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A Division of North American Aviation, Inc.

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OTHER		PROJECT Sodium-Cooled Reactor Design and Evaluation	DATE 9-19-60	
			PAGE 1 OF 22	

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SUBJECT: ADVANCED ONCE-THROUGH STEAM GENERATOR FOR SODIUM APPLICATION

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I STATEMENT OF PROBLEM

Perform preliminary design calculations for a once-through type steam generator and reheater for advanced sodium power plants in the 300 MWe range. The plant consists of four(4) steam generator units and two(2) reheater units.

The following design parameters shall be used:

Steam conditions at SH outlet: 2500 psia, 1050 F
Feedwater temperature: 540 F
Sodium temperatures: SH inlet: 1150 F, Preheater outlet: 600 F
Sodium temperatures: SH inlet: 1150 F, RH outlet: 825 F
Sodium flow through Superheater: 2.7×10^6 lbs/hr
Boiler and
Preheater : 3.58×10^6 lbs/hr
Reheater : 1.76×10^6 lbs/hr
Steam conditions at RH: Inlet: 600 psia/650 F
Outlet: 550 psia/1000 F

The following information shall be obtained:

1. Heating surfaces for
 - a) superheater
 - b) boiler section
 - c) preheater section
 - e) reheater

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2. Tube size and wall thickness, using
 - a) SS 316 for superheater and reheater
 - b) SA-213, 2 $\frac{1}{4}$ Cr-1 Mo for boiler and preheater
3. Approximate pressure drops on steam and water side.
4. Overall dimensions of units using vertical, cylindrical shell type design with straight tubes between flat tube sheets.
5. Temperature diagrams for 100% and 25% load points. The latter shall be based upon a sodium inlet temperature of 1170 F.

II. SUMMARY OF RESULTS AND RECOMMENDATIONS

The principal reason for this study was to establish approximate design data for preliminary stress analyses and to obtain general information on this type of high pressure-temperature unit as to the appropriate tube sizes, temperature conditions, overall dimensions and numbers of units. The system flow diagram is shown in Fig. 1. Due to the limited time allotted for this study the above data are not complete and no attempts have been made to optimize the various parameters. The system pressure drop calculations have not been extended to the sodium side. The pressure drops on the steam and water side have only been calculated once and no investigations have been made on flow stability problems under full and partial load conditions. The temperature diagrams for full load conditions for steam generator and reheater are indicated in Fig. 2.

In calculating the heat transfer and temperature conditions for the 25% turbine generator load point, it was assumed that the sodium inlet temperature would rise to 1170 F. Steam and sodium flow at this load point were calculated to be approximately 31% of total.

As indicated in temperature diagram Fig. 4, the sodium temperature at the boiler inlet does not vary appreciably from approximately 880 F over the load range and for the control characteristic assumed. Therefore, it appears, based on these two load points, that the temperature and stress properties of the tube material (2 $\frac{1}{4}$ Cr-1 Mo) in the boiler section are adequate for steady state and transient conditions.

The important parameters and performance data calculated for description units are as follows:

1. Superheater

Heating Surface (effective)	: 5860 ft ²
470 tubes - 3/4" OD, 10 BWG, SS 316	: 64 ft long
Shell Diameter	: 30"
Steam flow	: 530,000 lbs/hr
Steam pressure at SH outlet	: 2500 psia
Pressure drop through SH	: 70 psi
Sodium flow	: 2.7 x 10 ⁶ lbs/hr
Temperature at inlet	: 1150 F
Temperature at outlet	: 883 F

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2. Boiler

Heating Surface (effective) : 4500 ft²
500 tubes - 5/8" OD, 14 BWG., 2 1/4 Cr-1 Mo, 55 ft long
Shell Diameter : 30"
Steam flow to water separator : 540,600 lbs/hr
(includes 2% moisture)
Steam pressure at boiler outlet : 2600 psia
Pressure drop through boiler section : 48 psi
Sodium flow : 3.58 x 10⁶ lbs/hr
Temperature at inlet : 867 F
Temperature at outlet : 708 F

