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ENGINEERING

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SUPPLEMENT
NO. 1**

VOLUME IV

**LMFBR
DEMONSTRATION PLANT
STEAM GENERATING
SYSTEM**

AEC CONTRACT AT(11-1)-3031

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CE COMBUSTION DIVISION

COMBUSTION ENGINEERING, INC.

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APPENDIX G

THERMAL TRANSIENT MODEL CALCULATION

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TOMER AEC CONT. No. _____ MADE BY Jch Langer DATE 12/78
LOCATION _____ DWG. No. _____ CHK'D BY Jch DATE 12/78

All calculations for the steam generator nodal model are presented in this section. All calculations involving performance parameters were made for the nominal 100% load case; information obtained from computer output "Performance Study of Sodium Heated Steam Generator".

Node Designations - (all represent temperature, exceptions noted)

48 - steam in the separation drum (enthalpy)

49 - drum metal, upper portion

50 - mixed (separated & feed) water in the drum (enthalpy)

51 - drum metal, lower portion

115 - water within recirculation pumps.

133-142 - sodium in the superheater tube bundle

143-152 - pressure tube wall - superheater bundle

153-162 - steam annulus - superheater bundle

163-172 - Bayonet tube assembly - superheater bundle

173-182 - Riser tube steam - superheater bundle

183-188 - sodium ~~inlet~~ region - superheater

189-188 - sodium ~~inlet~~ region - superheater

189-197 - steam inlet and outlet regions including additional heat exchange above sodium level.

198-203 - sodium inlet and outlet regions - evaporator

204-212 - steam/water inlet and outlet regions including additional heat exchange above sodium level

213-218 - sodium piping between superheater and evaporator

229-243 - sodium in the evaporator tube bundle

244-258 - pressure tube wall - evaporator bundle

259-273 - steam/water annulus - evaporator bundle (enthalpy)

274-288 - bayonet tube assembly - evaporator bundle

289-303 - downcomer feedwater - evaporator bundle

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57-72 - Temperature vs enthalpy curve fit connecting nodes
386 - 400 with node 259-273, respectively.

72 - saturation temperature for node 362 which corresponds
to steam enthalpy node 48.

73 - Temperature vs enthalpy curve fit connecting node 363
with subcooled water node 50.

74 - Secondary sodium inlet temperature

75 - Feedwater enthalpy

76 - secondary sodium flow rate per module

77 - secondary sodium flow rate per superheater tube

78 - secondary sodium flow rate per evaporator tube

79 - steam flow rate per superheater module

80 - steam flow rate per superheater tube

81 - steam flow rate per loop

82 - feedwater flow rate per loop

83 - recirculation flow rate per evaporator module

84 - recirculation flow rate per evaporator tube

85 - recirculation flow rate loop

86 - saturated vapor enthalpy

87 - saturated liquid enthalpy

88 - saturated enthalpies: h_f/h_{fg}

89 - saturated enthalpies: h_f/h_{fg}

Other nodes and flow equations may be used to
effect particular transients or to obtain particular
printed output.

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304-309 - Piping from evaporator to separation drum
fluid nodes are enthalpy.

310-313 - piping from separation drum to recirculation pump.

333-338 - piping from separation drum to superheater

339-344 - piping from recirculation pump to evaporator

356 - saturated vapor enthalpy for drum node 48

357 - saturated liquid enthalpy for drum node 50

361 - enthalpy corresponding to node 303

362 - temperature corresponding to node 48

363 - temperature corresponding to node 50

364 - secondary sodium inlet temperature

365 - feedwater enthalpy

366 - separated water in drum

367 - separated steam in drum

368 - Steam quality (computed)

369 - unity node - needed for CEROS equation format

380-400 - steam/water temperatures corresponding to enthalpy
nodes 305, 307, 309, 205, 206, 207, 259 - 273 respectively.

Flow equations Designations

47 - Flow per loop of separated water in drum

50 - enthalpy vs Temperature Curve fit connecting node 361
with node 303.

51-56 - saturation temperature for nodes 380 - 385 which
correspond to enthalpy nodes 305, 307, 309, 205, 206, 207,
respectively

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The differential nodes are manipulated into the following standard format.

$$\dot{F}_i = y_i F_i + C_{ii} \omega_i F_i + \sum_j (C_{ij} F_j + C'_{ij} \omega_j F_j)$$

- i - node under consideration
 y_i, C_{ii} - self connector, including flow equation dependence
 j - all nodes to which node i is connected
 C_{ij}, C'_{ij} - connectors between nodes i and j .
 ω - flow equation

Algebraic nodes, non-differential connector between nodes

$$F_i = C_{ii} \omega F_i + \sum_j (C_{ij} F_j + C'_{ij} \omega F_j)$$

Flow equations are each defined by 10 constants, $(C_1, \dots, C_{10})$

1) If $C_1 < 0$, it must be an integer since τ refers to a variable $\tau = F_{i+1}$, and

$$\omega = C_2 \tau + C_3 \tau^2 + \frac{C_4}{\tau} + \frac{C_5}{\tau^2} + C_6 + C_7 \tau^3 + C_8 \tau^4 + C_9 \tau^5 + C_{10} \tau^6$$

2) If $C_1 \geq 0$, it must also be an integer since it refers to a variable $\tau = F_i$, ($\tau = 0$ if $C_1 = 0$). In addition

a) If $C_{10} = 0$

$$\omega = H + R(\tau) + C_2 + C_5 \exp(C_6 \tau + C_7 \tau^2); \quad \tau^* = \tau + C_9$$

b) If $C_{10} > 0$

$$\omega = \begin{cases} H + C_{10} & \tau \leq 0, \tau_m \leq 0 \\ H + R(\tau_m^*) + C_2 + C_5 \exp(C_6 \tau + C_7 \tau^2), & \tau_m > 0 \end{cases}$$

$$\tau_m = \tau - (C_8 + C_9) \text{ and } \tau_m^* = \tau_m + C_9$$

where

$$H = \begin{cases} 0 & C_1 = 0 \\ \tau & C_1 > 0 \end{cases}; \quad R(\tau) = \begin{cases} 0 & \tau \leq 0 \\ C_3 \tau + C_4 \tau^2 & \tau > 0 \end{cases}$$

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Superheater

I. Main Heat Transfer Region

As described below the transient model used is the "Outlet Temperature Model" where the nodal point is characterized by the properties at the outlet of the finite element which the node represents.

Due to the steepness of the steam temperature profile a strict adherence to this model will yield a low heat flux. Consequently it is assumed that the heat transfer is based on the average fluid temperature and fluid capacity is based on the outlet temperature.

Energy balances

$$-(UA)_1 [T_{NA} - T_{PT}] + (wcp)_{NA} T_{NA} = (wcp)_{NA} T_{NA} + (pvc)_{NA} \frac{dT_{NA}}{dt}$$

$$(UA)_1 [T_{NA} - T_{PT}] - (UA)_2 [T_{PT} - T_{ANN}] = (pvc)_{PT} \frac{dT_{PT}}{dt}$$

$$(UA)_2 [T_{PT} - T_{ANN}] - (UA)_3 [T_{ANN} - T_{BT}] + w_{ANN} h_{ANN} = w_{ANN} h_{ANN} + \frac{d}{dt} (pvu)_{ANN}$$

$$(UA)_3 [T_{ANN} - T_{BT}] - (UA)_4 [T_{BT} - T_R] = (pvc)_{BT} \frac{dT_{BT}}{dt}$$

$$(UA)_4 [T_{BT} - T_R] + w_R h_R = w_R h_R + \frac{d}{dt} (pvu)_R$$

For the steam in the annuli and risers the following assumptions are made:

$$\frac{dp}{dt} = 0$$

(implicit, since continuity has not been included in the formulation)

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$$dh = c_p dT$$

$$\frac{dP}{dt} \approx 0 \Rightarrow \frac{d(\rho u)}{dt} = \frac{d}{dt}(\rho h - p) = \frac{d}{dt}(\rho h) = \rho c_p \frac{dT}{dt}$$

and for all fluid node the "average" value is one half the sum of the inlet and outlet value.

$$T_{AV} = \frac{1}{2} (T_{IN} + T)$$

It should be noted that T_{IN} is the value associated with the previous node. The results of these assumptions are substituted into the energy balances. The equations are then rearranged into standard format.

$$\dot{T}_{NA} = -\frac{1}{2} \left[\frac{(UA)_1}{(PVC_p)_{NA}} \right] T_{NA} + \left[\frac{(UA)_1}{(PVC_p)_{NA}} \right] T_{PT} - \frac{1}{2} \left[\frac{(UA)_1}{(PVC_p)_{NA}} \right] T_{NA_{IN}} + \left(\frac{W}{PV} \right)_{NA_{IN}} T_{NA_{IN}} - \left(\frac{W}{PV} \right)_{NA} T_{NA}$$

$$\dot{T}_{PT} = -\left[\frac{(UA)_1}{(PVC_p)_{PT}} + \frac{(UA)_2}{(PVC_p)_{PT}} \right] T_{PT} + \frac{1}{2} \left[\frac{(UA)_1}{(PVC_p)_{PT}} \right] T_{NA_{IN}} + \frac{1}{2} \left[\frac{(UA)_1}{(PVC_p)_{PT}} \right] T_{NA} + \frac{1}{2} \left[\frac{(UA)_2}{(PVC_p)_{PT}} \right] T_{ANN_{IN}} + \frac{1}{2} \left[\frac{(UA)_2}{(PVC_p)_{PT}} \right] T_{ANN}$$

$$\dot{T}_{ANN} = -\frac{1}{2} \left[\frac{(UA)_2}{(PVC_p)_S} + \frac{(UA)_3}{(PVC_p)_S} \right] T_{ANN} + \left[\frac{(UA)_1}{(PVC_p)_S} \right] T_{PT} + \left[\frac{(UA)_3}{(PVC_p)_S} \right] T_{BT} - \frac{1}{2} \left[\frac{(UA)_2}{(PVC_p)_S} + \frac{(UA)_3}{(PVC_p)_S} \right] T_{ANN_{IN}} + \left(\frac{W}{PV} \right)_S T_{ANN_{IN}} - \left(\frac{W}{PV} \right)_S T_{ANN}$$

$$\dot{T}_{BT} = -\left[\frac{(UA)_3}{(PVC_p)_{BT}} + \frac{(UA)_4}{(PVC_p)_{BT}} \right] T_{BT} + \frac{1}{2} \left[\frac{(UA)_3}{(PVC_p)_{BT}} \right] T_{ANN_{IN}} + \frac{1}{2} \left[\frac{(UA)_3}{(PVC_p)_{BT}} \right] T_{ANN} + \frac{1}{2} \left[\frac{(UA)_4}{(PVC_p)_{BT}} \right] T_{R_{IN}} + \frac{1}{2} \left[\frac{(UA)_4}{(PVC_p)_{BT}} \right] T_R$$

$$\dot{T}_R = -\frac{1}{2} \left[\frac{(UA)_4}{(PVC_p)_R} \right] T_R + \left[\frac{(UA)_4}{(PVC_p)_R} \right] T_{BT} - \frac{1}{2} \left[\frac{(UA)_4}{(PVC_p)_R} \right] T_{R_{IN}} + \left(\frac{W}{PV} \right)_R T_{R_{IN}} - \left(\frac{W}{PV} \right)_R T_R$$

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Design parameters and axial variations of the properties of the superheater working fluids were obtained from the computer output "Performance Studies for Sodium Heated Steam Generator". A program was written for the GE Time Sharing Computer, which takes all the above data and calculates the coefficients for the equations governing the transient.

Input data:

1) T_{Na} , T_{srm} , P_{srm} , T_{srm} as functions of axial position.

2) steam and sodium flow rates per tube, sodium film coefficient (h_{Na}), riser steam film coefficient (h_r), annular steam film coefficient (h_s) as a function of axial position.

3) properties for sodium, pressure tube and bayonet tube materials, and steam in the bayonet tube insulation gap. In addition, $\bar{C}_p = \Delta h / \Delta T$ for each superheater sizing increment is input.

4) Tube geometry

$d_1, d_2 \sim$ inner bayonet tube ID, OD

$d_3, d_4 \sim$ outer bayonet tube ID, OD

$d_5, d_6 \sim$ pressure tube ID, OD

$P \sim$ pitch

$LT \sim$ heat transfer length of tubes.

The following parameters are computed:

1) Parameters that do not vary with axial position.

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This category includes the properties and parameters for the sodium, the pressure tube, and the bayonet tube assembly. The variation of properties and parameters of the steam in the riser is slight and may be neglected. This may not be done for the annular steam.

a) Volumes and Capacitances

$$V_{Na} = \left(\frac{\sqrt{3}}{2} P^2 - \frac{\pi}{4} d_6^2 \right) \Delta L \quad ; \quad C_{Na} = \rho_{Na} V_{Na} C_{pNa}$$

$$V_{PT} = \frac{\pi}{4} (d_6^2 - d_5^2) \Delta L \quad ; \quad C_{PT} = \rho_{PT} V_{PT} (C_p)_{PT}$$

$$V_{BT} = \frac{\pi}{4} [(d_4^2 - d_3^2) + (d_2^2 - d_1^2)] \Delta L \quad ; \quad C_{BT} = \rho_{BT} V_{BT} (C_p)_{BT}$$

$$V_{R_{sim}} = \frac{\pi}{4} d_1^2 \Delta L \quad ; \quad C_{R_{sim}} = \rho_{R_{sim}} V_{R_{sim}} (C_p)_{R_{sim}}$$

$$V_{Ann_{sim}} = \frac{\pi}{4} (d_5^2 - d_1^2) \Delta L$$

where ΔL = length of each nodal increment in the CERPS model.

b) Thermal Resistances

$$R_{Na} = \frac{1}{\pi d_6 \Delta L h_{Na}} \quad ; \quad R_{PT_1} = \frac{\ln(d_6/\bar{d})}{2\pi k_{PT} \Delta L}$$

$$\text{where } \bar{d} = \left(\frac{d_6^2 + d_5^2}{2} \right)^{1/2}$$

and

$$(UA)_1 = (R_{Na} + R_{PT_1})^{-1}$$

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$$R_{PT2} = \frac{\ln(\bar{d}/d_5)}{2\pi k_{PT} \Delta L}$$

$$R_{BT0} = \frac{\ln(d_4/d_3)}{2\pi k_{BT} \Delta L}$$

$$R_{gap} = \frac{\ln(d_3/d_2)}{2\pi k_{gap} \Delta L}$$

$$R_{BT1} = \frac{\ln(d_2/d_1)}{2\pi k_{BT} \Delta L}$$

$$R_{BT1} = R_{BT0} + \frac{1}{2} R_{gap}$$

$$R_{BT2} = \frac{1}{2} R_{gap} + R_{BT1}$$

$$R_{sim} = \frac{1}{\pi d_1 \Delta L h_R}$$

and

$$(UA)_4 = (R_{BT2} + R_{sim})^{-1}$$

2) Parameters that vary with axial position are then computed. Since the properties of the annular steam vary, the thermal capacitances and resistances also vary. Thus, node by node computations must be made.

The model employed is the "Outlet Temperature Model" wherein the node is characterized by the properties at the outlet of the finite element the node represents. For a set of nodes at a given axial position, the sodium and riser steam conditions are obtained at the given axial position, but the associated annular steam conditions exist a nodal

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increment away. Consequently the associated pressure tube and bayonet tube assembly average temperatures are "diagonal" averages. (see Figure)

The coefficients of the governing differential equations were calculated and a steady state temperature distribution obtained. The heat flux from the sodium to the annular steam was calculated from the output.

$$\frac{dq}{dA} = U_{NA \rightarrow SM} (T_{Na} - T_{SM})$$

This was then compared to the output of the sizing program. The heat flux distribution for the CERQS model was consistently and considerably below

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that of the Syng code model. The heat transfer coefficients in the two models were the same; the differences in heat fluxes were due to the differences in $(T_w - T_{sim})$.

The root cause of this disparity is the strict adherence to the "outlet Temperature Model" in the CERPS model. A fluid node is represented by the conditions at the outlet of the finite element which the node represents. Thus, for two fluids flowing counter to each other, the temperature between them would be a difference in the element outlet temperatures; this is indicated in the accompanying diagram. The difference in the average element temperature which is more representative of the actual situation is also indicated on the diagram. The temperature

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based on the outlet temperatures is always less than that for the average temperatures.

For regions where the temperature gradients are small and/or the nodal grid sufficiently fine, the "Outlet Temperature model" is a reasonable approximation. In the superheater the steam temperature profile is sufficiently steep that the energy transfer should be expressed in terms of the average fluid temperature. The derivation of the governing equations indicates the way that those average temperatures are related to the nodal (outlet) temperatures.

For each radial set of nodes, the outlet values of T_{na} , P_s , T_s , T_r are obtained by interpolation of the input data. The GE Mark II steam tables (Keenan & Keyes Steam Tables) are used to obtain the viscosity, specific heat, conductivity, and density of the annular steam.

In the formulation of the governing equations it was assumed that

$$dh = C_p dT$$

However, in the first section of the superheater, the steam has only a few degrees of superheat. For the pressure levels and pressure gradients that exists the specific heat from the steam tables is not a good approximation of dh/dT . An

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effective heat capacity is required

$$\bar{C}_p = \left(\frac{dh}{dT} \right)_{SH \text{ increments}}$$

This effective value is presented out as CPSH in the sizing code. The CPSH for each output line was associated with the end of each increment of the sizing code model, and an extrapolation of this array to $x=0$ was used for the initial point. This array was input to the time sharing computer program.

For the inlet and outlet of each element of the CERPS model a value of C_{psm} is obtained from interpolation of the input array. These two values are then averaged to obtain an accepted value of C_{psm} to be associated with the node; this supersedes the steam table value. The thermal capacity of each annular steam node is then calculated.

$$C_s = \frac{1}{\rho_{stm} V_{stm} C_{psm}}$$

The film coefficient for the annular steam is

$$h_s = \frac{k_{stm}}{D_c} [0.023 Re_s^{0.8} Pr_s^{0.4}]$$

$$Re_s = \frac{W_s}{A_{flow} \mu_{stm}}$$

$$Pr_s = \left(\frac{\mu_{stm}}{k} \right)_{stm}$$

$$D_c = d_5 - d_4$$

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These coefficients differed significantly with those printed out from the Sizing Code. The source of this difference is that the time sharing computer has only the Keenan & Keyes Steam Tables transport properties (μ, k), and the sizing program used the ASME steam tables transport properties; these two sources disagree considerably in the range of current interest. The ASME tables are considered to most up-to-date.

