected in the sizing analysis.

3.0 Pressure Loss Calculation Methods

3.1 Water/Steam Side Pressure Loss

The pressure drop correlations of Thom^[3.1] are employed in the following recommendation:

$$\Delta p = \frac{\lambda l}{D_e} \frac{f G^2}{2 g_c} r_{\text{frict.}} + \frac{v_f}{g_c} G^2 r_{\text{acc}} + \frac{g l \sin \theta}{g_c v_f} r_{\text{el}} + k_t \frac{v G^2}{2 g_c} \quad (21)$$

Pressure drop multipliers are as follows:

$$r_{\text{frict}} = 1 + \frac{\bar{x} v_{fg}}{v_f} \quad (22)$$

$$r_{\text{acc}} = \frac{v}{v_f} \quad (23)$$

$$r_{\text{el}} = \frac{v_f}{v_f + \bar{x} v_{fg}} \quad (24)$$

The tube side pressure loss correlation according to J. R. S. Thom (Figure 11 in Reference 3.1) correlates with data of Haywood et al^[3.2] within $\pm 10\%$.

Semi-analytical developments have resulted in the following hydraulic resistance laws for circular tubes with fully established flow.^[3.3]

Smooth turbulence -

$$\frac{1}{\sqrt{\lambda}} = 2 \log \text{Re} \sqrt{\lambda} - 0.8 \quad (25)$$

Rough turbulence -

$$\frac{1}{\sqrt{\lambda}} = 2 \log \frac{D_e}{2\epsilon} + 1.74 \quad (26)$$

Transition Law (Colebrook and White) -

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left(\frac{\epsilon}{3.7 D_e} + \frac{2.51}{\text{Re} \sqrt{\lambda}} \right) \quad (27)$$

Moody^[29] Approximation to Colebrook Relation

$$f = 0.0055 \left[1 + \left(20,000 \frac{\epsilon}{De} + \frac{10^6}{Re} \right)^{1/3} \right] \quad (28)$$

agrees with Colebrook relation within $\pm 5\%$ for $4000 \leq Re \leq 10^7$
and $0 \leq \epsilon/De \leq 0.01$.

These expressions form the basis for the Moody diagram or the so-called "universal friction diagram." Expression 28 is the relation used to define the friction factor for straight tubes.

The form losses are as follows:

<u>Form Loss</u>	<u>k_t</u>	<u>Reference</u>
Inlet plenum to tube flow area contraction	.5	3.5
Tube flow area to outlet plenum expansion	1.	3.5

These losses are based on the tube flow area mass velocity.

Due to the tube U-bend large radius of curvature and small portion of the total length, the J-tube is assumed to be straight for purposes of friction loss calculations.

3.2 Sodium Shell-Side Pressure Loss

For the calculation of shell-side pressure losses, Equations 21-24 are used as applied to an incompressible, variable-density fluid. A summary of friction and form loss calculation methods is given in Table 3.1.

Table 3.1
Shell Side (Sodium) Pressure Loss Calculations

Shell Side Pressure Loss	Flow Area Basis for Mass Velocity	f ($\lambda = 4f$)	l/D_e	k_t	Ref.
Inlet Nozzle Expansion (Sudden Expansion)	Inlet Nozzle Area			1	3.5
Entrance Flow Reversal	Bundle Free Flow Area			2	3.6
Baffle Loss				4.2	3.6
Parallel Flow Loss		$.0445 \text{ Re}^{-.196}$	$\frac{\text{Liner} + \text{U-Bend}}{\text{Bundle } D_e}$	-	3.7
Shell to U-Bend Sudden Expansion				1	3.5
U-Bend to Shell Sudden Contraction				.5	3.5
Shell to Outlet Plenum Sudden Expansion				1	3.5
Outlet Plenum to Outlet Nozzle Sudden Contraction	Outlet Nozzle Area			.5	3.5

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