3. Preheater

Heating Surface (effective) : 5260 ft²
500 tubes - 5/8" OD, 14 BWG, 2 1/4 Cr-1 Mo, 64 ft long
Shell Diameter : 30"
Water flow : 540 600 lbs/hr
Feedwater temperature at inlet : 540 F
Feedwater temperature at outlet : approximately 673 F
Sodium flow : 3.58 x 10⁶ lbs/hr
Temperature at inlet : 708 F
Temperature at outlet : 600 F

4. Reheater

Heating Surface (effective) : 4900 ft²
1165 tubes - 5/8" OD, 14 BWG, SS 316, 22' long
Shell Diameter : 38"
Steam flow : 870,000 lbs/hr
Steam conditions - inlet : 600 psia, 650 F
Steam conditions - outlet : 550 psia, 1000 F
Steam pressure drop through reheater : approximately 30 psi
(not including connecting piping)
Sodium flow : 1.61 x 10⁶ lbs/hr
Temperature at inlet : 1150 F
Temperature at outlet : 825 F

In view of the problems involved in designing of an once-through steam generator system it is recommended that further studies be made on:

1. Pressure drop conditions on the sodium side over the load and temperature range.
2. Two-phase flow stability problems in the boiler section for full and partial load performance.

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3. Moisture separation equipment at boiler outlet.
4. Performance characteristic of the steam generator in connection with various sodium side and steam side control systems.
5. Fast load response characteristics.
6. Important design details such as tube-to-tube sheet welds, expansion joints, tube sheet designs, thermal shields etc.

III. METHODS USED, DESCRIPTION OF EQUIPMENT

The following describes briefly the calculation methods used to establish the preliminary design parameters:

Total heat to steam generator: 5.13×10^8 Btu/hr
Steam generated: 530,000 lbs/hr

1) Superheater

a) Steam Conditions

p (outlet) = 2500 psia
p (inlet) = 2600 psia (assumed)

T (outlet) = 1050 F
T (inlet) = 674 F

$$\Delta T = \frac{W (\Delta h)}{W (\text{Sodium}) \times C_p}$$

$$\Delta T (\text{Sodium}) = \frac{530,000 (11491 - 1080)}{2.7 \times 10^6 \times 0.302} = 267^\circ \text{F}$$

$$\text{LMTD} = 1148^\circ \text{F}$$

$$\text{Heating Surface} = \frac{W (\Delta h)}{\text{LMTD} \times U}$$

$$= \frac{530000 \times 411}{1148 \times 250} = 5860 \text{ ft}^2$$

Overall U assumed - 250 Btu/ft² hr F

b) Tubes

Assume: 3/4" tubes, SS 316

p (Design) = 2700 psig

T (Design) = 1175 F

Tubes to be in accordance with ASME "Unfired Pressure Vessel Code",
Section VIII. Selected: 3/4" OD, 10 BWG, 0.134" wall thickness

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c) Velocity ConditionsSteam velocity at inlet $V_1 = 30$ fps (assumed)

$$\begin{aligned} \text{No. of tubes} &= \frac{W \times v}{3600 \times V_1 \times A_1} \\ &= \frac{530,000 \times 0.1213}{3600 \times 30 \times 0.001268} = 470 \text{ tubes} \end{aligned}$$

$$\text{Outlet velocity } V_2 = V_1 \frac{v_2}{v_1} = 30 \frac{0.3061}{0.1213} = \text{appr. } 76 \text{ fps}$$

$$\begin{aligned} \text{Tube length: } \frac{HS}{\text{No.} \times \frac{\text{ft}^2}{\text{ft}}} &= \frac{5860}{470 \times 0.1963} = 63.5' \\ &\text{approx. } \underline{64'} \end{aligned}$$

d) Steam Pressure Drop (Superheater)