In order to correct this difference the film coefficients from the sizing code print out was accepted. An array representing h_s as a function of axial position was input to the time sharing computer program. The h_s for each output line was associated with the end of the sizing code model increment, and an extrapolation of this array to $x=0$ was used for the initial point.

For the inlet and outlet of each element of the CERPS model a value of h_s is obtained from interpolation of the input array. These two values are then averaged to obtain an accepted value of h_s to be associated with the node. This procedure supersedes the need to obtain μ, k and the calculation sequence for h_s . The associated thermal resistances and conductances.

$$R_{s1} = \frac{1}{\pi d_s \Delta L h_s} \quad ; \quad R_{s2} = \frac{1}{\pi d_g \Delta L h_s}$$

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and

$$(UA)_2 = (R_{PT,2} + R_{S,1})^{-1} ; (UA)_3 = (R_{S,2} + R_{BT,1})^{-1}$$

The associated average temperatures for the pressure tube and bayonet tube assembly are then calculated.

$$T_{PT} = \frac{(UA)_1 T_{Na} + (UA)_2 T_S}{(UA)_1 + (UA)_2}$$

$$T_{BT} = \frac{(UA)_3 T_S + (UA)_4 T_R}{(UA)_3 + (UA)_4}$$

Since the values of T_{Na} , T_S , T_R were interpolated at the outlet of the nodal element, T_{PT} , T_{BT} are the "diagonal" averages. These 5 temperature values are not necessary for the CERP calculations so they have not been revised to reflect average temperatures. They have been calculated and printed out for informational purposes only.

Finally the coefficients of the governing differential equations are calculated.

$$C_1 = -\frac{C_2}{2} ; C_2 = \frac{(UA)_1}{C_{Na}} ; C_3 = \frac{1}{\rho_{Na} V_{Na}}$$

$$C_4 = 2(C_5 + C_6) ; C_5 = \frac{1}{2} \frac{(UA)_1}{C_{PT}} ; C_6 = \frac{1}{2} \frac{(UA)_2}{C_{PT}}$$

$$C_7 = \frac{1}{2} (C_8 + C_9) ; C_8 = \frac{(UA)_2}{C_S} ; C_9 = \frac{(UA)_3}{C_S} ;$$

$$C_{10} = \frac{1.0}{\rho_S V_{STM}}$$

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$$C_{11} = 2(C_{12} + C_{13}) ; C_{12} = \frac{1}{2} \frac{(UA)_3}{C_{BT}} ; C_{13} = \frac{1}{2} \frac{(UA)_4}{C_{BT}}$$

$$C_{14} = \left(\frac{C_{15}}{2} \right) ; C_{15} = \frac{(UA)_4}{C_R} ; C_{16} = \frac{1.0}{P_R V_{R_{SM}}}$$

GDLM03

02/13/73

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100 DIMENSION XTAB(29),YTAB(29),ZTAB(29),TTAB(29),PTAB(29)
101 DIMENSION HTAB(29),CPB(29)
110 NTAB=29; NPT=3; IERR=0
120 DATA XTAB/0.0,1.099,2.199,3.298,4.397,5.496,6.596,7.695,8.794,
121&9.894,10.993,12.092,13.191,14.291,15.390,16.489,17.589,18.688,
122&19.787,20.886,21.986,23.085,24.184,25.283,26.383,27.482,28.581,
123&29.681,30.78/
130 DATA YTAB/866.02,872.21,878.23,884.05,889.70,895.10,900.21,
131&905.14,909.79,914.21,918.36,922.29,925.96,929.42,932.66,
132&935.68,938.50,941.13,943.57,945.85,947.96,949.93,951.75,
133&953.44,955.02,956.47,957.81,959.06,960.21/
140 DATA ZTAB/903.60,904.28,904.94,905.58,906.21,906.81,907.38,
141&907.93,908.44,908.93,909.38,909.80,910.19,910.55,910.88,
142&911.17,911.44,911.67,911.88,912.07,912.22,912.36,912.47,
143&912.57,912.57,912.57,912.57,912.57,912.57/
150 DATA TTAB/674.28,678.85,684.78,691.38,699.38,708.87,718.12,
151&728.62,739.05,750.41,761.36,772.83,783.87,794.89,805.63,
152&816.08,826.20,835.85,845.10,853.91,862.08,870.05,877.40,
153&884.22,890.74,896.76,902.34,907.78,912.77/
155 DATA CPB/5.4,4.576,3.426,2.977,2.388,1.919,1.896,1.586,1.506,1.315,
156&1.278,1.157,1.123,1.058,1.016,0.9749,0.9391,0.9151,0.8897,
157&0.8677,0.8677,0.8284,0.8284,0.8284,0.7979,0.7979,0.7979,
158&0.7596,0.7596/
160 DATA PTAB/2606.07,2604.64,2603.12,2601.49,2599.77,
161&2597.96,2596.05,2594.04,2591.95,2589.76,2587.50,2585.15,2582.73,
162&2580.23,2577.66,2575.02,2572.32,2569.56,2566.75,2563.88,2560.96,
163&2557.99,2554.98,2551.93,2548.84,2545.71,2542.55,2539.36,2529.75/
165 DATA HTAB/7320.,5583.,4566.,3895.,3543.,3130.,2777.,2674.,
166&2445.,2346.,2184.,2128.,2019.,1975.,1913.,1869.,1828.,1792.,
167&1767.,1741.,1720.,1716.,1682.,1679.,1677.,1651.,1650.,1649.,1616./
170 D1=0.636; D2=0.716; D3=0.836; D4=0.916; D5=1.116; D6=1.5
175 P=2.0; XLT=30.78
180 WNA=29020.; WS=2648.52
190 CPNA=0.30168; XKNA=39.0; RH0NA=52.3; XMUNA=0.60; HNA=7780.
195 CPR=0.65; XKR=0.0505; RH0R=3.667; XMUR=0.0731; HR=1212.
200 CPT=0.155; XKPT=15.9; RH0PT=480.
205 CBT=0.155; XKBT=15.9; RH0BT=480.
210 XKG=0.12
220 NP=10; DX=3.0779
250 RNA=3.8197/(D6*DX*HNA)
255 DB=SQRT((D5**2+D6**2)/2.0)
256 RPT1=0.159155*ALOG(D6/DB)/(DX*XKPT)
257 RPT2=0.159155*ALOG(DB/D5)/(DX*XKPT)
260 RBT1=0.159155*ALOG(D4/D3)/(DX*XKBT)
261 RGAP=0.159155*ALOG(D3/D2)/(DX*XKG)
262 RBT0=0.159155*ALOG(D2/D1)/(DX*XKBT)
263 RBT1=RBT1+0.5*RGAP; RBT2=0.5*RGAP+RBT0
270 RSTM=3.8197/(D1*DX*HR)
280 UA1=0.000277777/(RNA+RPT1); UA4=0.000277777/(RBT2+RSTM)
300 A1=(0.866025*P**2-0.785398*D6**2)/144.; V1=A1*DX

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301 A2=0.785398*(D6**2-D5**2)/144.; V2=A2*DX
302 A3=0.785398*(D5**2-D4**2)/144.; V3=A3*DX
303 A4=0.785398*(D4**2+D2**2-D3**2-D1**2)/144.; V4=A4*DX
304 A5=0.785398*(D1**2)/144.; V5=A5*DX
305 DE=(D5-D4)/12.
310 CANA=RH0NA*V1*CPNA
311 CAR=RH0R*V5*CPR
312 CAPT=RH0PT*V2*CPT
313 CABT=RH0BT*V4*CBT
320 C2=UA1/CANA; C1=C2/2.0; C3=1.0/(RH0NA*V1)
325 C5=0.5*UA1/CAPT
330 C13=0.5*UA4/CABT
335 C15=UA4/CAR; C14=C15/2.0; C16=1.0/(RH0R*V5)
350 PRINT,"VOLUMES AND CAPACITIES"
351 PRINT,V1,CANA,V2,CAPT,V4,CABT,V5,CAR,V3
352 PRINT 200
353 200 FORMAT(/)
360 PRINT,"THERMAL RESISTANCES AND CONDUCTANCES"
361 PRINT,RNA,RPT1,"",UA1
362 PRINT,RPT2
363 PRINT,RBT1,RGAP,RBT0
364 PRINT,RBT1
365 PRINT,RBT2,RSTM,"",UA4
370 PRINT 300
371 300 FORMAT(/////))
400 DO 100 I=1,NP
405 XI=I; X1=(XI-1.0)*DX; X2=XI*DX
410 TNA=TNT1(X1,NTAB,XTAB,YTAB,NPT,IERR)
420 TR=TNT1(X1,NTAB,XTAB,ZTAB,NPT,IERR)
430 TS=TNT1(X2,NTAB,XTAB,TTAB,NPT,IERR)
440 PS=TNT1(X2,NTAB,XTAB,PTAB,NPT,IERR)
447 CP1=TNT1(X1,NTAB,XTAB,CPB,NPT,IERR)
448 CP2=TNT1(X2,NTAB,XTAB,CPB,NPT,IERR)
449 CPS=(CP1+CP2)/2.0
450 XMUS=STMNU(PS,TS); XKS=STMEK(PS,TS)
451 RH0S=SUPD(PS,TS); PRS=XMUS*CPS/XKS
455 RES=WS*DE/(A3*XMUS)
460 HS1=TNT1(X1,NTAB,XTAB,HTAB,NPT,IERR)
461 HS2=TNT1(X2,NTAB,XTAB,HTAB,NPT,IERR)
462 HS=0.5*(HS1+HS2)
465 RS1=3.8197/(D5*DX*HS); RS2=3.8197/(D4*DX*HS)
470 UA2=0.000277777/(RPT2+RS1); UA3=0.000277777/(RS2+RBT1)
480 C6=0.5*UA2/CAPT; C4=2.0*(C5+C6)
485 CAS=RH0S*V3*CPS
486 C8=UA2/CAS; C9=UA3/CAS; C7=0.5*(C8+C9); C10=1.0/(RH0S*V3)
490 C12=0.5*UA3/CABT; C11=2.0*(C12+C13)
500 TPT=(UA1*TNA+UA2*TS)/(UA1+UA2); TBT=(UA3*TS+UA4*TR)/(UA3+UA4)
510 PRINT,"TEMPERATURE DISTRIBUTION"
511 PRINT,TNA,TPT,TS,TBT,TR
512 PRINT 200

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GDLMD3

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520 PRINT,"STEAM PROPERTIES"  
521 PRINT,PS,XMUS,XKS,CPS,RHOS,PRS,CAS  
522 PRINT 200  
530 PRINT,"THERMAL CONDUCTANCES---STEAM"  
531 PRINT,HS,"",UA2,UA3  
532 PRINT 200  
540 PRINT,"COEFFICIENTS"  
541 PRINT,C1,C2,C3  
542 PRINT,C4,C5,C6  
543 PRINT,C7,C8,C9,C10  
544 PRINT,C11,C12,C13  
545 PRINT,C14,C15,C16  
546 PRINT 400  
547 400 FORMAT(///)  
600 100 CONTINUE  
650 STOP; END
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GDLMD3

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VOLUMES AND CAPACITIES

3.6271224E-02	5.7228243E-01	1.6863619E-02	1.2546532E+00
4.1686314E-03	3.1014618E-01	6.7904106E-03	1.6185283E-02
6.8223735E-03			

THERMAL RESISTANCES AND CONDUCTANCES

1.0634177E-04	4.1076677E-04		5.3717348E-01
5.5093606E-04			
2.9720538E-04	6.6768524E-02	3.8531824E-04	
3.3681468E-02			
3.3769581E-02	1.6099597E-03		7.8513456E-03

TEMPERATURE DISTRIBUTION

8.6602000E+02	7.9403857E+02	6.9000414E+02	7.9455402E+02
9.0360000E+02			

STEAM PROPERTIES

2.6018254E+03	5.3313203E-02	4.9688207E-02	4.2054472E+00
6.7048413E+00	4.5122550E+00	1.9236948E-01	

THERMAL CONDUCTANCES---STEAM

5.6608807E+03		3.7167041E-01	8.1889880E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
7.2437856E-01	2.1407249E-01	1.4811679E-01	
9.8731720E-01	1.9320654E+00	4.2569060E-02	2.1861301E+01
5.1718624E-02	1.3201820E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

8.8289999E+02	8.2022218E+02	7.1444817E+02	8.0815480E+02
9.0545338E+02			

STEAM PROPERTIES

2.5968261E+03	5.4499137E-02	4.5860374E-02	2.4312474E+00
5.9290938E+00	2.8892239E+00	9.8345157E-02	

THERMAL CONDUCTANCES---STEAM

3.4563881E+03		3.1830942E-01	8.1523025E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.8184809E-01	2.1407249E-01	1.2685155E-01	
1.6597753E+00	3.2366558E+00	8.2894804E-02	2.4721578E+01
5.1600340E-02	1.3142678E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

9.3265858E+02	9.0204276E+02	8.3394992E+02	8.7188133E+02
9.1087985E+02			

STEAM PROPERTIES

2.5701190E+03	6.0296931E-02	3.8343754E-02	9.6749391E-01
4.2377926E+00	1.5214189E+00	2.7971994E-02	

THERMAL CONDUCTANCES---STEAM

1.8559303E+03		2.4152328E-01	8.0722237E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.2064701E-01	2.1407249E-01	9.6251010E-02	
4.4615250E+00	8.6344676E+00	2.8858235E-01	3.4587949E+01
5.1342143E-02	1.3013579E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

9.4061711E+02	9.1573631E+02	8.5888464E+02	8.8490471E+02
9.1162702E+02			

STEAM PROPERTIES

2.5621356E+03	6.1506674E-02	3.7916113E-02	8.9201447E-01
4.0446371E+00	1.4470060E+00	2.4614269E-02	

THERMAL CONDUCTANCES---STEAM

1.7633191E+03		2.3509078E-01	8.0632401E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.1552009E-01	2.1407249E-01	9.3687553E-02	
4.9392898E+00	9.5509956E+00	3.2758397E-01	3.6239729E+01
5.1313177E-02	1.2999096E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

9.4713532E+02	9.2702270E+02	8.8018910E+02	8.9597041E+02
9.1216473E+02			

STEAM PROPERTIES

2.5537659E+03	6.2540291E-02	3.7705201E-02	8.4672751E-01
3.8965544E+00	1.4044371E+00	2.2509192E-02	

THERMAL CONDUCTANCES---STEAM

1.7024461E+03		2.3068831E-01	8.0568150E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.1201118E-01	2.1407249E-01	9.1933098E-02	
5.3032807E+00	1.0248627E+01	3.5793444E-01	3.7616966E+01
5.1292461E-02	1.2988738E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

9.5244098E+02	9.3620390E+02	8.9790757E+02	9.0511706E+02
9.1251117E+02			

STEAM PROPERTIES

2.5450824E+03	6.3399927E-02	3.7615499E-02	8.1315000E-01
3.7816577E+00	1.3705488E+00	2.0979173E-02	

THERMAL CONDUCTANCES---STEAM

1.6629438E+03		2.2775353E-01	8.0524000E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.0967206E-01	2.1407249E-01	9.0763538E-02	
5.6200005E+00	1.0856173E+01	3.8382828E-01	3.8759869E+01
5.1278226E-02	1.2981621E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

TEMPERATURE DISTRIBUTION

9.5674593E+02	9.4374459E+02	9.1276566E+02	9.1266904E+02
9.1256999E+02			

STEAM PROPERTIES

2.5297617E+03	6.4120788E-02	3.7567820E-02	7.7874130E-01
3.6780893E+00	1.3291563E+00	1.9541188E-02	

THERMAL CONDUCTANCES---STEAM

1.6324250E+03		2.2544268E-01	8.0488460E-03
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COEFFICIENTS

4.6932550E-01	9.3865100E-01	5.2715229E-01	
6.0783023E-01	2.1407249E-01	8.9842625E-02	
5.9743431E+00	1.1536795E+01	4.1189133E-01	3.9851277E+01
5.1266767E-02	1.2975891E-02	1.2657492E-02	
2.4254582E-01	4.8509165E-01	4.0159940E+01	

PROGRAM STOP AT 650

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{133} = -(0.469326)T_{133} + (0.469326)T_{134} + (0.938651)T_{143} \\ + (0.527152)\dot{\omega}_{Na}T_{134} - (0.527152)\dot{\omega}_{Na}T_{133}$$

$$\dot{T}_{134} = -(0.469326)T_{134} - (0.469326)T_{135} + (0.938651)T_{144} \\ + (0.527152)\dot{\omega}_{Na}T_{135} - (0.527152)\dot{\omega}_{Na}T_{134}$$

$$\dot{T}_{135} = -(0.469326)T_{135} - (0.469326)T_{136} + (0.938651)T_{145} \\ + (0.527152)\dot{\omega}_{Na}T_{136} - (0.527152)\dot{\omega}_{Na}T_{135}$$

$$\dot{T}_{136} = -(0.469326)T_{136} - (0.469326)T_{137} + (0.938651)T_{146} \\ + (0.527152)\dot{\omega}_{Na}T_{137} - (0.527152)\dot{\omega}_{Na}T_{136}$$

$$\dot{T}_{137} = -(0.469326)T_{137} - (0.469326)T_{138} + (0.938651)T_{147} \\ + (0.527152)\dot{\omega}_{Na}T_{138} - (0.527152)\dot{\omega}_{Na}T_{137}$$

$$\dot{T}_{138} = -(0.469326)T_{138} - (0.469326)T_{139} + (0.938651)T_{148} \\ + (0.527152)\dot{\omega}_{Na}T_{139} - (0.527152)\dot{\omega}_{Na}T_{138}$$

$$\dot{T}_{139} = -(0.469326)T_{139} - (0.469326)T_{140} + (0.938651)T_{149} \\ + (0.527152)\dot{\omega}_{Na}T_{140} - (0.527152)\dot{\omega}_{Na}T_{139}$$

$$\dot{T}_{140} = -(0.469326)T_{140} - (0.469326)T_{141} + (0.938651)T_{150} \\ + (0.527152)\dot{\omega}_{Na}T_{141} - (0.527152)\dot{\omega}_{Na}T_{140}$$

$$\dot{T}_{141} = -(0.469326)T_{141} - (0.469326)T_{142} + (0.938651)T_{151} \\ + (0.527152)\dot{\omega}_{Na}T_{142} - (0.527152)\dot{\omega}_{Na}T_{141}$$

$$\dot{T}_{142} = -(0.469326)T_{142} - (0.469326)T_{188} + (0.938651)T_{152} \\ + (0.527152)\dot{\omega}_{Na}T_{188} - (0.527152)\dot{\omega}_{Na}T_{142}$$

$$\dot{\omega}_{Na} = \text{sodium flow per tube} = \dot{\omega}_{77}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

$$\dot{T}_{143} = -(0.724379) T_{143} + (0.214072) T_{133} + (0.214072) T_{134} \\ + (0.148117) T_{153} + (0.148117) T_{192}$$

$$\dot{T}_{144} = -(0.681848) T_{144} + (0.214072) T_{134} + (0.214072) T_{135} \\ + (0.126852) T_{153} + (0.126852) T_{154}$$

$$\dot{T}_{145} = -(0.656272) T_{145} + (0.214072) T_{135} + (0.214072) T_{136} \\ + (0.114064) T_{154} + (0.114064) T_{155}$$

$$\dot{T}_{146} = -(0.639981) T_{146} + (0.214072) T_{136} + (0.214072) T_{137} \\ + (0.105918) T_{155} + (0.105918) T_{156}$$

$$\dot{T}_{147} = -(0.628741) T_{147} + (0.214072) T_{137} + (0.214072) T_{138} \\ + (0.100298) T_{156} + (0.100298) T_{157}$$

$$\dot{T}_{148} = -(0.620647) T_{148} + (0.214072) T_{138} + (0.214072) T_{139} \\ + (0.0962510) T_{157} + (0.0962510) T_{158}$$

$$\dot{T}_{149} = -(0.615520) T_{149} + (0.214072) T_{139} + (0.214072) T_{140} \\ + (0.0936876) T_{158} + (0.0936876) T_{159}$$

$$\dot{T}_{150} = -(0.612011) T_{150} + (0.214072) T_{140} + (0.214072) T_{141} \\ + (0.0919331) T_{159} + (0.0919331) T_{160}$$

$$\dot{T}_{151} = -(0.609672) T_{151} + (0.214072) T_{141} + (0.214072) T_{142} \\ + (0.0907635) T_{160} + (0.0907635) T_{161}$$

$$\dot{T}_{152} = -(0.607830) T_{152} + (0.214072) T_{142} + (0.214072) T_{188} \\ + (0.0898426) T_{161} + (0.0898426) T_{162}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\begin{aligned}
 \dot{T}_{153} &= -(0.987317) T_{153} - (0.987317) T_{192} + (1.93207) T_{143} + (0.0425691) T_{163} \\
 &\quad + (21.8613) \dot{\omega}_s T_{192} - (21.8613) \dot{\omega}_s T_{153} \\
 \dot{T}_{154} &= -(1.65978) T_{154} - (1.65978) T_{153} + (3.23666) T_{144} + (0.0838948) T_{164} \\
 &\quad + (24.7216) \dot{\omega}_s T_{153} - (24.7216) \dot{\omega}_s T_{154} \\
 \dot{T}_{155} &= -(2.46634) T_{155} - (2.46634) T_{154} + (4.79654) T_{145} + (0.136142) T_{165} \\
 &\quad + (27.6055) \dot{\omega}_s T_{154} - (27.6055) \dot{\omega}_s T_{155} \\
 \dot{T}_{156} &= -(3.20880) T_{156} - (3.20880) T_{155} + (6.22744) T_{146} + (0.189853) T_{166} \\
 &\quad + (30.3009) \dot{\omega}_s T_{155} - (30.3000) \dot{\omega}_s T_{156} \\
 \dot{T}_{157} &= -(3.92351) T_{157} - (3.92351) T_{156} + (7.60277) T_{147} + (0.244249) T_{167} \\
 &\quad + (32.6138) \dot{\omega}_s T_{156} - (32.6138) \dot{\omega}_s T_{157} \\
 \dot{T}_{158} &= -(4.46153) T_{158} - (4.46153) T_{157} + (8.63447) T_{148} + (0.288582) T_{168} \\
 &\quad + (34.5879) \dot{\omega}_s T_{157} - (34.5879) \dot{\omega}_s T_{158} \\
 \dot{T}_{159} &= -(4.93929) T_{159} - (4.93929) T_{158} + (9.55100) T_{149} + (0.327584) T_{169} \\
 &\quad + (36.2397) \dot{\omega}_s T_{158} - (36.2397) \dot{\omega}_s T_{159} \\
 \dot{T}_{160} &= -(5.30328) T_{160} - (5.30328) T_{159} + (10.2486) T_{150} + (0.357934) T_{170} \\
 &\quad + (37.6170) \dot{\omega}_s T_{159} - (37.6170) \dot{\omega}_s T_{160} \\
 \dot{T}_{161} &= -(5.62000) T_{161} - (5.62000) T_{160} + (10.8562) T_{151} + (0.383828) T_{171} \\
 &\quad + (38.7599) \dot{\omega}_s T_{160} - (38.7599) \dot{\omega}_s T_{161} \\
 \dot{T}_{162} &= -(5.97434) T_{162} - (5.97434) T_{161} + (11.5368) T_{152} + (0.411891) T_{172} \\
 &\quad + (39.8513) \dot{\omega}_s T_{161} - (39.8513) \dot{\omega}_s T_{162}
 \end{aligned}$$

$$\dot{\omega}_s = \text{steam flow per tube} = \dot{\omega}_{f0}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

$$\dot{T}_{163} = -(0.0517186) T_{163} + (0.0132018) T_{192} + (0.0132018) T_{153} \\ + (0.0126575) T_{173} + (0.0126575) T_{174}$$

$$\dot{T}_{164} = -(0.0516003) T_{164} + (0.0131427) T_{153} + (0.0131427) T_{154} \\ + (0.0126575) T_{174} + (0.0126575) T_{175}$$

$$\dot{T}_{165} = -(0.0515081) T_{165} + (0.0130969) T_{154} + (0.0130969) T_{155} \\ + (0.0126575) T_{175} + (0.0126575) T_{176}$$

$$\dot{T}_{166} = -(0.0514392) T_{166} + (0.0130621) T_{155} + (0.0130621) T_{156} \\ + (0.0126575) T_{176} + (0.0126575) T_{177}$$

$$\dot{T}_{167} = -(0.0513850) T_{167} + (0.0130350) T_{156} + (0.0130350) T_{157} \\ + (0.0126575) T_{177} + (0.0126575) T_{178}$$

$$\dot{T}_{168} = -(0.0513421) T_{168} + (0.0130136) T_{157} + (0.0130136) T_{158} \\ + (0.0126575) T_{178} + (0.0126575) T_{179}$$

$$\dot{T}_{169} = -(0.0513132) T_{169} + (0.0129991) T_{158} + (0.0129991) T_{159} \\ + (0.0126575) T_{179} + (0.0126575) T_{180}$$

$$\dot{T}_{170} = -(0.0512925) T_{170} + (0.0129887) T_{159} + (0.0129887) T_{160} \\ + (0.0126575) T_{180} + (0.0126575) T_{181}$$

$$\dot{T}_{171} = -(0.0512782) T_{171} + (0.0129816) T_{160} + (0.0129816) T_{161} \\ + (0.0126575) T_{181} + (0.0126575) T_{182}$$

$$\dot{T}_{172} = -(0.0512668) T_{172} + (0.0129759) T_{161} + (0.0129759) T_{162} \\ + (0.0126575) T_{182} + (0.0126575) T_{162}$$

$$\sim (0.0256334)$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\begin{aligned}
 \dot{T}_{173} &= -(0.242546) T_{173} - (0.242546) T_{174} + (0.485092) T_{163} \\
 &\quad + (40.1599) \dot{\omega}_s T_{174} - (40.1599) \dot{\omega}_s T_{173} \\
 \dot{T}_{174} &= -(0.242546) T_{174} - (0.242546) T_{175} + (0.485092) T_{164} \\
 &\quad + (40.1599) \dot{\omega}_s T_{175} - (40.1599) \dot{\omega}_s T_{174} \\
 \dot{T}_{175} &= -(0.242546) T_{175} - (0.242546) T_{176} + (0.485092) T_{165} \\
 &\quad + (40.1599) \dot{\omega}_s T_{176} - (40.1599) \dot{\omega}_s T_{175} \\
 \dot{T}_{176} &= -(0.242546) T_{176} - (0.242546) T_{177} + (0.485092) T_{166} \\
 &\quad + (40.1599) \dot{\omega}_s T_{177} - (40.1599) \dot{\omega}_s T_{176} \\
 \dot{T}_{177} &= -(0.242546) T_{177} - (0.242546) T_{178} + (0.485092) T_{167} \\
 &\quad + (40.1599) \dot{\omega}_s T_{178} - (40.1599) \dot{\omega}_s T_{177} \\
 \dot{T}_{178} &= -(0.242546) T_{178} - (0.242546) T_{179} + (0.485092) T_{168} \\
 &\quad + (40.1599) \dot{\omega}_s T_{179} - (40.1599) \dot{\omega}_s T_{178} \\
 \dot{T}_{179} &= -(0.242546) T_{179} - (0.242546) T_{180} + (0.485092) T_{169} \\
 &\quad + (40.1599) \dot{\omega}_s T_{180} - (40.1599) \dot{\omega}_s T_{179} \\
 \dot{T}_{180} &= -(0.242546) T_{180} - (0.242546) T_{181} + (0.485092) T_{170} \\
 &\quad + (40.1599) \dot{\omega}_s T_{181} - (40.1599) \dot{\omega}_s T_{180} \\
 \dot{T}_{181} &= -(0.242546) T_{181} - (0.242546) T_{182} + (0.485092) T_{171} \\
 &\quad + (40.1599) \dot{\omega}_s T_{182} - (40.1599) \dot{\omega}_s T_{181} \\
 \dot{T}_{182} &= -(0.242546) T_{182} - (0.242546) T_{162} + (0.485092) T_{172} \\
 &\quad + (40.1599) \dot{\omega}_s T_{162} - (40.1599) \dot{\omega}_s T_{182}
 \end{aligned}$$

$$\dot{\omega}_s = \text{steam flow per tube} = \dot{\omega}_{80}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

II Sodium Inlet and Outlet Regions

Energy balances for inlet and outlet plenums: The regions are assumed to be bounded by adiabatic walls.

$$(wC_p)_{Na} T_{Na} = (wC_p)_{Na} T_{Na} + (pVC_p)_{Na} \frac{dT_{Na}}{dt}$$

In standard format

$$\dot{T}_{Na} = \left(\frac{w}{pV} \right)_{Na} T_{Na} - \left(\frac{w}{pV} \right)_{Na} T_{Na}$$

Energy balances for inlet and outlet nozzles:

$$-(UA)[T_{noz} - T_{Na}] = (pVC)_{noz} \frac{dT_{noz}}{dt}$$

$$(UA)[T_{noz} - T_{Na}] + (wC_p)_{Na} T_{Na} = (wC_p)_{Na} T_{Na} + (pVC_p)_{Na} \frac{dT_{Na}}{dt}$$

In standard format

$$\dot{T}_{noz} = - \left[\frac{(UA)}{(pVC)_{noz}} \right] T_{noz} + \left[\frac{(UA)}{(pVC)_{noz}} \right] T_{Na}$$

$$\dot{T}_{Na} = - \left[\frac{(UA)}{(pVC_p)_{Na}} \right] T_{Na} + \left[\frac{(UA)}{(pVC_p)_{Na}} \right] T_{noz} + \left(\frac{w}{pV} \right)_{Na} T_{Na} - \left(\frac{w}{pV} \right)_{Na} T_{Na}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Sodium Inlet Region

$$\dot{W}_{Na} = 4.353 \times 10^6 \text{ lbm/hr} = 1209 \text{ lbm/sec (Design)}$$

Properties are evaluated at temperature for full load

$$T = 960^\circ\text{F} \Rightarrow \begin{aligned} k_{Na} &= 38.2 \text{ Btu/m-ft}^\circ\text{F} & k_{Na2} &= 16.3 \text{ Btu/m-ft}^\circ\text{F} \\ \rho_{Na} &= 51.7 \text{ lbm/ft}^3 & \rho_{Na2} &= 478 \text{ lbm/ft}^3 \\ C_{pNa} &= 0.301 \text{ Btu/lbm}^\circ\text{F} & C_{pNa2} &= 0.159 \text{ Btu/lbm}^\circ\text{F} \\ \mu_{Na} &= 0.559 \text{ lbm/ft}^\circ\text{F} \end{aligned}$$

Heat Transfer coefficient

$$1) \dot{G}_{Na} = \frac{\dot{W}_{Na}}{A} = \frac{4.353 \times 10^6}{\frac{\pi}{4} (16\frac{7}{8}/12)^2} = 2.803 \times 10^6 \frac{\text{lbm}}{\text{m}^2\text{-hr}}$$

$$V_{Na} = \frac{\dot{G}_{Na}}{\rho_{Na}} = \frac{2.803 \times 10^6 / 3600}{51.7} = 15.06 \text{ ft/sec}$$

$$Re_{Na} = \frac{\dot{G}_{Na} D_i}{\mu_{Na}} = \frac{(2.803 \times 10^6) (\frac{16\frac{7}{8}}{12})}{0.559} = 7.051 \times 10^6$$

$$Pe = Re \frac{\mu C_p}{k} = (7.051 \times 10^6) \frac{0.559(0.301)}{38.2} = 31060$$

$$\begin{aligned} h_{Na} &= \frac{k_{Na}}{D_i} [5.0 + 0.025 Pe^{0.8}] = \frac{38.2}{16\frac{7}{8}/12} [5.0 + 0.025 (31060)^{0.8}] \\ &= 2801 \frac{\text{Btu}}{\text{m}^2\text{-ft}^\circ\text{F}} = 0.7780 \frac{\text{Btu}}{\text{sec}^2\text{-ft}^\circ\text{F}} \end{aligned}$$

Entrance effects on the heat transfer coefficient are neglected.

2) The average diameter for the nozzle is computed at the thickest section.

SODIUM INLET PLENUM

$$V_{Na} = \left\{ \frac{\pi}{4} (40 \frac{5}{8})^2 (9) + \frac{2\pi}{3} (20 \frac{5}{16})^3 \right\} - \left\{ \pi (30 \frac{5}{8}) (1) (16) + \frac{\pi (3)}{6} (3 (16 \frac{7}{8})^2 + 3^2) \right\}$$

$$= 26300 \text{ cm}^3 = 15.2 \text{ ft}^3$$

SODIUM INLET NOZZLE

$$V_{Na} = \frac{\pi}{4} (16 \frac{7}{8})^2 (18) = 4030 \text{ cm}^3 = 2.33 \text{ ft}^3$$

$$V_{Noz} = \frac{\pi}{4} (18^2 - 16 \frac{7}{8}^2) (4) + \left\{ \pi \frac{1.5}{12} (18^2 + 19 \frac{1}{2} (18) + 19 \frac{1}{2}^2) - \pi \frac{(1.5)}{12} (16 \frac{7}{8}^2 + 16 \frac{7}{8} (18 \frac{3}{4}) + 18 \frac{3}{4}^2) \right\}$$

$$+ \left\{ \pi \frac{12 \frac{1}{2}}{12} (19 \frac{1}{2}^2 + (19 \frac{1}{2}) (21 \frac{1}{2}) + 21 \frac{1}{2}^2) - \pi \frac{(18 \frac{3}{4})^2}{4} (12 \frac{1}{2}) \right\}$$

$$= 986 \text{ cm}^3 = 0.570 \text{ ft}^3$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{18^{3/8^2} + 21^{1/2^2}}{2} \right)^{1/2} = 20.0''$$

Assume, for the entire length of the nozzle, that there is a $1/2''$ thermal liner ($2^{1/4}$ Cr-1Mo) and a $1/4''$ stagnant sodium gap between the flowing sodium and the nozzle. In addition the resistance of the thickest section of the nozzle will characterize the nozzle for its entire length.

$$\begin{aligned} UA &= \frac{2 \pi L}{\frac{2}{h_{Na}(D)_{noz}} + \frac{\ln(OD/ID)_{liner}}{k_{liner}} + \frac{\ln(OD/ID)_{gap}}{k_{gap}} + \frac{\ln(\bar{D}/D_i)}{k_{noz}}} \\ &= \frac{2 \pi (18/12)}{\frac{2}{2801 \left(\frac{16^{7/8}}{12} \right)} + \frac{\ln(17^{3/8}/16^{7/8})}{16.3} + \frac{\ln(1^{3/4}/17^{3/8})}{38.2} + \frac{\ln(20/18^{3/8})}{16.3}} \\ &= 946.2 \frac{Btu}{hr \cdot ^\circ F} = 0.2628 \frac{Btu}{sec \cdot ^\circ F} \end{aligned}$$

Volumes

$$(V_{Na})_{noz} = 2.33 \text{ ft}^3$$

$$(V_{thermal})_{noz} = 0.570 \text{ ft}^3$$

$$(V_{Na})_{plenum} = 15.2 \text{ ft}^3$$

Computations are shown on the figure.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{\rho v}\right)_{Na, \text{ plenum}} = \frac{1}{(51.7)(15.2)} = 0.001273 \text{ lbm}^{-1}$$

$$\left[\frac{UA}{(\rho v C_p)_{Na}}\right] = \frac{0.2628}{(478)(570)(15.9)} = 0.006066 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(\rho v C_p)_{Na}}\right] = \frac{0.2628}{(51.7)(2.33)(301)} = 0.007248 \text{ sec}^{-1}$$

$$\left(\frac{1}{\rho v}\right)_{Na, \text{ Noz}} = \frac{1}{(51.7)(2.33)} = 0.008301 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Sodium Outlet Region

$$W_{Na} = 4.353 \times 10^6 \text{ lbm/hr} = 1209 \text{ lbm/sec (Design)}$$

Properties are evaluated at temperature for full load

$$T = 866^\circ \text{F} \Rightarrow \begin{aligned} k_{Na} &= 39.6 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}}; & k_{Na2} &= 16.3 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}} \\ \rho_{Na} &= 52.5 \frac{\text{lbm}}{\text{ft}^3}; & \rho_{Na2} &= 47.8 \frac{\text{lbm}}{\text{ft}^3} \\ c_{pNa} &= 0.303 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}; & c_{pNa2} &= 0.151 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}} \\ \mu_{Na} &= 0.605 \frac{\text{lbm}}{\text{ft-hr}} \end{aligned}$$

Heat transfer coefficient

$$1) \quad G_{Na} = \frac{W_{Na}}{A} = \frac{(4.353 \times 10^6)/2}{\frac{\pi (1)^2}{4}} = 2.771 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \text{hr}}$$

$$V_{Na} = \frac{G_{Na}}{\rho_{Na}} = \frac{2.771 \times 10^6 / 3600}{52.5} = 14.67 \text{ ft/sec}$$

$$Re = \frac{G D}{\mu_{Na}} = \frac{(2.771 \times 10^6)(1)}{0.605} = 4.581 \times 10^6$$

$$Pe = Re \left(\frac{\mu_{Na}}{k_{Na}} \right) = (4.581 \times 10^6) \frac{0.605(0.303)}{39.6} = 21204$$

$$h_{Na} = \frac{k_{Na}}{D} [5 + 0.25 Pe^{0.8}] = \frac{39.6}{(1)} [5 + 0.25 (21204)^{0.8}]$$

$$= 3061 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}} = 0.8502 \frac{\text{Btu}}{\text{sec-ft}^\circ\text{F}}$$

Entrance effects on the heat transfer coefficient are neglected.