Fritzsche Formula (Tube Turn)

$$\Delta p = \frac{21.082 v^{1.85}}{10^6 d^{4.97}}$$

Flow in tube = $530,000 / 470 = 1128$ lbs/hr tube

$$p = \frac{21.082 \times 0.2137^2 \times 1128^{1.85}}{10^6 \times 0.482^{4.97}}$$

$$p = 76 \text{ psi/100 ft of tube}$$

(total equivalent tube length of superheater = 64 ft plus inlet and outlet losses = 100 ft assumed)

e) Steam Heat Transfer (SH)

$$\frac{h_1 D}{k_b} = 0.023 \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)^{0.4} \quad \left(\begin{array}{l} \text{McAdams} \\ \text{Third Edition} \\ \text{page 219} \end{array} \right)$$

$$\frac{h_1 \times 0.0402}{0.036} = 0.023 \left(\frac{0.0402 \times 890000}{0.092} \right)^{0.8} \times \left(\frac{0.72 \times 0.092}{0.036} \right)^{0.4}$$

$$h_1 = \underline{783} \text{ Btu/}^{\circ}\text{F hr F}$$

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f) Tube Sheet

No. of tubes: 470

pitch $D_c = 1.25"$ assumed

$N_c =$ No. of tube holes in tube sheet

$$\frac{D_s}{D_c} = 0.96 + \sqrt{(N_c - 3.7/0.907)}$$

$$\frac{D_s}{D_c} = 0.96 + \sqrt{470 - 3.7/0.907}$$

$$D_s = 23.56 \times 1.25 = 29.4"$$

Select: 30" pipe for shell

g) Sodium Flow

Shell: 28.75" ID.

470 tubes - 0.75" OD.

$A_o = 0.00305 \text{ ft}^2/\text{tube}$

Total flow area:

$$4.5 - 470 \times 0.00305 = 3.068 \text{ ft}^2$$

Sodium velocity

$$V = \frac{2.7 \times 10^6}{3600 \times 3.068 \times 51} = \text{approx. } 4.8 \text{ fps}$$

Selected: 5 fps

h) Sodium Heat Transfer

Assumption: Sodium flows parallel to tube bundle.

Hydraulic Diameter

$$D_h = \frac{4F}{U}$$

$$F = S_1 \times S_2 - \frac{d^2 \pi}{4}$$

$$U = 2(S_1 - d) + 2(\sqrt{S_2^2 + m^2} - d) + d \pi$$

$$D_h = \frac{4 \times 0.936}{4.33}$$

$$D_h = \underline{0.86"} \text{ or } \underline{0.0712 \text{ ft}}$$

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Heat Transfer Coefficient
from "Unbaffled Shell" equation (Donohue)

$$\frac{hD_o}{k} = 0.128 (D_o' P_o)^{0.6} \quad (\text{MSA Tech. Report 39, August 1955})$$

D_o' = shell side equivalent diameter (inches)

$$V = 5 \times 3600 = 18000 \text{ ft/hr}$$

$$P_o = D_o' V \frac{C_p \rho}{k} = \frac{0.0712 \times 18000 \times 0.3 \times 51}{38} = 516$$

$$\frac{h \times 0.07}{38} = 0.128 (0.86 \times 516)^{0.6}$$

$$h = \frac{0.128 \times 39 \times 38}{0.07} = 2710 \text{ Btu/ft}^2 \text{ hr F}$$

1) Overall Heat Transfer Coefficient of Superheater

$$U_o = \frac{1}{\frac{1}{h_o} + r_o + r_w + r_i \left(\frac{D_o}{D_i} \right) + \frac{1}{h_i \left(\frac{D_i}{D_o} \right)}}$$

$$h_o = 2710 \text{ Btu/ft}^2 \text{ hr F}$$

$$r_o = 0 \text{ (fouling factor - outside)}$$

$$r_w = \frac{\text{tube wall thickness}}{\text{conductivity}} = \frac{0.134}{12 \times 13} = 0.00086$$

$$r_i = 0.0005 \text{ (fouling factor on steam side)}$$

This fouling factor is in accordance with the TEMA Standards, however, is probably very conservative.

$$\frac{D_o}{D_i} = \frac{0.75}{0.482} = 1.55$$

$$h_i = 783 \text{ Btu/ft}^2 \text{ hr F}$$

$$U_o = \frac{1}{\frac{1}{2710} + 0 + 0.00086 + 0.0005 \times 1.55 + \frac{1}{783 \left(\frac{0.482}{0.75} \right)}}$$

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$$U_o = \underline{251} \text{ vs } 250 \text{ assumed}$$

2. Boiler Section

Steam flow: 530,000 lbs/hr

p (outlet) = 2600 psia, 2% moisture

Sodium temperature at inlet = 867 F
(After mixing with reheater return stream, see Fig. 1)