2) The average diameter for the nozzle is computed at the thickest section.

SODIUM OUTLET PLENUM

$$V_{Na} = \frac{\pi}{4} (46\frac{5}{8}^2 - 31\frac{5}{8}^2) 85 = 78400 \text{ cm}^3 = 45.3 \text{ ft}^3$$

SODIUM OUTLET NOZZLE

$$V_{Na} = \frac{\pi}{4} (12)^2 (18) = 2040 \text{ cm}^3 = 1.18 \text{ ft}^3$$

$$\begin{aligned} V_{Noz} &= \frac{\pi}{4} (12\frac{3}{4}^2 - 12^2) (4) + \frac{\pi (1.5)}{12} \left\{ (13\frac{1}{4}^2 + 13\frac{1}{4} (12\frac{3}{4}) + 12\frac{3}{4}^2) - (13^2 + 13 (12) + 12^2) \right\} \\ &\quad + \left\{ \frac{\pi (5\frac{1}{2})}{12} (16\frac{1}{2}^2 + 16\frac{1}{2} (13\frac{3}{4}) + 13\frac{3}{4}^2) - \frac{\pi}{4} (13)^2 (5\frac{1}{2}) \right\} + \frac{\pi}{4} (16\frac{1}{2}^2 - 13^2) (7) \\ &= 910 \text{ cm}^3 = 0.526 \text{ ft}^3 \end{aligned}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{13^2 + 16\frac{1}{2}^2}{2} \right)^{1/2} = 14.85''$$

Assume a $\frac{1}{4}''$ thermal liner (24Cr-1Mo) and $\frac{1}{4}''$ stagnant sodium gap between the flowing sodium and the nozzle for the entire length of the outlet nozzle. In addition, the resistance of the thickest section of the nozzle characterizes the nozzle for its entire length.

$$\begin{aligned} UA &= \frac{2\pi L}{\frac{2}{h_{nc}(D)_{noz}} + \frac{\ln(OD/ID)_{liner}}{k_{liner}} + \frac{\ln(OD/ID)_{gap}}{k_{gap}} + \frac{\ln(D/\bar{D})}{k_{noz}}} \\ &= \frac{2\pi (18/12)}{\frac{2}{3061(1.0)} + \frac{\ln(12\frac{1}{8}/12)}{16.3} + \frac{\ln(13.0/12.5)}{39.6} + \frac{\ln(14.85/13)}{16.3}} \\ &= 766.2 \frac{Btu}{hr \cdot ^\circ F} = 0.2128 \frac{Btu}{sec \cdot ^\circ F} \end{aligned}$$

Volumes

$$(V_{Na})_{noz} = 1.18 \text{ ft}^3$$

$$(V_{metal})_{noz} = 0.526 \text{ ft}^3$$

$$(V_{Na})_{plenum} = 45.3 \text{ ft}^3$$

Computations are shown on the figure.

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{pV}\right)_{Na_{plutonium}} = \frac{1}{(52.5)(45.3)} = 0.0004205 \text{ lbm}^{-1}$$

$$\left[\frac{2A}{(pVC)_{NO_2}}\right] = \frac{2(0.2128)}{478[2(0.526)](1.01)} = 0.005605 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(pV(p)_{Na}}\right] = \frac{2(0.2128)}{52.5[2(1.18)](3.03)} = 0.01134 \text{ sec}^{-1}$$

$$\left(\frac{1}{pV}\right)_{Na_{NO_2}} = \frac{1}{52.5[2(1.18)]} = 0.008071 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{183} = -(0.005605)T_{183} + (0.005605)T_{184}$$

$$\dot{T}_{184} = -0.01134 T_{184} + 0.01134 T_{183} + (0.008071)\omega_{Na} T_{185} - (0.008071)\omega_{Na} T_{184}$$

$$\dot{T}_{185} = (0.0004205)\omega_{Na} T_{183} - (0.0004205)\omega_{Na} T_{185}$$

$$\dot{T}_{186} = -(0.006066)T_{186} + (0.006066)T_{187}$$

$$\dot{T}_{187} = -(0.007248)T_{187} + (0.007248)T_{186} + (0.008301)\omega_{Na} T_{364}^* - (0.008301)\omega_{Na} T_{187}$$

$$\dot{T}_{188} = (0.001273)\omega_{Na} T_{187} - (0.001273)\omega_{Na} T_{188}$$

$$\omega_{Na} = \text{Sodium flow per module} = \dot{w}_{76}$$

* Algebraic equation for sodium inlet temperature

$$T_{364} = (1.0) \dot{w}_{74} F_{369} \quad ; \quad F_{369} = 1.0$$

This equation is written in the CEROS format. The "flow equation" $\dot{w}_{74}$ is the structure of the function $T_{in}(t)$.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

*

III Steam Inlet and Outlet Regions

Energy balances for the additional heat exchange between the inlet and outlet steam in the region above the sodium level: The pressure tube wall is assumed to be an adiabatic boundary.

$$-(UA)'_3 [T_{ANN} - T_{BT}] + \dot{w}_{ANN} h_{ANN} = \dot{w}_{ANN} h_{ANN} + \frac{d}{dt} (pVU)_{ANN}$$

$$(UA)'_3 [T_{ANN} - T_{BT}] - (UA)'_4 [T_{BT} - T_R] = (PVC)_{BT} \frac{dT_{BT}}{dt}$$

$$(UA)'_4 [T_{BT} - T_R] + \dot{w}_R h_R = \dot{w}_R h_R + \frac{d}{dt} (pVU)_R$$

Recalling the assumptions made in I. Main Heat Transfer Region, and rearranging into the standard format

$$\dot{T}_{ANN} = - \left[\frac{(UA)'_3}{(PVC)_A} \right] T_{ANN} + \left[\frac{(UA)'_3}{(PVC)_A} \right] T_{BT} + \left(\frac{\dot{w}}{PV} \right)_{ANN} T_{ANN} - \left(\frac{\dot{w}}{PV} \right)_{ANN} T_{ANN}$$

$$\dot{T}_{BT} = - \left[\frac{(UA)'_3}{(PVC)_{BT}} + \frac{(UA)'_4}{(PVC)_{BT}} \right] T_{BT} + \left[\frac{(UA)'_3}{(PVC)_{BT}} \right] T_{ANN} + \left[\frac{(UA)'_4}{(PVC)_{BT}} \right] T_R$$

$$\dot{T}_R = - \left[\frac{(UA)'_4}{(PVC)_R} \right] T_R + \left[\frac{(UA)'_4}{(PVC)_R} \right] T_{BT} + \left(\frac{\dot{w}}{PV} \right)_R T_R - \left(\frac{\dot{w}}{PV} \right)_R T_R$$

Energy balances for the inlet and outlet plenums: The regions are assumed to be bounded by adiabatic walls.

$$\dot{w}_{s,m} h_{s,m} = \dot{w}_{s,m} h_{s,m} + \frac{d}{dt} (pVU)_{s,m}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Recalling the assumptions made above concerning steam enthalpy and internal energy, and then rearranging the equations into standard format

$$\dot{T}_{stm} = \left[\left(\frac{w}{pV} \right)_{stm} \frac{T_{stm}}{IN} - \left(\frac{w}{pV} \right)_{stm} T_{stm} \right]_{stm} = (ANN, R)$$

Energy balances for the inlet and outlet nozzles:

$$-(UA)[T_{noz} - T_{stm}] = (pvc)_{noz} \frac{dT_{noz}}{dt}$$

$$(UA)[T_{noz} - T_{stm}] + w_{stm} h_{stm} = w_{stm} h_{stm} + \frac{d}{dt}(evu)_{stm}$$

Applying the same assumptions as above, and rearranging the equations into standard format

$$\dot{T}_{noz} = - \left[\frac{(UA)}{(pvc)_{noz}} \right] T_{noz} + \left[\frac{(UA)}{(pvc)_{noz}} \right] T_{stm}$$

$$\dot{T}_{stm} = - \left[\frac{(UA)}{(pvc)_{stm}} \right] T_{stm} + \left[\frac{(UA)}{(pvc)_{stm}} \right] T_{noz} + \left(\frac{w}{pV} \right)_{stm} \frac{T_{stm}}{IN} - \left(\frac{w}{pV} \right)_{stm} T_{stm}$$

$$STM = (ANN, R)$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

STEAM INLET Region

$$W_s = 397278 \text{ lbm/hr} = 110.355 \text{ lbm/sec (design)}$$

Properties are evaluated at pressure and temperature for full load.

$$p = 2612 \text{ psi}, T = 674.6^\circ\text{F} \Rightarrow \begin{aligned} k_s &= 0.0531 \frac{\text{BTU}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} & k_{\text{NO}_2} &= 16.3 \frac{\text{BTU}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} \\ \rho_s &= 8.325 \frac{\text{lbm}}{\text{ft}^3} & \rho_{\text{NO}_2} &= 481 \frac{\text{lbm}}{\text{ft}^3} \\ C_p &= 4.28 \frac{\text{BTU}}{\text{lbm} \cdot ^\circ\text{F}} & C_{\text{NO}_2} &= 0.136 \frac{\text{BTU}}{\text{lbm} \cdot ^\circ\text{F}} \\ \mu_s &= 0.0526 \frac{\text{lbm}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} \end{aligned}$$

Heat Transfer coefficients

$$1) G_s = \frac{W_s}{A} = \frac{397278}{\frac{\pi}{4} (11^{3/8}/12)^2} = 5.629 \times 10^5 \frac{\text{lbm}}{\text{ft}^2 \cdot \text{hr}}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{5.629 \times 10^5 / 3600}{8.325} = 18.78 \text{ ft/sec}$$

$$Re_s = \frac{G_s D}{\mu_s} = \frac{(5.629 \times 10^5) (\frac{11^{3/8}}{12})}{0.0526} = 1.014 \times 10^7$$

$$Pr_s = \frac{\mu_s C_p}{k_s} = \frac{0.0526 (4.28)}{0.0531} = 4.24$$

$$\begin{aligned} h_s &= \frac{k_s}{D} [0.023 Re_s^{1/4} Pr_s^{1/4}] = \frac{0.0531}{11^{3/8}/12} [0.023 (1.014 \times 10^7)^{1/4} (4.24)^{1/4}] \\ &= 924.7 \frac{\text{BTU}}{\text{in} \cdot \text{ft}^2 \cdot ^\circ\text{F}} = 0.2569 \frac{\text{BTU}}{\text{sec} \cdot \text{ft}^2 \cdot ^\circ\text{F}} \end{aligned}$$

2) The average diameter for the nodule is computed at the thickest section.

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{11^{3/8/2} + 21^2}{2} \right)^{1/2} = 16.89''$$

SATURATED STEAM INLET NOZZLE

$$V_{stm} = \frac{\pi}{4} (11\frac{3}{8})^2 (19) = 1930 \text{ in}^3 = 1.12 \text{ ft}^3$$

$$V_{noz} = \frac{\pi}{4} (14^2 - 11\frac{3}{8}^2) (4\frac{1}{2}) + \left\{ \pi \frac{4\frac{1}{2}}{12} (21^2 + 21(14) + 14^2) - \frac{\pi}{4} (11\frac{3}{8})^2 (4\frac{1}{2}) \right\} + \frac{\pi}{4} (21^2 - 11\frac{3}{8}^2) (10) = 3320 \text{ in}^3 = 1.92 \text{ ft}^3$$

COMBUSTION ENGINEERING
NUCLEAR POWER DEPARTMENT

STEAM INLET PLENUM

$$\begin{aligned}
 V_{stm} &= \frac{\pi}{4} (40\frac{1}{4})^2 41 + \frac{\pi}{4} (40\frac{1}{4}^2 - 32\frac{1}{4}^2) (29) - \frac{\pi}{4} (12\frac{3}{4}^2 - 12^2) (6 + \frac{\pi}{2} (17) + 8) \\
 &\quad - \{ \text{estimate of additional items in plenum} \} \\
 &= 64900 - \{ \text{estimate} \} \\
 &= 64400 \text{ in}^3 = 37.3 \text{ ft}^3
 \end{aligned}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

The thermal resistance of the thickest section of the nozzle is assumed to characterize the nozzle for its entire length. In addition entrance effects on the steam heat transfer coefficient are neglected.

$$\begin{aligned}
 UA &= \frac{2\pi L}{\frac{2}{h_s(D)_{\text{noz}}} + \frac{\ln(D_o/D_i)}{k_{\text{noz}}}} \\
 &= \frac{2\pi (19/12)}{\frac{2}{924.7(\frac{113}{12})} + \frac{\ln(16.89/11.3)}{16.3}} \\
 &= 374.9 \frac{\text{Btu}}{\text{M} \cdot \text{O} \cdot \text{F}} = 0.1041 \frac{\text{Btu}}{\text{sq} \cdot \text{O} \cdot \text{F}}
 \end{aligned}$$

Volumes

$$(V_s)_{\text{noz}} = 1.12 \text{ ft}^3$$

$$(V_{\text{metal}})_{\text{noz}} = 1.92 \text{ ft}^3$$

$$(V_s)_{\text{plenum}} = 37.3 \text{ ft}^3$$

Computations are shown on the figures.

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{pV}\right)_{\text{Stm}} = \frac{1}{(8.325)(37.3)} = 0.003220 \text{ lbm}^{-1}$$

$$\left[\frac{2A}{(pVC)_{\text{No}_2}}\right] = \frac{0.1041}{(481)(1.92)(.136)} = 0.0008288 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(pVC)_S}\right] = \frac{0.1041}{(8.325)(1.12)(4.28)} = 0.002609 \text{ sec}^{-1}$$

$$\left(\frac{1}{pV}\right)_{\text{No}_2} = \frac{1}{(8.325)(1.12)} = 0.1073 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Steam Outlet Region

$$W_s = 397278 \text{ lbm/hr} = 110.355 \text{ lbm/sec (design)}$$

Properties are evaluated at pressure and temperature for full load.

$$p = 2500 \text{ psia}, T = 900^\circ\text{F} \Rightarrow k_s = 0.374 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}}, k_{\text{no2}} = 16.3 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}}$$

$$\rho_s = 3.689 \frac{\text{lbm}}{\text{ft}^3}, \rho_{\text{no2}} = 479 \frac{\text{lbm}}{\text{ft}^3}$$

$$C_{p_s} = 0.751 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}, C_{\text{no2}} = 0.154 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}$$

$$\mu_s = 0.0635 \frac{\text{lbm}}{\text{ft}^\circ\text{F}}$$

Heat Transfer coefficients

$$1) G_s = \frac{W}{A} = \frac{397278}{\frac{\pi}{4} (10/12)^2} = 7.284 \times 10^5 \frac{\text{lbm}}{\text{hr-ft}^2}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{7.284 \times 10^5 / 3600}{3.689} = 54.85 \text{ ft/sec}$$

$$Re_s = \frac{G_s D}{\mu_s} = \frac{(7.284 \times 10^5)^{1/2}}{0.0635} = 9.559 \times 10^6$$

$$Pr_s = \frac{\mu_s C_{p_s}}{k_s} = \frac{0.0635 (0.751)}{0.374} = 1.27$$

$$h_s = \frac{k_s}{D} [0.023 Re_s^{0.8} Pr_s^{0.4}] = \frac{0.374}{10/12} [0.023 (9.55 \times 10^6)^{0.8} (1.27)^{0.4}]$$

$$= 436.1 \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}} = 0.1212 \frac{\text{Btu}}{\text{sec-ft}^\circ\text{F}}$$

Entrance effects on the heat transfer coefficients are neglected.

2) The average diameter for the nozzle is computed at the thickest section.

STEAM OUTLET NOZZLE

$$V_{\text{stm}} = \frac{\pi}{4} (10)^2 (20) + \frac{\pi}{4} (10\frac{7}{8})^2 (4) = 1940 \text{ m}^3 = 1.12 \text{ ft}^2$$

$$V_{\text{noz}} = \frac{\pi}{4} (21^2 - 10\frac{7}{8}^2) (10) + \left\{ \pi \frac{3}{12} (21^2 + 21(14) + 14^2) - \frac{\pi(3)}{4} (10\frac{7}{8})^2 \right\} \\ + \frac{\pi}{4} (14^2 - 10\frac{7}{8}^2) (11) = 3660 \text{ m}^3 = 2.12 \text{ ft}^3$$

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STEAM OUTLET PLENUM

$$V_{stm} = \frac{\pi}{4} (30)^2 (23) + \frac{\pi}{4} (10)^2 (5) = 16700 \text{ m}^3 = 9.64 \text{ ft}^3$$

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$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{10.78^2 + 21^2}{2} \right)^{1/2} = 16.72''$$

Assume a $1/4''$ thermal liner ($2\frac{1}{4}Cr-1Mo$) and $3/16''$ stagnant superheated steam gap between the flowing superheated steam and the nozzle for the entire length of the outlet nozzle. In addition, the resistance of the thickest section of the nozzle characterizes the nozzle for its entire length.

$$\begin{aligned} UA &= \frac{2\pi L}{\frac{2}{h_s(D)_{noz}} + \frac{\ln(OD/ID)_{liner}}{k_{liner}} + \frac{\ln(OD/ID)_{gap}}{k_{gap}} + \frac{\ln(\bar{D}/D_i)}{k_{noz}}} \\ &= \frac{2\pi (24/12)}{\frac{2}{(436.1)(1\%)}} + \frac{\ln(10.78/10)}{16.3} + \frac{\ln(10.78/10.78)}{0.0374} + \frac{\ln(16.72/10.78)}{16.3} \\ &= 12.91 \frac{Btu}{hr \cdot ft^2} = 0.003587 \frac{Btu}{sec \cdot ft^2} \end{aligned}$$

Volumes

$$(V_s)_{noz} = 1.12 \text{ ft}^3$$

$$(V_{total})_{noz} = 2.12 \text{ ft}^3$$

$$(V_s)_{plenum} = 9.64 \text{ ft}^3$$

Computations are shown on the figures.