Total sodium flow: 3.58×10^6 lbs/hr

a) Heating Surface

$$\Delta T = \frac{W (\Delta h)}{W(\text{sodium}) \times C_p} = \frac{530,000 (1080-750)}{3.58 \times 10^6 \times 0.307} = 159^\circ \text{F}$$

867

LMTD = 93 F

$$HS = \frac{W(\Delta h)}{LMTD \times U} = \frac{530,000 (330)}{93 \times 420} = \underline{4500 \text{ ft}^2}$$

Overall U assumed - 420 Btu/ft² hr F

b) Tubes

Assume: 5/8" OD, 2 1/4 Cr-1 Mo

p (Design) = 2800 psig

T (") = 950 F

Tubes to be in accordance with ASME "Unfired Pressure Vessel Code",
Section VIII. Selected: 5/8" OD, 14 BWG, 0.083" wall thickness

c) Velocity Conditions:

Water entering: 530,000 lbs/hr
plus 2% blowdown 10,600
Total 540,600 lbs/hr

Water velocity at inlet (assumed): 8 fps

$$\text{No tubes} = \frac{W \times v}{3600 \times V_1 \times A_1} = \frac{540,600 \times 0.0305}{3600 \times 8 \times 0.00115} = \underline{500 \text{ tubes}}$$

Outlet velocity V_2 : (Sat. steam, 2% moisture)

$$V_2 = V_1 \frac{v_2}{v_1} = \frac{8 \times 0.1213}{0.0305} = 31.8 = \underline{32 \text{ fps}}$$

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$$\text{Tube length: } \frac{HS}{N_o \times \frac{ft^2}{ft}} = \frac{4500}{500 \times 0.1636} = 55 \text{ ft}$$

d) Pressure Drop - Water Side

Solution for one-phase flow

$$W(\text{tube}) = \frac{540,600}{60 \times 500} = 18 \text{ lbs/min/tube}$$

$$\text{GPM} = \frac{18 \times 0.0295}{8.3 \times 0.01603} = 4 \text{ GPM}$$

$$D_1 = 0.459"$$

From "Tube Turn" diagram, p. 262

$$p/100 \text{ ft} = 15 \text{ psi (water only)}$$

Total equivalent tube length = 55 feet plus
inlet and outlet losses = 100 ft (assumed)

Exit quality (% vapour by weight) = 98%

Steam pressure - appr. 2600 psia

$$\frac{p(\text{two-phase})}{p(\text{single-phase})} = 3.2$$

(Source; Personal communication with MIT, 1956, using Martinelli's correlations.)

Two-phase pressure drop through boiler section

$$p = 15 \times 3.2 = 48 \text{ psi}$$

This pressure drop may be inadequate to prevent flow instabilities at lower loads and should be studied in detail.

e) Boiling Heat Transfer

$$\text{Average Heat Flux: } \frac{W(\text{steam}) \times \Delta h}{HS} = \frac{530000 \times 330}{4500} = 39,000 \text{ Btu/ft}^2\text{-hr}$$

On the basis of this heat flux, the $\Delta T_m = (T_{\text{wall}} - T_{\text{bulk}})$ for water boiling is in the order of 2-6 F in accordance with diagrams. Fig. 14-8, 14-16, 14-27, McAdams, III Edition.

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Since the total temperature difference between sodium and water will vary from 35 F to 194 F over the length of the boiler section, considerable local changes in heat flux will result.

As the water in the once-through boiler is progressively vaporized, the local overall heat transfer coefficient first increases, and then decreases sharply toward values similar to that of superheated steam. Fig. 14-26 (Mc Adams, p 398) shows an appreciable decrease in heat transfer coefficient beyond the point where 60% of the water is vaporized. This is due to the insufficient wetting of the wall.

Since the local heat transfer coefficient is also controlled by the combined influence of boiling and forced convection at high mass flow rates, it is difficult to determine the overall heat transfer coefficient in such a boiler section without detailed and sectionalized analysis.