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Coefficients

$$\left(\frac{1}{pV}\right)_{\text{Plenum}} = \frac{1}{(3.689)(9.64)} = 0.02812 \text{ lhm}^{-1}$$

$$\left[\frac{2A}{(pVC)_{\text{No2}}}\right] = \frac{0.003587}{(479)(2.12)(1.154)} = 0.00002294 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(pVC)_S}\right] = \frac{0.003587}{3.689(1.12)(.751)} = 0.001156 \text{ sec}^{-1}$$

$$\left(\frac{1}{pV}\right)_{\text{Stn No2}} = \frac{1}{(3.689)(1.12)} = 0.2420 \text{ lhm}^{-1}$$

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Additional Heat Exchange Region

$$W_s = 2648.52 \text{ lbm/m/tube} = 0.7357 \text{ lbm/sec/tube (design)}$$

Properties are evaluated at pressure and temperature for full load.

$$\begin{aligned} P &= 2612 \text{ psi}, T = 674.6^\circ \text{F}; T = 789^\circ \text{F}; P = 2500 \text{ psi}, T = 900^\circ \text{F} \\ k_{\text{sat}} &= 0.0531 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ \text{F}}; k_{\text{noz}} = 15.9 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ \text{F}}; k_{\text{ss}} = 0.0374 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ \text{F}} \\ \rho_{\text{sat}} &= 8.325 \frac{\text{lbm}}{\text{ft}^3}; \rho_{\text{noz}} = 480 \frac{\text{lbm}}{\text{ft}^3}; \rho_{\text{ss}} = 3.689 \frac{\text{lbm}}{\text{ft}^3} \\ C_{p_{\text{sat}}} &= 4.28 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}}; C_{p_{\text{noz}}} = 0.155 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}}; C_{p_{\text{ss}}} = 0.751 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}} \\ \mu_{\text{sat}} &= 0.0526 \frac{\text{lbm}}{\text{in} \cdot \text{ft}}; \mu_{\text{ss}} = 0.0635 \frac{\text{lbm}}{\text{in} \cdot \text{ft}} \end{aligned}$$

Heat Transfer Coefficients - Thermal Resistances

1) For 12" (19%) of the additional heat transfer length the inlet saturated steam flows obliquely about the bayonet tube assembly (typical heat exchanger shellside flow pattern). For the remaining 53" the saturated steam flows in the annuli defined by the pressure tubes and bayonet tube assemblies. For purposes of characterizing the heat transfer the latter flow pattern is assumed for the entire length.

$$G_s = \frac{W_s}{A_s} = \frac{2648.52}{\frac{\pi}{4} (1.116^2 - .916^2) / 144} = 1.195 \times 10^6 \frac{\text{lbm}}{\text{in} \cdot \text{ft}^2}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{1.195 \times 10^6 / 3600}{8.325} = 39.87 \text{ ft/sec}$$

$$Re_s = \frac{G_s D_e}{\mu} = \frac{(1.195 \times 10^6) (\frac{1.116 - .916}{12})}{.0526} = 3.786 \times 10^5$$

$$Pr_s = \frac{0.0526 (4.28)}{.0531} = 4.24$$

ADDITION HEAT EXCHANGE LENGTH

$$L = 12 + 9 + 42 = 63''$$

$$\begin{array}{lll} d_1 = 0.636'' & , & d_3 = 0.836'' \quad d_5 = 1.116'' \\ d_2 = 0.716'' & , & d_4 = 0.916'' \quad d_6 = 1.50'' \end{array}$$

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$$h_s = \frac{k_s}{D_e} [0.023 Re_s^{0.8} Pr_s^{0.4}] = \frac{0.0531}{0.2/12} [0.023 (3.786 \times 10^5)^{0.8} (4.24)^{0.4}]$$

$$= 3789 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot ^\circ\text{F}} = 1,052 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot ^\circ\text{F}}$$

$$R_s = \frac{1}{\pi d_o L h_s} = \frac{1}{\pi \left(\frac{0.916}{12}\right) \frac{63}{12} (3789)} = 0.0002096 \frac{\text{m}^2 \cdot \text{ft}^2}{\text{Btu}}$$

2) Outer Bayonet Tube Resistance

$$R_{R_o} = \frac{\ln(d_4/d_3)}{2\pi k L} = \frac{\ln(0.916/0.836)}{2\pi (15.9) (63/12)} = 0.0001742 \frac{\text{m}^2 \cdot \text{ft}^2}{\text{Btu}}$$

3) Insulation Gap Resistance

$$R_{\text{gap}} = \frac{\ln(d_3/d_2)}{2\pi k_g L} = \frac{\ln(0.836/0.716)}{2\pi (1.2) (63/12)} = 0.03914 \frac{\text{m}^2 \cdot \text{ft}^2}{\text{Btu}}$$

4) Inner Bayonet Tube Resistance

$$R_{R_i} = \frac{\ln(d_2/d_1)}{2\pi k L} = \frac{\ln(0.716/0.636)}{2\pi (15.9) (63/12)} = 0.0002259 \frac{\text{m}^2 \cdot \text{ft}^2}{\text{Btu}}$$

5) Superheated steam

$$G_s = \frac{W_s}{A_s} = \frac{2648.52}{\frac{\pi}{4} (0.636/12)^2} = 1.200 \times 10^6 \frac{\text{lbm}}{\text{m}^2 \cdot \text{ft}^2}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{1.200 \times 10^6 / 3600}{3.689} = 90.40 \text{ ft/sec}$$

$$Re_s = \frac{G_s D}{\mu_s} = \frac{(1.200 \times 10^6) \left(\frac{0.636}{12}\right)}{0.0335} = 1.002 \times 10^6$$

$$Pr_s = \frac{\mu_s C_p}{k_s} = \frac{0.0335 (0.751)}{0.0374} = 1.27$$

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$$h_{ss} = \frac{k_s}{D} [0.023 Re_s^{.8} Pr_s^{.4}] = \frac{.0374}{.636/12} [0.023 (1.002 \times 10^6)^{.8} (1.77)^{.4}]$$

$$= 1129 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}} = 0.3135 \frac{\text{Btu}}{\text{sec-ft}^2\text{-}^\circ\text{F}}$$

$$R_{ss} = \frac{1}{\pi d_1 L h_{ss}} = \frac{1}{\pi (.636/12)(63/12) 1129} = 0.001013 \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$$

$$(UA)_3' = (R_s + R_{br} + \frac{1}{2} R_{gap})^{-1} = (.0002096 + .0001742 + \frac{.0374}{2})^{-1}$$

$$= 50.11 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}} = 0.01392 \frac{\text{Btu}}{\text{sec-ft}^2\text{-}^\circ\text{F}}$$

$$(UA)_4' = (\frac{1}{2} R_{gap} + R_{br} + R_{ss})^{-1} = (\frac{.0374}{2} + .0002259 + .001013)^{-1}$$

$$= 48.05 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}} = 0.01335 \frac{\text{Btu}}{\text{sec-ft}^2\text{-}^\circ\text{F}}$$

Volumes

$$V_{\text{steam}} = \frac{\pi}{4} (d_s^2 - d_v^2) L = \frac{\pi}{4} \left(\frac{1.116^2 - .916^2}{144} \right) \frac{63}{12} = 0.01164 \text{ ft}^3$$

$$V_{br} = \frac{\pi}{4} [(d_v^2 - d_o^2) + (d_o^2 - d_1^2)] L = \frac{\pi}{4} \left[\frac{.916^2 - .836^2 + .716^2 - .636^2}{144} \right] \frac{63}{12}$$

$$= 0.007110 \text{ ft}^3$$

$$V_{ss} = \frac{\pi}{4} d_1^2 L = \frac{\pi}{4} \left(\frac{.636}{12} \right)^2 \frac{63}{12} = 0.01158$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Coefficients

$$\left[\frac{(UA)_3'}{(PVC_p)_H} \right] = \frac{0.01392}{(8325)(0.01164)(4.28)} = 0.03356 \text{ sec}^{-1}$$

$$\left(\frac{1}{P_V} \right)_H = \frac{1}{(8325)(0.01164)} = 10.32 \text{ lbm}^{-1}$$

$$\left[\frac{(UA)_5'}{(PVC)_{Gr}} \right] = \frac{0.01392}{480(0.007110)(1.55)} = 0.02631 \text{ sec}^{-1}$$

$$\left[\frac{(UA)_4'}{(PVC)_{Gr}} \right] = \frac{0.01335}{480(0.007110)(1.55)} = 0.02524 \text{ sec}^{-1}$$

$$\left[\frac{(UA)_4'}{(PVC)_{ss}} \right] = \frac{0.01335}{3.689(0.01158)(.751)} = 0.4161 \text{ sec}^{-1}$$

$$\left(\frac{1}{P_V} \right)_{ss} = \frac{1}{(3.689)(0.01158)} = 23.41 \text{ lbm}^{-1}$$

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Summary

$$\dot{T}_{189} = -(0.0008288) T_{189} + (0.0008288) T_{150}$$

$$\dot{T}_{190} = -(0.002609) T_{190} + (0.002609) T_{189} + (0.1073) \dot{\omega}_s T_{138} = (0.1073) \dot{\omega}_s T_{190}$$

$$\dot{T}_{191} = (0.003220) \dot{\omega}_s T_{190} - (0.003220) \dot{\omega}_s T_{191}$$

$$\dot{\omega}_s = \text{steam flow per module} = \dot{\omega}_{19}$$

$$\dot{T}_{192} = -(1.03356) T_{192} + (1.03356) T_{193} + (10.32) \dot{\omega}_s T_{191} - (10.32) \dot{\omega}_s T_{192}$$

$$\dot{T}_{193} = -(0.05155) T_{193} + (0.02631) T_{192} + (0.02524) T_{194}$$

$$\dot{T}_{194} = -(0.4161) T_{194} + (0.4161) T_{193} + (23.41) \dot{\omega}_s T_{173} - (23.41) \dot{\omega}_s T_{194}$$

$$\dot{\omega}_s = \text{steam flow per tube} = \dot{\omega}_{80}$$

$$\dot{T}_{195} = (0.02812) \dot{\omega}_s T_{194} - (0.02812) \dot{\omega}_s T_{195}$$

$$\dot{T}_{196} = -(0.001156) T_{196} + (0.001156) T_{197} + (1.2420) \dot{\omega}_s T_{195} - (1.2420) \dot{\omega}_s T_{196}$$

$$\dot{T}_{197} = -(0.00002294) T_{197} + (0.00002294) T_{196}$$

$$\dot{\omega}_s = \text{steam flow per module} = \dot{\omega}_{19}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Evaporator

I Main Heat Transfer Region

Energy balances:

$$-(UA)_1 [T_{Na} - T_{PT}] + (WC_p)_{Na} T_{Na} = (WC_p) T_{Na} + (PVC_p)_{Na} \frac{dT_{Na}}{dt}$$

$$(UA)_1 [T_{Na} - T_{PT}] - (UA)_2 [T_{PT} - T_{ANN}] = (PVC)_{PT} \frac{dT_{PT}}{dt}$$

$$(UA)_2 [T_{PT} - T_{ANN}] - (UA)_3 [T_{ANN} - T_{BT}] + W_{ANN} h_{ANN} = W_{ANN} h_{ANN} + \frac{d}{dt} (PVC)_{ANN}$$

$$(UA)_3 [T_{ANN} - T_{BT}] - (UA)_4 [T_{BT} - T_{DC}] = (PVC)_{BT} \frac{dT_{BT}}{dt}$$

$$(UA)_4 [T_{BT} - T_{DC}] + (WC_p)_{DC} T_{DC} = (WC_p)_{DC} T_{DC} + (PVC_p)_{DC} \frac{dT_{DC}}{dt}$$

The water in the downcomer has already been treated as an incompressible fluid. This cannot be done in the annulus due to the two phase flow in the last portion of the flow channel. The following assumptions are made for the annular flow:

$$\frac{dP}{dt} = 0 \quad (\text{implicit, since continuity has not been included in the formulation})$$

$$\frac{dP}{dt} = 0 \rightarrow \frac{d(\rho u)}{dt} = \frac{d(\rho h - P)}{dt} = \frac{d(\rho h)}{dt}$$

The results of these assumptions are substituted into the energy balances. The equations are then rearranged.

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In standard format

$$\dot{T}_{Na} = - \left[\frac{(UA)_1}{(PVC)_{Na}} \right] T_{Na} + \left[\frac{(UA)_1}{(PVC)_{Na}} \right] T_{PT} + \left(\frac{w}{PVC} \right)_{Na} T_{Na} - \left(\frac{w}{PVC} \right)_{Na} T_{Na}$$

$$\dot{T}_{PT} = - \left[\frac{(UA)_1}{(PVC)_{PT}} + \frac{(UA)_2}{(PVC)_{PT}} \right] T_{PT} + \left[\frac{(UA)_1}{(PVC)_{PT}} \right] T_{Na} + \left[\frac{(UA)_2}{(PVC)_{PT}} \right] T_{ANN}$$

$$\dot{h}_{ANN} = - \left[\frac{(UA)_2}{(PVC)_{ANN}} + \frac{(UA)_3}{(PVC)_{ANN}} \right] T_{ANN} + \left[\frac{(UA)_2}{(PVC)_{ANN}} \right] T_{PT} + \left[\frac{(UA)_3}{(PVC)_{ANN}} \right] T_{BT} \\ + \left(\frac{w}{PVC} \right)_{ANN} h_{ANN} - \left(\frac{w}{PVC} \right)_{ANN} h_{ANN}$$

$$\dot{T}_{BT} = - \left[\frac{(UA)_3}{(PVC)_{BT}} + \frac{(UA)_4}{(PVC)_{BT}} \right] T_{BT} + \left[\frac{(UA)_3}{(PVC)_{BT}} \right] T_{ANN} + \left[\frac{(UA)_4}{(PVC)_{BT}} \right] T_{DC}$$

$$\dot{T}_{DC} = - \left[\frac{(UA)_4}{(PVC)_{DC}} \right] T_{DC} + \left[\frac{(UA)_4}{(PVC)_{DC}} \right] T_{BT} + \left(\frac{w}{PVC} \right)_{DC} T_{DC} - \left(\frac{w}{PVC} \right)_{DC} T_{DC}$$

In addition, a curve fit of T_{ANN} vs h_{ANN} at a given pressure connects each h_{ANN} node with a corresponding T_{ANN} node.

For the axial node which is the inlet to the annulus the term in the energy balance for inlet enthalpy becomes

$$\left(\frac{w}{PVC} \right)_{ANN} h_{ANN} \rightarrow \left(\frac{wC_p}{PVC} \right)_{ANN} T_{DC \text{ OUT}}$$

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Design parameters and axial distributions of pressure and temperature for the evaporator working fluids were obtained from the computer output.

"Performance Studies for Sodium Heated Steam Generator". A computer program was written for the GE time sharing computer, which takes all the above data and computes the coefficients for the transient equations.

Input data

1) T_{Na} , $T_{Na,NN}$, $P_{Na,NN}$, $T_{w,downcomer}$, $X_{Na,NN}$ as functions of axial position.

2) Tube geometry: d_1, d_2 - inner bayonet tube ID, OD
 d_3, d_4 - outer bayonet tube ID, OD
 d_5, d_6 - pressure tube ID, OD

P - tube pitch, L_T - tube heat transfer length

3) properties for sodium, pressure tube, bayonet tubes, water in downcomers, and water in the bayonet tube insulation gap.

4) water and sodium flows per tube, sodium film coefficient (h_{Na}), downcomer water film coefficient (h_w).

The following parameters are computed:

1) Fixed quantities

a) Volumes and thermal capacitances

$$V_{Na} = \left(\frac{\sqrt{3}}{6} P^2 - \frac{\pi}{4} d_6^2 \right) \Delta L$$

$$C_{Na} = \rho_{Na} V_{Na} C_{pNa}$$

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where ΔL = length of each nodal increment.

$$V_{PT} = \frac{\pi}{4} (d_s^2 - d_v^2) \Delta L$$

$$C_{PT} = \rho_{PT} V_{PT} (C_p)_{PT}$$

$$V_{BT} = \frac{\pi}{4} [(d_4^2 - d_3^2) + (d_2^2 - d_1^2)] \Delta L$$

$$C_{BT} = \rho_{BT} V_{BT} (C_p)_{BT}$$

$$V_w = \frac{\pi}{4} d_1^2 \Delta L$$

$$C_w = \rho_w V_w (C_p)_w$$

$$V_{STM/w}^{ANN} = \frac{\pi}{4} (d_s^2 - d_v^2) \Delta L$$

The properties of the water in the downcomers do not vary significantly so they may be considered constant. The properties for the fluid in the annuli must be computed node by node due to the two distinct fluid regimes that exist.

b) The thermal resistances.

$$R_{wa} = \frac{1}{\pi d_o \Delta L h_{wa}}$$

$$R_{PT_i} = \frac{\ln(d_o / \bar{d})}{2\pi k_{PT} \Delta L} ; \quad \bar{d} = \left(\frac{d_s^2 + d_o^2}{2} \right)^{1/2}$$

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$$(UA)_1 = \frac{1.0}{R_{Na} + R_{PT_1}}$$

$$R_{PT_2} = \frac{\ln(T/d_5)}{2\pi k_{PT} \Delta L}$$

$$R_{BT_0} = \frac{\ln(d_4/d_3)}{2\pi k_{BT} \Delta L}$$

$$R_{gop} = \frac{\ln(d_3/d_2)}{2\pi k_{gop} \Delta L}$$

$$R_{BT_1} = \frac{\ln(d_2/d_1)}{2\pi k_{BT} \Delta L}$$

$$R_{BT_1} = R_{BT_0} + \frac{1}{2} R_{gop}$$

$$R_{BT_2} = \frac{1}{2} R_{gop} + R_{BT_1}$$

$$R_w = \frac{1.0}{\pi d_1 \Delta L h_w}$$

$$(UA)_4 = \frac{1.0}{R_{BT_2} + R_w}$$

2) Quantities that vary with axial position are then computed. Since the properties of the annular fluid vary, the thermal capacitance and resistances also vary. Thus node by node computations are performed.

The transient model used is the "outlet Temperature model" wherein the nodal point is characterized by the properties at the outlet of the element. For a set of nodes at a given axial position, the sodium and downcomer water conditions are obtained at the given axial position, but the

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associated annular water/steam is a nodal increment away. Consequently, the associated pressure tube and bayonet tube assembly average temperatures are "diagonal" averages (see figure).

x - nodal outlet
 a - "diagonal"
 average
 o - nodal point
 for tubes

For each radial set T_{in} , P_{ann} , T_{ann} , T_w are obtained by interpolation of the input data.

If the outlet of the annular fluid node is in the two phase zone, the quality of the mixture is also obtained by interpolation of the input data.