In evaluating all possible influences, an average boiling heat transfer factor of

$$h = \underline{1500} \text{ Btu/ft}^2 \text{ hr F}$$

was assumed for this preliminary calculation.

f) Tube Sheet

No. of tubes: 500, 5/8" OD
Pitch: 1.2" (assumed)

$$\frac{D_s}{D_c} = 0.94 + \sqrt{(N-3.7/0.907)}$$

$$\frac{D_s}{1.2} = 0.94 + \sqrt{(500-3.7/0.907)}$$

$$D_s = 24.34 \times 1.2 = 29.2"$$

Select: 30" pipe for shell

g) Sodium Flow

Shell: 28.75" ID
500 tubes - 0.625" OD
 $A_o = 0.002125 \text{ ft}^2/\text{tube}$
Total flow area:
 $4.5 = 500 \times 0.002125 = 3.438 \text{ ft}^2$
Sodium velocity

$$V = \frac{3.58 \times 10^6}{3600 \times 3.438 \times 53.5} = \underline{5.4 \text{ fps}}$$

h) Sodium Heat Transfer

Assumption: Sodium flows parallel to tube bundle

Hydraulic Diameter

$$D_h = \frac{4F}{U}$$

$$F = S_1 \times S_2 - \frac{d^2 \pi}{4}$$

$$U = 2(S_1 - d) + 2(\sqrt{S_2^2 + m^2} - d) + d\pi$$

$$F = 0.893 \text{ inch}^2$$

$$U = 3.82 \text{ inch}$$

$$D_h = \frac{4 \times 0.893}{3.82} = 0.94" \quad \text{or } 0.0783 \text{ ft}$$

Heat transfer Coefficient from "Unbaffled Shell Equation", (Donohue)

$$\frac{hD}{k} = 0.128 (D_e' P_e)^{0.6}$$

$$P_e = D_e' V \frac{C_p \rho}{k} = 0.0783 \times 5.4 \times 3600 \times \frac{0.305 \times 53.5}{41} = 608$$

$$\frac{h \times 0.0783}{41} = 0.128 (0.94 \times 608)^{0.6}$$

$$h = \text{appr. } 3000 \text{ Btu/ft}^2 \text{ hr } F$$

1) Overall Heat Transfer Coefficient for Boiler Section

$$U_o = \frac{1}{\frac{1}{h_o} + r_o + r_w + r_i \left(\frac{D_o}{D_i} \right) + \frac{1}{h_i \left(\frac{D_i}{D_o} \right)}}$$

$$h_o = 3000 \text{ Btu/ft}^2 \text{ hr } F$$

$$r_o = 0$$

$$r_w = \frac{0.083}{12 \times 15} = 0.000461$$

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$r_1 = 0.0005$ (fouling factor on water side)
This factor can be considered adequate for high quality
boiling water flowing with high velocities.

$$\frac{B_o}{D_1} = \frac{0.625}{0.459} = 1.36$$

$$U_o = \frac{1}{\frac{1}{3000} + 0 + 0.000461 + 0.0005 \times 1.36 + \frac{1}{1500 \left(\frac{0.459}{0.625} \right)}}$$

$$U_o = 418 \text{ Btu/ft}^2 \text{ hr F} \quad \text{vs } 420 \text{ assumed}$$

3. Preheater Section

Water flow: 540,600 lbs/hr

p (outlet): approx. 2650 psig

t(inlet): 540 F

t(outlet): 673 F

Sodium temperature at inlet: 708 F

Sodium flow: 3.58×10^6 lbs/hr

a) Heating Surface

$$\Delta T = \frac{W (\Delta h)}{W (\text{sodium}) \times C_p} = \frac{540600 (750-536)}{3.58 \times 10^6 \times 0.31} = 104 \text{ F}$$

assumed: 108 F

708

LMTD = 46 F

$$HS = \frac{W (\Delta h)}{LMTD \times U} = \frac{540600 (214)}{46 \times 480} = 5260 \text{ ft}^2$$

Overall U assumed - 480 Btu/ft² hr F

b) Tubes

The same as in boiler section:

500 tubes - 5/8" OD, 14 BWG, 0.083" wall thickness

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c) Velocity Conditions

Water flow: 540,600 lbs/hr

$$\text{Outlet velocity: } \frac{540,600 \times 0.0305}{3600 \times 500 \times 0.00115} = 8.0 \text{ fps}$$

$$\text{Inlet velocity: } 8.0 \frac{0.0215}{0.0305} = 5.64 \text{ fps}$$

$$\text{Tube length: } \frac{HS}{N_p \times \frac{ft^2}{ft}} = \frac{5260}{500 \times 0.1636} = 64.5 \text{ feet}$$

use 65 feet

d) Pressure Drop - Water Side

$$W (\text{tube}) = \frac{540,600}{60 \times 500} = 18 \text{ lbs/Min/tube}$$

$$\text{GPM} = \frac{18 \times 0.0260}{8.3 \times 0.01603} = 3.52 \text{ GPM}$$

$$D_1 = 0.459"$$

From "Tube Turn" Diagram, p. 242

$$p/100 \text{ ft} = 12 \text{ psi}$$

This pressure drop is possibly inadequate to prevent flow instabilities at lower loads and should be studied in detail.

f) Heat Transfer - Water Side

$$\frac{h_1 D}{k_b} = 0.023 \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

$$G_1 = \frac{540,600}{500 \times 0.00115} = 940,000 \text{ lbs/ft}^2 \text{ hr}$$

$$\frac{h \times 0.0382}{0.275} = 0.023 \left(\frac{0.0382 \times 940,000}{0.193} \right)^{0.8} \left(\frac{1.0 \times 0.193}{0.275} \right)^{0.4}$$

$$h = \underline{2300} \text{ Btu/ft}^2 \text{ hr } F$$

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g) Sodium Heat Transfer

h (assumed-similar to boiler section) = 2800 Btu/ft² to F

h) Overall Heat Transfer Coefficient for Preheater Section

$$U_o = \frac{1}{\frac{1}{h_o} + r_o + r_w + r_i \left(\frac{D_o}{D_i} \right) + \frac{1}{h_i \left(\frac{D_i}{D_o} \right)}}$$

$$U_o = \frac{1}{\frac{1}{2800} + 0 + 0.000461 + 0.0005 \times 1.36 + \frac{1}{2300 \left(\frac{0.459}{0.625} \right)}}$$

$$U_o = \underline{478} \text{ Btu/ft}^2 \text{ hr F} \quad \text{vs } 480 \text{ assumed}$$

4. Reheater

4a) Design Conditions

Sodium flow from two (2) steam generator loops: (See Fig. 1)

$$2 \times 0.88 \times 10^6 = 1.76 \times 10^6 \text{ lbs/hr}$$

$$t \text{ (inlet)} = 1150 \text{ F}$$

$$t \text{ (outlet)} = \frac{825 \text{ F}}{325 \text{ F}}$$

Steam Conditions: (assumed)

$$p \text{ (out)} = 550 \text{ psia, } 1000 \text{ F}$$

$$p \text{ (in)} = 600 \text{ psia, } 650 \text{ F}$$

Steam flow:

$$W = \frac{1.76 \times 10^6 \times 0.3 \times 325}{(1518 - 1321)} = 870,000 \text{ lbs/hr}$$

$$\Delta t = \frac{870,000 (1518 - 1321)}{176 \times 10^6 \times 0.3} = 324 \text{ F}$$

approx. 325 F

1150

1000
150

LMTD = 161 F

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$$\text{Heating Surface: } \frac{870,000 \times 197}{161 \times 220} = 4860 \text{ ft}^2$$

Overall U assumed - 220 Btu/ ft² hr F

b) Tubes

Assume: 3/4" OD tubes, SS 316

p (Design): 700 psig

t (Design): 1175 F

Tubes to be in accordance with ASME Unfired Pressure Vessel Code, Section VIII

Selected: 3/4" OD, 16 BWG, 0.065" wall thickness

c) Velocity Conditions

Steam velocity at inlet: 100 fps (assumed)

$$\text{No. of tubes: } \frac{870,000 \times 1.01}{3600 \times 100 \times 0.002095} = 1165 \text{ tubes}$$

$$\text{Outlet velocity: } 100 \times \frac{1.541}{1.00} = 154 \text{ fps}$$

$$\text{Tube length} = \frac{4860}{1165 \times 0.1963} = 21.2 = \text{appr. } \underline{22 \text{ feet}}$$

d) Steam Pressure Drop (Reheater)