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The GE Mark II Steam Tables (curve fits to Keenan & Keyes) are used to obtain density and enthalpy for the saturated liquid and saturated vapor. The average for the mixture

$$\bar{\rho} = \frac{\rho_f \rho_g}{(1-x)\rho_g + x\rho_f}$$

$$\bar{H} = (1-x)H_f + xH_g$$

The thermal capacity of the node

$$C_{ANN} = \frac{1}{\bar{\rho} V_{ANN}}$$

The heat transfer coefficient is calculated from the Levy correlation. This requires knowledge of the wall temperature.

$$h = \frac{P^{1/3}}{495} (T_w - T_{sat})^2 = \frac{P^{1/3}}{495} \Delta T^2$$

From a steady state energy balance across the pressure tube

$$\frac{T_{wall} - T_{ANN}}{R} = \frac{T_{Na} - T_{ANN}}{R_{TOT}}$$

Noting that

$$R = (\pi d_s \Delta L) / h$$

$$R_{TOT} = R_{Na} + R_{PT_1} + R_{PT_2} + R$$

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These equations are combined and a cubic equation for h is obtained.

$$h^3 + \left(2 \frac{Z_1}{Z_2}\right) h^2 + \left(\frac{Z_1}{Z_2}\right)^2 h - Z_4 \left(\frac{Z_1 Z_3}{Z_2}\right)^2 = 0$$

where $Z_1 = \frac{1}{\pi d_5 \Delta L}$

$$Z_2 = R_{Na} + R_{PT_1} + R_{PT_2}$$

$$Z_3 = T_{Na} - T_{ANN}$$

$$Z_4 = P^{1/3} / 495$$

A special subroutine was written to obtain the appropriate root of this polynomial. The associated thermal resistance

$$R_{ANN} = \frac{1}{\pi d_5 \Delta L h}$$

For the film coefficient of the mixture on the outer wall of the outer bayonet tube, the quantity used in the scaling computer program was adopted.

$$h_{B_2} = 4056 \frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$$

so

$$R_{ANN} = \frac{1.0}{\pi d_4 \Delta L h_{B_2}}$$

If the outlet of the annular fluid node is in the single phase water region, then the

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density, enthalpy, viscosity, specific heat, and thermal conductivity of the water are obtained from the GE Mark II steam tables. The thermal capacitance of the node is calculated.

$$C_{ANN} = \frac{1.0}{\rho_{ANN} V_{ANN}}$$

The film coefficient

$$h = \frac{k}{D_e} [0.023 Re^{0.8} Pr^{0.4}]$$

where $Re = \frac{W_{co}}{A_{Flow}} \frac{D_e}{\mu_{ANN}}$

$$Pr = \left(\frac{C_p}{k} \right)_{ANN}$$

$$D_e = d_s - d_y$$

and the associated thermal resistances

$$R_{ANN1} = \frac{1.0}{\pi d_s \Delta L h} ; R_{ANN2} = \frac{1.0}{\pi d_y \Delta L h}$$

In either region the remaining calculations are the same. The overall conductances

$$(UA)_2 = \frac{1.0}{(R_{PT2} + R_{ANN1})} ; (UA)_3 = \frac{1.0}{(R_{ANN2} + R_{BT1})}$$

The associated "diagonal" average temperature for the pressure tube and the bayonet tube assembly is then calculated.

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$$\bar{T}_{PT} = \frac{(UA)_1 T_{Na} + (UA)_2 T_{ANN}}{(UA)_1 + (UA)_2}$$

$$\bar{T}_{BT} = \frac{(UA)_3 T_{ANN} + (UA)_4 T_w}{(UA)_3 + (UA)_4}$$

Finally the coefficients of the governing differential equations are calculated.

$$C_1 = \frac{(UA)_1}{C_{Na}} \quad ; \quad C_2 = \frac{1}{\rho_{Na} V_{Na}}$$

$$C_3 = C_4 + C_5 \quad ; \quad C_4 = \frac{(UA)_1}{C_{PT}} \quad ; \quad C_5 = \frac{(UA)_2}{C_{PT}}$$

$$C_6 = C_7 + C_8 \quad ; \quad C_7 = \frac{(UA)_2}{C_{ANN}} \quad ; \quad C_8 = \frac{(UA)_3}{C_{ANN}} \quad ; \quad C_9 = \frac{1.0}{\rho V_{ANN}}$$

$$C_{10} = C_{11} + C_{12} \quad ; \quad C_{11} = \frac{(UA)_3}{C_{BT}} \quad ; \quad C_{12} = \frac{(UA)_4}{C_{BT}}$$

$$C_{13} = \frac{(UA)_4}{C_w} \quad ; \quad C_{14} = \frac{1.0}{\rho_w V_w}$$

GFD

02/13/73

```
100 DIMENSION XTAB(37),YTAB(37),ZTAB(37),TTAB(37),PTAB(37),XTBI(13),
101&QTAB(13)
110 NTAB=37; NTBI=13; NPT=3; IERR=0
120 DATA XTAB/0.0,0.51658,1.0570,1.6254,2.2245,2.8580,3.5328,
121&4.2518,5.0210,5.8481,6.7425,7.7161,8.7842,9.7842,10.7842,11.7842,
122&12.7842,13.7842,14.7842,15.7842,16.7842,17.7842,18.7842,
123&19.7842,20.7842,21.7842,22.7842,23.7842,24.7842,25.7842,26.7842,
124&27.7842,28.7842,29.7842,30.7842,31.7842,32.45/
130 DATA YTAB/866.02,857.78,849.56,841.34,833.11,824.89,816.62,
131&808.35,800.07,791.79,783.49,775.17,766.84,760.43,754.37,748.64,
132&743.21,738.05,733.14,728.47,724.00,719.74,715.65,711.74,707.98,
133&704.37,700.90,697.55,694.33,691.22,688.21,685.30,682.49,679.77,
134&677.13,674.57,672.92/
140 DATA ZTAB/634.49,634.55,634.63,634.70,634.78,634.86,634.95,
141&635.04,635.14,635.25,635.36,635.49,635.62,635.75,635.86,635.97,
142&636.08,636.18,636.27,636.36,636.44,636.51,636.58,636.65,636.71,
143&636.76,636.81,636.85,636.89,636.92,636.95,636.97,636.99,637.00,
144&637.01,637.02,637.02/
150 DATA TTAB/676.46,676.47,676.49,676.50,676.51,676.53,676.54,
151&676.56,676.58,676.60,676.62,676.64,676.66,674.86,673.03,
152&671.17,669.31,667.44,665.60,663.73,661.96,660.19,658.44,656.72,
153&655.03,653.36,651.72,650.09,648.49,646.91,645.35,643.82,642.32,
154&640.84,639.39,637.95,637.01/
160 DATA PTAB/2644.92,2645.15,2645.39,2645.63,2645.89,2646.18,
161&2646.42,2646.72,2647.02,2647.35,2647.70,2648.07,2648.47,2648.81,
162&2649.16,2649.51,2649.86,2650.21,2650.57,2650.93,2651.28,2651.64,
163&2652.00,2652.37,2652.73,2653.10,2653.46,2653.83,2654.20,2654.57,
164&2654.94,2655.31,2655.69,2656.06,2656.43,2656.81,2657.06/
170 DATA XTBI/0.0,0.51658,1.0570,1.6254,2.2245,2.8580,3.5328,
171&4.2518,5.0210,5.8481,6.7425,7.7161,8.7842/
180 DATA QTAB/0.285714,0.261905,0.238095,0.214286,0.190476,
181&0.166667,0.142857,0.107143,0.095238,0.071428,0.047619,
182&0.023809,0.0/
190 D1=0.501; D2=0.581; D3=0.701; D4=0.781; D5=1.156; D6=1.50
195 P=2.0; XLT=32.45; XLB=8.784
200 WNA=4353000./380.; WW=3.5*397278./380.
210 CPT=0.142; XKPT=15.7; RH0PT=482.
220 CBT=0.143; XKBT=15.6; RH0BT=482.
230 CPNA=0.30508; XKNA=41.5; RH0NA=53.8; XMUNA=0.72; HNA=5701.
240 CPW=1.66; XKW=0.283; RH0W=40.5; XMUW=0.193; HW=6855.
250 XKG=0.64
260 NP=15; DX=2.163
270 RNA=3.8197/(D6*DX*HNA)
280 DB=SQR((D5**2+D6**2)/2.0)
285 RPT1=0.159155*ALOG(D6/DB)/(DX*XKPT)
286 RPT2=0.159155*ALOG(DB/D5)/(DX*XKPT)
290 RBT0=0.159155*ALOG(D4/D3)/(DX*XKBT)
291 RGAP=0.159155*ALOG(D3/D2)/(DX*XKG)
292 RBT1=0.159155*ALOG(D2/D1)/(DX*XKBT)
300 RBT1=RBT0+0.5*RGAP; RBT2=0.5*RGAP+RBT1
```

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310 RW=3.8197/(D1*DX*HW)
320 UA1=0.000277777/(RNA+RPT1); UA4=0.000277777/(RBT2+RW)
330 HB2=4056.
331 Z1=3.8197/(D5*DX); Z2=RNA+RPT1+RPT2
350 A1=(0.866025*P**2-0.785398*D6**2)/144.; V1=A1*DX
355 A2=0.785398*(D6**2-D5**2)/144.; V2=A2*DX
360 A3=0.785398*(D5**2-D4**2)/144.; V3=A3*DX
365 A4=0.785398*(D4**2+D2**2-D3**2-D1**2)/144.; V4=A4*DX
370 A5=0.785398*(D1**2)/144.; V5=A5*DX
380 DE=(D5-D4)/12.
390 CANA=RH0NA*V1*CPNA
395 CAW=RH0W*V5*CPW
400 CAPT=RH0PT*V2*CPT
405 CABT=RH0BT*V4*CBT
410 C1=UA1/CANA; C2=1.0/(RH0NA*V1)
420 C4=UA1/CAPT
430 C12=UA4/CABT
440 C13=UA4/CAW; C14=1.0/(RH0W*V5)
450 PRINT,"VOLUMES AND CAPACITIES"
451 PRINT,V1,CANA,V2,CAPT,V4,CABT,V5,CAW,V3
455 PRINT 200
456 200 FORMAT(/)
460 PRINT,"THERMAL RESISTANCES AND CONDUCTANCES"
461 PRINT,RNA,RPT1,"",UA1
465 PRINT,RPT2
470 PRINT,RBT0,RGAP,RBT1
475 PRINT,RBT1
480 PRINT,RBT2,RW,"",UA4
490 PRINT 300
491 300 FORMAT(////////)
500 DO 100 I=1,NP
510 XI=I; X1=XI*DX; X2=(XI-1.0)*DX
520 TNA=TNT1(X1,NTAB,XTAB,YTAB,NPT,IERR)
525 TW=TNT1(X1,NTAB,XTAB,ZTAB,NPT,IERR)
530 TA=TNT1(X2,NTAB,XTAB,TTAB,NPT,IERR)
535 PA=TNT1(X2,NTAB,XTAB,PTAB,NPT,IERR)
540 IF(X2-XLB) 40,50,50
550 40 QUAL=TNT1(X2,NTB1,XTB1,QTAB,NPT,IERR)
560 DENF=SALD(PA); DENG=SATD(PA); RH0=DENF*DENG/((1.-QUAL)*DENG+
561&QUAL*DENF)
565 CANN=RH0*V3
570 HLIQ=SALH(PA); HVAP=SATH(PA); ENTH=(1.-QUAL)*HLIQ+QUAL*HVAP
580 Z3=TNA-TA; Z4=(PA**1.33333)/495.
590 CALL B0IL(Z1,Z2,Z3,Z4,HF)
600 RA1=3.8197/(D5*DX*HF); RA2=3.8197/(D4*DX*HB2)
610 GO TO 75
620 50 RH0=WATDPT(PA,TA); CANN=RH0*V3
630 ENTH=WATH(PA,TA)
640 XMU=WATNU(TA); CP=WATCP(TA); XK=WATEK(TA); PR=XMU*CP/XK
650 RE=WW*DE/(A3*XMU)
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660 HF=XK*0.023*(RE**0.8)*(PR**0.4)/DE
670 RA1=3.8197/(D5*DX*HF); RA2=3.8197/(D4*DX*HF)
680 75 UA2=0.000277777/(RPT2+RA1)
690 UA3=0.000277777/(RA2+RBT1)
700 C5=UA2/CAPT; C3=C4+C5
710 C7=UA2/CANN; C8=UA3/CANN; C6=C7+C8; C9=1.0/CANN
720 C11=UA3/CABT; C10=C11+C12
730 TPT=(UA1*TNA+UA2*TA)/(UA1+UA2)
740 TBT=(UA3*TA+UA4*TW)/(UA3+UA4)
750 PRINT,"TEMPERATURE DISTRIBUTION"
751 PRINT,TNA,TPT,TA,TBT,TW
760 PRINT 200
770 PRINT,"WATER/STEAM PROPERTIES"
771 PRINT,ENTH,PA,RH0,CANN
772 PRINT 200
780 PRINT,"THERMAL CONDUCTANCES"
781 PRINT,HF,"",UA2,UA3
783 PRINT 200
790 PRINT,"COEFFICIENTS"
791 PRINT,C1,C2
792 PRINT,C3,C4,C5
793 PRINT,C6,C7,C8,C9
794 PRINT,C10,C11,C12
795 PRINT,C13,C14
800 PRINT 400
801 400 FORMAT(///)
810 100 CONTINUE
820 STOP; END
900 SUBROUTINE BOIL(Z1,Z2,Z3,Z4,HF)
910 EXTERNAL FUNC
920 COMMON Z11,Z12,Z13
930 Z11=2.0*Z1/Z2; Z12=(Z1/Z2)**2; Z13=Z4*(Z1*Z3/Z2)**2
940 IERR=0; IND=1; EPS=1.0; T0P=15000.; B0T=5000.
950 HF=S0LN(IND,FUNC,B0T,T0P,EPS,IERR)
960 IF(IERR) 900,901,900
970 900 PRINT,IERR
980 901 RETURN
990 END
1000 FUNCTION FUNC(X)
1010 COMMON Z11,Z12,Z13
1020 FUNC=X*X*X+Z11*X*X+Z12*X-Z13
1030 RETURN
1040 END
```


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VOLUMES AND CAPACITIES

2.5489671E-02	4.1836971E-01	1.0778798E-02	7.3774404E-01
2.4198689E-03	1.6679188E-01	2.9611423E-03	1.9907759E-01
8.5692873E-03			

THERMAL RESISTANCES AND CONDUCTANCES

2.0650494E-04	5.3181092E-04		3.7623057E-01
6.8906281E-04			
5.0972197E-04	2.1586400E-02	6.9875536E-04	
1.1302922E-02			
1.1491955E-02	5.1419465E-04		2.3136226E-02

TEMPERATURE DISTRIBUTION

8.3393433E+02	7.5909934E+02	6.7646000E+02	6.5574304E+02
6.3477149E+02			

WATER/STEAM PROPERTIES

8.4231775E+02	2.6449200E+03	1.8285841E+01	1.5669662E-01
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THERMAL CONDUCTANCES

1.2099915E+04		3.4069976E-01	2.3420553E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
9.7178736E-01	5.0997440E-01	4.6181296E-01	
2.3237279E+00	2.1742636E+00	1.4946431E-01	6.3817585E+00
2.7913097E-01	1.4041782E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

8.0752571E+02	7.4595827E+02	6.7650900E+02	6.5590584E+02
6.3504948E+02			

WATER/STEAM PROPERTIES

8.1214240E+02	2.6458630E+03	2.1471983E+01	1.8399959E-01
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THERMAL CONDUCTANCES

1.0485305E+04		3.3353204E-01	2.3420553E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
9.6207163E-01	5.0997440E-01	4.5209723E-01	
1.9399640E+00	1.8126781E+00	1.2728589E-01	5.4347947E+00
2.7913097E-01	1.4041782E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.8577349E+02	7.3509418E+02	6.7656199E+02	6.5607178E+02
6.3532977E+02			

WATER/STEAM PROPERTIES

7.8356899E+02	2.6467499E+03	2.5710924E+01	2.2032429E-01
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THERMAL CONDUCTANCES

9.3342590E+03		3.2575406E-01	2.3420553E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
9.5152871E-01	5.0997440E-01	4.4155431E-01	
1.5848212E+00	1.4785209E+00	1.0630037E-01	4.5387641E+00
2.7913097E-01	1.4041782E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.6782576E+02	7.2609218E+02	6.7661450E+02	6.5623479E+02
6.3560462E+02			

WATER/STEAM PROPERTIES

7.6719107E+02	2.6476015E+03	2.8997521E+01	2.4848809E-01
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THERMAL CONDUCTANCES

8.2017517E+03		3.1734411E-01	2.3420553E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
9.4012916E-01	5.0997440E-01	4.3015476E-01	
1.3713521E+00	1.2770999E+00	9.4252214E-02	4.0243377E+00
2.7913097E-01	1.4041782E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.5418859E+02	7.1921886E+02	6.7665763E+02	6.5638508E+02
6.3586339E+02			

WATER/STEAM PROPERTIES

7.5060365E+02	2.6484208E+03	3.3305418E+01	2.8540369E-01
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THERMAL CONDUCTANCES

7.2906113E+03		3.0912365E-01	2.3420553E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
9.2898646E-01	5.0997440E-01	4.1901206E-01	
1.1651713E+00	1.0831102E+00	8.2061142E-02	3.5038089E+00
2.7913097E-01	1.4041782E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.4218890E+02	7.1502344E+02	6.7297317E+02	6.5456091E+02
6.3610017E+02			

WATER/STEAM PROPERTIES

7.3574105E+02	2.6491708E+03	3.4980706E+01	2.9975972E-01
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THERMAL CONDUCTANCES

3.3662839E+03		2.4305374E-01	2.3197155E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3942977E-01	5.0997440E-01	3.2945538E-01	
8.8821438E-01	8.1082855E-01	7.7385831E-02	3.3360053E+00
2.7779159E-01	1.3907844E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.3144621E+02	7.0700649E+02	6.6894836E+02	6.5263979E+02
6.3630212E+02			

WATER/STEAM PROPERTIES

7.2698895E+02	2.6499278E+03	3.5680295E+01	3.0575469E-01
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THERMAL CONDUCTANCES

3.3161418E+03		2.4160316E-01	2.3177497E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3746354E-01	5.0997440E-01	3.2748914E-01	
8.6599050E-01	7.9018627E-01	7.5804222E-02	3.2705958E+00
2.7767373E-01	1.3896058E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.2175945E+02	6.9961565E+02	6.6493623E+02	6.5071385E+02
6.3647764E+02			

WATER/STEAM PROPERTIES

7.1668003E+02	8.6506985E+03	3.6334065E+01	3.1135704E-01
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THERMAL CONDUCTANCES

3.2696284E+03		2.4023385E-01	2.3158753E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3560746E-01	5.0997440E-01	3.2563306E-01	
8.4595037E-01	7.7157031E-01	7.4380052E-02	3.2117468E+00
2.7756135E-01	1.3884820E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.1296076E+02	6.9279221E+02	6.6103996E+02	6.4883523E+02
6.3662780E+02			

WATER/STEAM PROPERTIES

7.1079535E+02	2.6514659E+03	3.6932339E+01	3.1648382E-01
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THERMAL CONDUCTANCES

3.2275784E+03		2.3897580E-01	2.3141370E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3390220E-01	5.0997440E-01	3.2392779E-01	
8.2821664E-01	7.5509641E-01	7.3120231E-02	3.1597192E+00
2.7745713E-01	1.3874398E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

7.0491689E+02	6.8646030E+02	6.5726234E+02	6.4700521E+02
6.3675294E+02			

WATER/STEAM PROPERTIES

7.0346392E+02	2.6522516E+03	3.7481884E+01	3.2119304E-01
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THERMAL CONDUCTANCES

3.1895876E+03		2.3782237E-01	2.3125295E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3233874E-01	5.0997440E-01	3.2236433E-01	
8.1243250E-01	7.4043438E-01	7.1998119E-02	3.1133925E+00
2.7736075E-01	1.3864760E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

6.9752110E+02	6.8056297E+02	6.5361620E+02	6.4522861E+02
6.3685036E+02			

WATER/STEAM PROPERTIES

6.9660304E+02	2.6530423E+03	3.7986780E+01	3.2551963E-01
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THERMAL CONDUCTANCES

3.1553586E+03		2.3676917E-01	2.3110499E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.3091114E-01	5.0997440E-01	3.2093675E-01	
7.9835330E-01	7.2735758E-01	7.0995715E-02	3.0720113E+00
2.7727204E-01	1.3855890E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

6.9069578E+02	6.7504585E+02	6.5007578E+02	6.4349487E+02
6.3692516E+02			

WATER/STEAM PROPERTIES

6.9012553E+02	2.6538333E+03	3.8455349E+01	3.2953494E-01
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THERMAL CONDUCTANCES

3.1242877E+03		2.3580147E-01	2.3096805E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.2959944E-01	5.0997440E-01	3.1962504E-01	
7.8564742E-01	7.1555833E-01	7.0089092E-02	3.0345796E+00
2.7718994E-01	1.3847679E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

6.8434808E+02	6.6985397E+02	6.4664057E+02	6.4180319E+02
6.3697670E+02			

WATER/STEAM PROPERTIES

6.8399948E+02	2.6546336E+03	3.8891439E+01	3.3327191E-01
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THERMAL CONDUCTANCES

3.0960724E+03		2.3491289E-01	2.3084145E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.2839499E-01	5.0997440E-01	3.1842059E-01	
7.7413376E-01	7.0486856E-01	6.9265199E-02	3.0005529E+00
2.7711404E-01	1.3840089E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

6.7844581E+02	6.6497079E+02	6.4331447E+02	6.4015536E+02
6.3700498E+02			

WATER/STEAM PROPERTIES

6.7820548E+02	2.6554361E+03	3.9297722E+01	3.3675347E-01
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THERMAL CONDUCTANCES

3.0704701E+03		2.3409840E-01	2.3072469E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.2729096E-01	5.0997440E-01	3.1731656E-01	
7.6367698E-01	6.9516256E-01	6.8514423E-02	2.9695314E+00
2.7704403E-01	1.3833089E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

TEMPERATURE DISTRIBUTION

6.7293223E+02	6.6036924E+02	6.4011444E+02	6.3856474E+02
6.3702002E+02			

WATER/STEAM PROPERTIES

6.7274919E+02	2.6562442E+03	3.9674970E+01	3.3998621E-01
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THERMAL CONDUCTANCES

3.0473477E+03		2.3335599E-01	2.3061766E-02
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COEFFICIENTS

8.9927774E-01	7.2921148E-01		
8.2628463E-01	5.0997440E-01	3.1631023E-01	
7.5420046E-01	6.8636899E-01	6.7831473E-02	2.9412957E+00
2.7697986E-01	1.3826672E-01	1.3871314E-01	
1.1621713E-01	8.3384572E+00		

PROGRAM STOP AT 820

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Summary

$$\begin{aligned}
 \dot{T}_{229} &= -(.899278) \dot{T}_{209} + (.899278) \dot{T}_{244} + (.729211) \dot{\omega}_{Na} \dot{T}_{200} - (.729211) \dot{\omega}_{Na} \dot{T}_{229} \\
 \dot{T}_{230} &= -(.899278) \dot{T}_{230} + (.899278) \dot{T}_{245} + (.729211) \dot{\omega}_{Na} \dot{T}_{229} - (.729211) \dot{\omega}_{Na} \dot{T}_{230} \\
 \dot{T}_{231} &= -(.899278) \dot{T}_{231} + (.899278) \dot{T}_{246} + (.729211) \dot{\omega}_{Na} \dot{T}_{230} - (.729211) \dot{\omega}_{Na} \dot{T}_{231} \\
 \dot{T}_{232} &= -(.899278) \dot{T}_{232} + (.899278) \dot{T}_{247} + (.729211) \dot{\omega}_{Na} \dot{T}_{231} - (.729211) \dot{\omega}_{Na} \dot{T}_{232} \\
 \dot{T}_{233} &= -(.899278) \dot{T}_{233} + (.899278) \dot{T}_{248} + (.729211) \dot{\omega}_{Na} \dot{T}_{232} - (.729211) \dot{\omega}_{Na} \dot{T}_{233} \\
 \dot{T}_{234} &= -(.899278) \dot{T}_{234} + (.899278) \dot{T}_{249} + (.729211) \dot{\omega}_{Na} \dot{T}_{233} - (.729211) \dot{\omega}_{Na} \dot{T}_{234} \\
 \dot{T}_{235} &= -(.899278) \dot{T}_{235} + (.899278) \dot{T}_{250} + (.729211) \dot{\omega}_{Na} \dot{T}_{234} - (.729211) \dot{\omega}_{Na} \dot{T}_{235} \\
 \dot{T}_{236} &= -(.899278) \dot{T}_{236} + (.899278) \dot{T}_{251} + (.729211) \dot{\omega}_{Na} \dot{T}_{235} - (.729211) \dot{\omega}_{Na} \dot{T}_{236} \\
 \dot{T}_{237} &= -(.899278) \dot{T}_{237} + (.899278) \dot{T}_{252} + (.729211) \dot{\omega}_{Na} \dot{T}_{236} - (.729211) \dot{\omega}_{Na} \dot{T}_{237} \\
 \dot{T}_{238} &= -(.899278) \dot{T}_{238} + (.899278) \dot{T}_{253} + (.729211) \dot{\omega}_{Na} \dot{T}_{237} - (.729211) \dot{\omega}_{Na} \dot{T}_{238} \\
 \dot{T}_{239} &= -(.899278) \dot{T}_{239} + (.899278) \dot{T}_{254} + (.729211) \dot{\omega}_{Na} \dot{T}_{238} - (.729211) \dot{\omega}_{Na} \dot{T}_{239} \\
 \dot{T}_{240} &= -(.899278) \dot{T}_{240} + (.899278) \dot{T}_{255} + (.729211) \dot{\omega}_{Na} \dot{T}_{239} - (.729211) \dot{\omega}_{Na} \dot{T}_{240} \\
 \dot{T}_{241} &= -(.899278) \dot{T}_{241} + (.899278) \dot{T}_{256} + (.729211) \dot{\omega}_{Na} \dot{T}_{240} - (.729211) \dot{\omega}_{Na} \dot{T}_{241} \\
 \dot{T}_{242} &= -(.899278) \dot{T}_{242} + (.899278) \dot{T}_{257} + (.729211) \dot{\omega}_{Na} \dot{T}_{241} - (.729211) \dot{\omega}_{Na} \dot{T}_{242} \\
 \dot{T}_{243} &= -(.899278) \dot{T}_{243} + (.899278) \dot{T}_{258} + (.729211) \dot{\omega}_{Na} \dot{T}_{242} - (.729211) \dot{\omega}_{Na} \dot{T}_{243}
 \end{aligned}$$

$$\dot{\omega}_{Na} = \text{Sodium flow per tube} = \dot{\omega}_{78}$$

$$\begin{aligned}
 \dot{T}_{244} &= -(.981787) \dot{T}_{244} + (.509974) \dot{T}_{229} + (.461813) \dot{T}_{386} \\
 \dot{T}_{245} &= -(.962072) \dot{T}_{245} + (.509974) \dot{T}_{230} + (.452097) \dot{T}_{387} \\
 \dot{T}_{246} &= -(.961529) \dot{T}_{246} + (.509974) \dot{T}_{231} + (.441655) \dot{T}_{388} \\
 \dot{T}_{247} &= -(.940129) \dot{T}_{247} + (.509974) \dot{T}_{232} + (.430155) \dot{T}_{389} \\
 \dot{T}_{248} &= -(.928986) \dot{T}_{248} + (.509974) \dot{T}_{233} + (.419012) \dot{T}_{390} \\
 \dot{T}_{249} &= -(.839430) \dot{T}_{249} + (.509974) \dot{T}_{234} + (.329455) \dot{T}_{391} \\
 \dot{T}_{250} &= -(.837464) \dot{T}_{250} + (.509974) \dot{T}_{235} + (.327489) \dot{T}_{392} \\
 \dot{T}_{251} &= -(.835607) \dot{T}_{251} + (.509974) \dot{T}_{236} + (.325633) \dot{T}_{393}
 \end{aligned}$$

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$$\begin{aligned}\dot{T}_{252} &= -(0.833902) \dot{T}_{252} + (0.509974) \dot{T}_{237} + (0.323928) \dot{T}_{394} \\ \dot{T}_{253} &= -(0.832338) \dot{T}_{253} + (0.509974) \dot{T}_{238} + (0.322364) \dot{T}_{395} \\ \dot{T}_{254} &= -(0.830911) \dot{T}_{254} + (0.509974) \dot{T}_{239} + (0.320137) \dot{T}_{396} \\ \dot{T}_{255} &= -(0.829599) \dot{T}_{255} + (0.509974) \dot{T}_{240} + (0.319625) \dot{T}_{397} \\ \dot{T}_{256} &= -(0.828395) \dot{T}_{256} + (0.509974) \dot{T}_{241} + (0.318420) \dot{T}_{398} \\ \dot{T}_{257} &= -(0.827291) \dot{T}_{257} + (0.509974) \dot{T}_{242} + (0.317317) \dot{T}_{399} \\ \dot{T}_{258} &= -(0.826285) \dot{T}_{258} + (0.509974) \dot{T}_{243} + (0.316310) \dot{T}_{400}\end{aligned}$$

$$\begin{aligned}\dot{h}_{259} &= -(2.32373) \dot{T}_{386} + (2.17426) \dot{T}_{244} + (0.149464) \dot{T}_{274} \\ &\quad + (6.38176) \dot{\omega}_n \dot{h}_{260} - (6.38176) \dot{\omega}_n \dot{h}_{259}\end{aligned}$$

$$\begin{aligned}\dot{h}_{260} &= -(1.93996) \dot{T}_{387} + (1.81268) \dot{T}_{245} + (0.127286) \dot{T}_{275} \\ &\quad + (5.34379) \dot{\omega}_n \dot{h}_{261} - (5.34379) \dot{\omega}_n \dot{h}_{260}\end{aligned}$$

$$\begin{aligned}\dot{h}_{261} &= -(1.58482) \dot{T}_{388} + (1.47852) \dot{T}_{246} + (0.106300) \dot{T}_{276} \\ &\quad + (4.53876) \dot{\omega}_n \dot{h}_{262} - (4.53876) \dot{\omega}_n \dot{h}_{261}\end{aligned}$$

$$\begin{aligned}\dot{h}_{262} &= -(1.37135) \dot{T}_{389} + (1.27710) \dot{T}_{247} + (0.0942522) \dot{T}_{277} \\ &\quad + (4.02434) \dot{\omega}_n \dot{h}_{263} - (4.02434) \dot{\omega}_n \dot{h}_{262}\end{aligned}$$

$$\begin{aligned}\dot{h}_{263} &= -(1.16517) \dot{T}_{390} + (1.08311) \dot{T}_{248} + (0.0820611) \dot{T}_{278} \\ &\quad + (3.50381) \dot{\omega}_n \dot{h}_{264} - (3.50381) \dot{\omega}_n \dot{h}_{263}\end{aligned}$$

$$\begin{aligned}\dot{h}_{264} &= -(0.888214) \dot{T}_{391} + (0.810829) \dot{T}_{249} + (0.0773858) \dot{T}_{279} \\ &\quad + (3.33601) \dot{\omega}_n \dot{h}_{265} - (3.33601) \dot{\omega}_n \dot{h}_{264}\end{aligned}$$

$$\begin{aligned}\dot{h}_{265} &= -(0.865991) \dot{T}_{392} + (0.790186) \dot{T}_{250} + (0.0758042) \dot{T}_{280} \\ &\quad + (3.27060) \dot{\omega}_n \dot{h}_{266} - (3.27060) \dot{\omega}_n \dot{h}_{265}\end{aligned}$$