Fritzsche Formula

$$p = \frac{21.082 \times v^{1.85}}{10^6 d^{4.97}}$$

$$v = 1.27 \text{ ft}^3/\text{lb}$$

$$W = \frac{870,000}{1165} = 747 \text{ lbs/hr/tube}$$

$$d = 0.62"$$

$$\Delta p = \frac{21.082 \times 1.27 \times 747^{1.85}}{10^6 \times 0.62^{4.95}} = 60 \text{ psi/100 ft}$$

Total equivalent tube length of reheater = 22 feet plus inlet and outlet losses = 50 ft (assumed)

p = 30 psi through reheater

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e) Steam Heat Transfer

$$\frac{h_1 D}{k} = 0.023 \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

$$\frac{h \times 0.0517}{0.032} = 0.023 \left(\frac{0.0517 \times 356,000}{0.063} \right)^{0.8} \left(\frac{0.55 \times 0.063}{0.032} \right)^{0.4}$$

$$h = \underline{353} \text{ Btu/ft}^2 \text{ hr F}$$

f) Tube Sheet

No. of tubes: 1165

pitch: 1.0" (assumed)

$$\frac{D_s}{D_c} = 0.94 + \sqrt{(N_c - 3.7/0.907)}$$

$$\frac{D_s}{1.0} = 0.96 + \sqrt{(1165 - 3.7/0.907)}$$

$$D_s = 36.86",$$

Select: 38" ID Shell

g) Sodium Flow

Shell: 38" ID

1165 tubes - 0.75" OD

$$A_o = 0.00305 \text{ ft}^2/\text{tube}$$

Total flow area:

$$7.84 = 1165 \times 0.00305 = 4.29 \text{ ft}^2$$

Sodium velocity

$$V = \frac{1.76 \times 10^6}{3600 \times 4.29 \times 51.5} = 2.21 \text{ fps}$$

This velocity is too low. Reheater shell to be cross-baffled.

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h) Sodium Heat Transfer

Equation for liquid metal (MAA-SR-3969, p. 12)
flowing over staggered tubes

$$\frac{hD}{k} = 1.17 \left(\frac{DG_{\max} Cp}{k} \right)^{0.8} \left(\frac{Cp}{k} \right)^{0.333}$$

$$D = 0.0625 \text{ ft}$$

$$G = \frac{1.76 \times 10^6}{4.29} = 410,000 \text{ lbs/hr ft}^2 \quad \left. \vphantom{\frac{1.76 \times 10^6}{4.29}} \right\} \begin{array}{l} \text{simplified} \\ \text{assumptions} \end{array}$$

$$\frac{h \times 0.0625}{39} = 1.17 \left(\frac{0.0625 \times 410,000 \times 0.3}{39} \right)^{0.8} \left(\frac{0.3 \times 0.6}{39} \right)^{0.333}$$

$$h = 8300 \text{ Btu/ft}^2 \text{ hr F}$$

i) Overall Heat Transfer Coefficient of Reheater

$$U_o = \frac{1}{\frac{1}{h_o} + r_o + r_w + r_1 \left(\frac{D_o}{D_1} \right) + \frac{1}{h_1 \left(\frac{D_1}{D_o} \right)}}$$

$$h_o = 8300$$

$$r_o = 0$$

$$r_w = \frac{0.065}{12 \times 13} = 0.000417$$

$$r_1 = 0.0005 \text{ (fouling factor on steam side, see "Superheater").}$$

$$\frac{D_o}{D_1} = \frac{0.75}{0.65} = 1.21$$

$$h_1 = 353$$

$$U_o = \frac{1}{\frac{1}{8300} + 0 + 0.000417 + 0.0005 \times 1.21 + \frac{1}{353 \left(\frac{0.65}{0.75} \right)}}$$

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$$U_o = \frac{1}{0.004572} = \underline{219} \text{ Btu/ft}^2 \text{ hr } F$$

vs 220 assumed

5. 25% load performance of steam generator and reheater is indicated in Fig. 4.

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FLOW DIAGRAM FIG. 1

N 100-12 687 20

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APPROXIMATE TUBE BUNDLE SIZES

FIG. 3

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TEMPERATURE DIAGRAM

FIG. 4

25 % TURBINE LOAD

31 % STEAM FLOW

31 % SODIUM FLOW