$$\begin{aligned}\dot{h}_{266} &= -(0.845950) \dot{T}_{393} + (0.771570) \dot{T}_{251} + (0.0743801) \dot{T}_{281} \\ &\quad + (3.21175) \dot{\omega}_n \dot{h}_{267} - (3.21175) \dot{\omega}_n \dot{h}_{266}\end{aligned}$$

$$\begin{aligned}\dot{h}_{267} &= -(0.828217) \dot{T}_{394} + (0.755096) \dot{T}_{252} + (0.0731202) \dot{T}_{282} \\ &\quad + (3.15972) \dot{\omega}_n \dot{h}_{268} - (3.15972) \dot{\omega}_n \dot{h}_{267}\end{aligned}$$

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$$\begin{aligned} \dot{h}_{268} &= -(0.812433) \bar{T}_{398} + (0.740434) \bar{T}_{253} + (0.0719981) \bar{T}_{243} \\ &\quad + (3.11339) \dot{w}_r h_{269} - (3.11339) \dot{w}_r h_{268} \\ \dot{h}_{269} &= -(0.798353) \bar{T}_{396} + (0.727358) \bar{T}_{254} + (0.0709951) \bar{T}_{284} \\ &\quad + (3.07201) \dot{w}_r h_{270} - (3.07201) \dot{w}_r h_{269} \\ \dot{h}_{270} &= -(0.785647) \bar{T}_{317} + (0.715559) \bar{T}_{255} + (0.0700891) \bar{T}_{285} \\ &\quad + (3.03458) \dot{w}_r h_{271} - (3.03458) \dot{w}_r h_{270} \\ \dot{h}_{271} &= -(0.774134) \bar{T}_{398} + (0.704869) \bar{T}_{256} + (0.0692652) \bar{T}_{246} \\ &\quad + (3.00055) \dot{w}_r h_{272} - (3.00055) \dot{w}_r h_{271} \\ \dot{h}_{272} &= -(0.763677) \bar{T}_{399} + (0.695163) \bar{T}_{257} + (0.0685144) \bar{T}_{287} \\ &\quad + (2.96953) \dot{w}_r h_{273} - (2.96953) \dot{w}_r h_{272} \\ \dot{h}_{273} &= -(0.754200) \bar{T}_{400} + (0.686369) \bar{T}_{258} + (0.0678315) \bar{T}_{288} \\ &\quad + (2.94130) \dot{w}_r h_{361} - (2.94130) \dot{w}_r h_{273} \end{aligned}$$

$\dot{w}_r = \text{Total water flow per tube} = \dot{w}_{84}$

$$\begin{aligned} \dot{T}_{274} &= -(0.279131) \bar{T}_{274} + (0.140418) \bar{T}_{386} + (0.138713) \bar{T}_{289} \\ \dot{T}_{275} &= -(0.279131) \bar{T}_{275} + (0.140418) \bar{T}_{387} + (0.138713) \bar{T}_{290} \\ \dot{T}_{276} &= -(0.279131) \bar{T}_{276} + (0.140418) \bar{T}_{388} + (0.138713) \bar{T}_{291} \\ \dot{T}_{277} &= -(0.279131) \bar{T}_{277} + (0.140418) \bar{T}_{389} + (0.138713) \bar{T}_{292} \\ \dot{T}_{278} &= -(0.279131) \bar{T}_{278} + (0.140418) \bar{T}_{390} + (0.138713) \bar{T}_{293} \\ \dot{T}_{279} &= -(0.277791) \bar{T}_{279} + (0.139078) \bar{T}_{391} + (0.138713) \bar{T}_{294} \\ \dot{T}_{280} &= -(0.277674) \bar{T}_{280} + (0.138961) \bar{T}_{392} + (0.138713) \bar{T}_{295} \\ \dot{T}_{281} &= -(0.277561) \bar{T}_{281} + (0.138848) \bar{T}_{393} + (0.138713) \bar{T}_{296} \\ \dot{T}_{282} &= -(0.277457) \bar{T}_{282} + (0.138744) \bar{T}_{394} + (0.138713) \bar{T}_{297} \\ \dot{T}_{283} &= -(0.277361) \bar{T}_{283} + (0.138748) \bar{T}_{395} + (0.138713) \bar{T}_{298} \\ \dot{T}_{284} &= -(0.277272) \bar{T}_{284} + (0.138559) \bar{T}_{396} + (0.138713) \bar{T}_{299} \\ \dot{T}_{285} &= -(0.277190) \bar{T}_{285} + (0.138477) \bar{T}_{397} + (0.138713) \bar{T}_{300} \\ \dot{T}_{286} &= -(0.277114) \bar{T}_{286} + (0.138401) \bar{T}_{398} + (0.138713) \bar{T}_{301} \end{aligned}$$

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$$\dot{T}_{287} = -(0.277044) \dot{T}_{287} + (0.138331) \dot{T}_{399} + (0.138713) \dot{T}_{302}$$

$$\dot{T}_{288} = -(0.276980) \dot{T}_{288} + (0.138266) \dot{T}_{400} + (0.138713) \dot{T}_{303}$$

$$\dot{T}_{289} = -(0.116217) \dot{T}_{289} + (0.116217) \dot{T}_{274} + (8.33846) \dot{W}_n \dot{T}_{209} - (8.33846) \dot{W}_n \dot{T}_{289}$$

$$\dot{T}_{290} = -(0.116217) \dot{T}_{290} + (0.116217) \dot{T}_{275} + (8.33846) \dot{W}_n \dot{T}_{219} - (8.33846) \dot{W}_n \dot{T}_{290}$$

$$\dot{T}_{291} = -(0.116217) \dot{T}_{291} + (0.116217) \dot{T}_{276} + (8.33846) \dot{W}_n \dot{T}_{290} - (8.33846) \dot{W}_n \dot{T}_{291}$$

$$\dot{T}_{292} = -(0.116217) \dot{T}_{292} + (0.116217) \dot{T}_{277} + (8.33846) \dot{W}_n \dot{T}_{291} - (8.33846) \dot{W}_n \dot{T}_{292}$$

$$\dot{T}_{293} = -(0.116217) \dot{T}_{293} + (0.116217) \dot{T}_{278} + (8.33846) \dot{W}_n \dot{T}_{292} - (8.33846) \dot{W}_n \dot{T}_{293}$$

$$\dot{T}_{294} = -(0.116217) \dot{T}_{294} + (0.116217) \dot{T}_{279} + (8.33846) \dot{W}_n \dot{T}_{293} - (8.33846) \dot{W}_n \dot{T}_{294}$$

$$\dot{T}_{295} = -(0.116217) \dot{T}_{295} + (0.116217) \dot{T}_{280} + (8.33846) \dot{W}_n \dot{T}_{294} - (8.33846) \dot{W}_n \dot{T}_{295}$$

$$\dot{T}_{296} = -(0.116217) \dot{T}_{296} + (0.116217) \dot{T}_{281} + (8.33846) \dot{W}_n \dot{T}_{295} - (8.33846) \dot{W}_n \dot{T}_{296}$$

$$\dot{T}_{297} = -(0.116217) \dot{T}_{297} + (0.116217) \dot{T}_{282} + (8.33846) \dot{W}_n \dot{T}_{296} - (8.33846) \dot{W}_n \dot{T}_{297}$$

$$\dot{T}_{298} = -(0.116217) \dot{T}_{298} + (0.116217) \dot{T}_{283} + (8.33846) \dot{W}_n \dot{T}_{297} - (8.33846) \dot{W}_n \dot{T}_{298}$$

$$\dot{T}_{299} = -(0.116217) \dot{T}_{299} + (0.116217) \dot{T}_{284} + (8.33846) \dot{W}_n \dot{T}_{298} - (8.33846) \dot{W}_n \dot{T}_{299}$$

$$\dot{T}_{300} = -(0.116217) \dot{T}_{300} + (0.116217) \dot{T}_{285} + (8.33846) \dot{W}_n \dot{T}_{299} - (8.33846) \dot{W}_n \dot{T}_{300}$$

$$\dot{T}_{301} = -(0.116217) \dot{T}_{301} + (0.116217) \dot{T}_{286} + (8.33846) \dot{W}_n \dot{T}_{300} - (8.33846) \dot{W}_n \dot{T}_{301}$$

$$\dot{T}_{302} = -(0.116217) \dot{T}_{302} + (0.116217) \dot{T}_{287} + (8.33846) \dot{W}_n \dot{T}_{301} - (8.33846) \dot{W}_n \dot{T}_{302}$$

$$\dot{T}_{303} = -(0.116217) \dot{T}_{303} + (0.116217) \dot{T}_{288} + (8.33846) \dot{W}_n \dot{T}_{302} - (8.33846) \dot{W}_n \dot{T}_{303}$$

$$\dot{W}_n = \text{total water flow per tube} = \dot{W}_{84}$$

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The last element of the downcomer represents temperature and is connected to the first annular node which represents enthalpy. An auxiliary node is associated with the last downcomer node which is the enthalpy corresponding to the downcomer temperature. These two nodes are connected by a "flow equation"; this equation is an algebraic equation whose constants are specialized to an enthalpy-temperature curve fit at a given pressure.

$$\dot{W} = \epsilon_2 Z + \epsilon_3 Z^2 + \frac{\epsilon_4}{Z} + \frac{\epsilon_5}{Z^2} \\ + \epsilon_6 + \epsilon_7 Z^3 + \epsilon_8 Z^4 + \epsilon_9 Z^5 + \epsilon_{10} Z^6$$

$$k = \epsilon_1 < 0.0 \Rightarrow Z = \bar{T}_{1k1} = \text{nodal value}$$

the value ϵ_1 indicates which node temperature ($\bar{T}_{1k1}$) is to be used.

The selected pressure is 2645 which is the pressure of the steam/water mixture at the exit of the main heat transfer region of the evaporator and very nearly the pressure in the drum. The effect of the higher pressure in the downcomer tubes of the evaporator will be very small since the properties of compressed water are a weak function of pressure.

The values of enthalpy-temperature were obtained from the G E Mark II steam tables (curve fits to Keenan and Keyes tables). G E Mark II program POLFIT was then used to obtain the coefficients for a

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polynomial curve fit,

$$h = -(7371.36) + (38.792)T - (6.50377 \times 10^{-2})T^2 \\ + (3.75985 \times 10^{-5})T^3$$

valid for $T \leq T_{sat}^*$

Consequently

$$C_2 = 38.792$$

$$C_3 = -6.50377 \times 10^{-2}$$

$$C_4 = 0$$

$$C_5 = 0$$

$$C_6 = -7371.36$$

$$C_7 = 3.75985 \times 10^{-5}$$

$$C_8 = 0$$

$$C_9 = 0$$

$$C_{10} = 0$$

In CEROS format the h node is equated to the product of the flow equation with the unity node.

$$h_{361} = (1.0) \omega_{50} F_{369} ; E_1 = -303$$

* If downcomer boiling were to occur this curve fit must be revised for that particular portion of the transient.

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The modes representing the temperature of the water or steam/water mixture in the annuli are connected to the corresponding enthalpy nodes by a "flow equation". This equation is an algebraic equation whose constants are specialized to a temperature-enthalpy curve fit at a given pressure.

$$\dot{w} = C_2 Z + C_3 Z^2 + \frac{C_4}{Z} + \frac{C_5}{Z^2} \\ + C_6 + C_7 Z^3 + C_8 Z^4 + C_9 Z^5 + C_{10} Z^6$$

$$k = C_i < 0.0 \Rightarrow Z = F_{|k|} = \text{nodal value}$$

the value C_i indicates which node enthalpy ($F_{|k|}$) is to be selected.

The selected pressure is 2645 psia which is the pressure of the steam/water mixture at the exit of the main heat transfer region. All temperature-enthalpy correspondance is at this pressure. This causes some inaccuracies for the water in the economizer region which is at higher pressure. This effect is small since properties of compressed water are a very weak function of pressure.

The values of temperature-enthalpy were obtained from the GE Mark II steam tables (curve fits to Keenan & Keyes tables). GE MARK II program POLFIT was then used to obtain the coefficients for a polynomial curve fit.

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$$T = (-1083.24) + (4.9272)h + (-3.50727 \times 10^{-3})h^2 \\ + (-7.16029 \times 10^{-7})h^3 + (1.05166 \times 10^{-9})h^4$$

Consequently for all curve fits

$$C_2 = 4.9272$$

$$C_3 = -3.50727 \times 10^{-3}$$

$$C_4 = 0$$

$$C_5 = 0$$

$$C_6 = -1083.24$$

$$C_7 = -7.16029 \times 10^{-7}$$

$$C_8 = 1.05166 \times 10^{-9}$$

$$C_9 = 0$$

$$C_{10} = 0$$

In the CEROS format the T node is equated to the product of the particular flow equation with the unity node (F_{369}).

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Summary

$$T_{386} = \dot{W}_{57} F_{369} \quad ; \quad e_1 = -259$$

$$T_{387} = \dot{W}_{58} F_{369} \quad ; \quad e_1 = -260$$

$$T_{388} = \dot{W}_{59} F_{369} \quad ; \quad e_1 = -261$$

$$T_{389} = \dot{W}_{60} F_{369} \quad ; \quad e_1 = -262$$

$$T_{390} = \dot{W}_{61} F_{369} \quad ; \quad e_1 = -263$$

$$T_{391} = \dot{W}_{62} F_{369} \quad ; \quad e_1 = -264$$

$$T_{392} = \dot{W}_{63} F_{369} \quad ; \quad e_1 = -265$$

$$T_{393} = \dot{W}_{64} F_{369} \quad ; \quad e_1 = -266$$

$$T_{394} = \dot{W}_{65} F_{369} \quad ; \quad e_1 = -267$$

$$T_{395} = \dot{W}_{66} F_{369} \quad ; \quad e_1 = -268$$

$$T_{396} = \dot{W}_{67} F_{369} \quad ; \quad e_1 = -269$$

$$T_{397} = \dot{W}_{68} F_{369} \quad ; \quad e_1 = -270$$

$$T_{398} = \dot{W}_{69} F_{369} \quad ; \quad e_1 = -271$$

$$T_{399} = \dot{W}_{70} F_{369} \quad ; \quad e_1 = -272$$

$$T_{400} = \dot{W}_{71} F_{369} \quad ; \quad e_1 = -273$$

$$T_{361} = \dot{W}_{50} F_{369} \quad ; \quad e_1 = -303$$

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II Sodium Inlet and Outlet Regions

Energy balances for the inlet and outlet plenums:
The regions are assumed to be bounded by adiabatic walls.

$$(wC_p)_{Na} T_{Na} = (wC_p)_{Na} T_{Na} + (pVC_p)_{Na} \frac{dT_{Na}}{dt}$$

In standard format

$$\dot{T}_{Na} = \left(\frac{w}{pV}\right)_{Na} T_{Na} - \left(\frac{w}{pV}\right)_{Na} T_{Na}$$

Energy balances for the inlet and outlet nozzles:

$$-(UA)[T_{noz} - T_{Na}] = (pVC)_{noz} \frac{dT_{noz}}{dt}$$

$$(UA)[T_{noz} - T_{Na}] + (wC_p)_{Na} T_{Na} = (wC_p)_{Na} T_{Na} + (pVC_p)_{Na} \frac{dT_{Na}}{dt}$$

In standard format

$$\dot{T}_{noz} = -\left[\frac{(UA)}{(pVC)_{noz}}\right] T_{noz} + \left[\frac{(UA)}{(pVC)_{noz}}\right] T_{Na}$$

$$\dot{T}_{Na} = -\left[\frac{(UA)}{(pVC_p)_{Na}}\right] T_{Na} + \left[\frac{(UA)}{(pVC_p)_{Na}}\right] T_{noz} + \left(\frac{w}{pV}\right)_{Na} T_{Na} - \left(\frac{w}{pV}\right)_{Na} T_{Na}$$

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Sodium Inlet Region

$$W_{Na} = 4.353 \times 10^6 \text{ lbm/hr} = 1209 \text{ lbm/sec} \quad (\text{Design})$$

Properties are evaluated at temperature for full load

$$T = 866^\circ\text{F} \Rightarrow k_{Na} = 39.6 \text{ Btu/m-ft-}^\circ\text{F}; k_{Noz} = 16.3 \text{ Btu/m-ft-}^\circ\text{F}$$

$$\rho_{Na} = 52.5 \text{ lbm/ft}^3; \rho_{Noz} = 478 \text{ lbm/ft}^3$$

$$C_{pNa} = 0.303 \text{ Btu/lbm-}^\circ\text{F}; C_{pNoz} = 0.151 \text{ Btu/lbm-}^\circ\text{F}$$

$$\mu_{Na} = 0.605 \text{ lbm/ft-hr}$$

Heat Transfer coefficient

$$1) G_{Na} = \frac{W_{Na}}{A} = \frac{(4.353 \times 10^6)/2}{\frac{\pi}{4} (1)^2} = 2.771 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}$$

$$V_{Na} = \frac{G_{Na}}{\rho_{Na}} = \frac{(2.771 \times 10^6)/3600}{52.5} = 14.67 \text{ ft/sec}$$

$$Re = \frac{GD}{\mu} = \frac{(2.771 \times 10^6)(1)}{0.605} = 4.581 \times 10^6$$

$$Pe = Re \frac{4C_p}{k} = (4.581 \times 10^6) \frac{0.605(0.303)}{39.6} = 21204$$

$$h_{Na} = \frac{k_{Na}}{D} [5 + 0.025 Pe^{0.8}] = \frac{39.6}{(1)} [5.0 + 0.025(21204)^{0.8}]$$

$$= 3061 \frac{\text{Btu}}{\text{m-ft}^2\text{-}^\circ\text{F}} = 0.8502 \frac{\text{Btu}}{\text{sec-ft}^2\text{-}^\circ\text{F}}$$

Entrance effects on the heat transfer coefficient are neglected.

e) The average diameter for the nozzle is computed at the thickest section.

SODIUM INLET PLENUM

$$V_{Na} = \frac{\pi}{4} (63\frac{1}{2}^2 - 49\frac{3}{8}^2) (77) = 94900 \text{ cm}^3 = 54.9 \text{ ft}^3$$

SODIUM INLET NOZZLE

$$V_{Na} = \frac{\pi}{4} (12)^2 (18\frac{3}{4}) = 2120 \text{ cm}^3 = 1.23 \text{ ft}^3$$

$$\begin{aligned} V_{Noz} &= \frac{\pi}{4} (12\frac{3}{4}^2 - 12^2) (5) + \frac{\pi (2)}{12} \left\{ (15^2 + 15(12\frac{3}{4}) + 12\frac{3}{4}^2) - (13\frac{3}{4}^2 + (12\frac{3}{4})12 + 12^2) \right\} \\ &\quad + \left\{ \frac{\pi (11\frac{3}{4})}{12} (18^2 + 18(15) + 15^2) - \frac{\pi (13\frac{3}{4})^2 (11\frac{3}{4})}{4} \right\} \\ &= 890 \text{ cm}^3 = 0.515 \text{ ft}^3 \end{aligned}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

$$\bar{D} = \left(\frac{D_c^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{13.74^2 + 18^2}{2} \right)^{1/2} = 16.02''$$

Assume a $1/2''$ thermal liner ($2\frac{3}{4}$ Cr-1Mo) and $3/8''$ stagnant sodium gap between the flowing sodium and the nozzle for the entire length of the inlet nozzle. In addition, the resistance for the thickest section of the nozzle is assumed to characterize the nozzle for its entire length.

$$\begin{aligned} (UA) &= \frac{2 \pi L}{\frac{2}{h_{Na}(D)_{noz}} + \frac{\ln(OD/ID)_{liner}}{k_{liner}} + \frac{\ln(OD/ID)_{gap}}{k_{gap}} + \frac{\ln(\bar{D}/D_c)}{k_{noz}}} \\ &= \frac{2 \pi (18\frac{3}{4}/12)}{\frac{2}{3061(1.0)} + \frac{\ln(18/12)}{16.3} + \frac{\ln(13.74/13)}{39.6} + \frac{\ln(16.02/13.74)}{16.3}} \\ &= 600.3 \frac{Btu}{hr \cdot ^\circ F} = 0.1667 \frac{Btu}{sec \cdot ^\circ F} \end{aligned}$$

Volumes

$$(V_{Na})_{noz} = 1.23 \text{ ft}^3$$

$$(V_{metal})_{noz} = 0.515 \text{ ft}^3$$

$$(V_{in})_{plenum} = 54.9 \text{ ft}^3$$

Computations are shown on the figure.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{Pv}\right)_{NG} = \frac{1}{(52.5) 54.9} = 0.0003470 \text{ lbm}^{-1}$$

$$\left[\frac{2A}{(PVC)_{NO_2}}\right] = \frac{2(0.1667)}{478[2(0.515)](0.151)} = 0.004485 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(PVC)_{H_2O}}\right] = \frac{2(0.1667)}{52.5[2(1.23)](0.303)} = 0.008520 \text{ sec}^{-1}$$

$$\left(\frac{1}{Pv}\right)_{NO_2} = \frac{1}{52.5[2(1.23)]} = 0.007743 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Sodium Outlet Region

$$\dot{W}_{Na} = 4.353 \times 10^6 \text{ lbm/hr} = 1209 \text{ lbm/sec (Design)}$$

Properties are evaluated at temperature for full load

$$T = 673^\circ\text{F} \rightarrow \begin{aligned} k_{Na} &= 42.6 \text{ Btu/hr-ft}^\circ\text{F} ; k_{NO_2} = 16.3 \text{ Btu/hr-ft}^\circ\text{F} \\ \rho_{Na} &= 54.1 \text{ lbm/ft}^3 ; \rho_{NO_2} = 478 \text{ lbm/ft}^3 \\ c_{p,Na} &= 0.308 \text{ Btu/lbm}^\circ\text{F} ; c_{p,NO_2} = 0.136 \text{ Btu/lbm}^\circ\text{F} \\ \mu_{Na} &= 0.736 \text{ lbm/ft-hr} \end{aligned}$$

Heat Transfer Coefficient

$$D \quad G_{Na} = \frac{\dot{W}_{Na}}{A} = \frac{4.353 \times 10^6}{\frac{\pi}{4} (16\frac{7}{8}/12)^2} = 2.803 \times 10^6 \text{ lbm/hr-ft}^2$$

$$V_{Na} = \frac{G_{Na}}{\rho_{Na}} = \frac{2.803 \times 10^6 / 3600}{54.1} = 14.39 \text{ ft/sec}$$

$$Re = \frac{GD}{\mu} = \frac{(2.803 \times 10^6) (\frac{16\frac{7}{8}}{12})}{.736} = 5.355 \times 10^6$$

$$Pe = Re \frac{4c_p}{k} = (5.355 \times 10^6) \frac{.736 (.308)}{42.6} = 28500$$

$$\begin{aligned} h_{Na} &= \frac{k_{Na}}{D} [5.0 + 0.025 Pe^{.8}] = \frac{42.6}{16\frac{7}{8}/12} [5 + 0.025 (28500)^{.8}] \\ &= 2925 \frac{\text{Btu}}{\text{hr-ft}^2\text{F}} = 0.8126 \frac{\text{Btu}}{\text{sec-ft}^2\text{F}} \end{aligned}$$

Entrance effects on the heat transfer coefficient are neglected.

2) The average diameter for the nozzle is computed at the thickest section.

SODIUM OUTLET PLENUM

$$V_{Na} = \left\{ \frac{\pi}{4} (55 \frac{5}{8})^2 (9) + \frac{2\pi}{3} (27 \frac{13}{16})^3 \right\} - \left\{ \pi (47 \frac{5}{8}) (1) (16) + \frac{\pi (3)}{6} (3(16 \frac{7}{8})^2 + 2(14)^2) \right\}$$

$$= 63100 \text{ mm}^3 = 36.5 \text{ ft}^3$$

SODIUM OUTLET NOZZLE

$$V_{Na} = \frac{\pi}{4} (16 \frac{7}{8})^2 (48) = 4030 \text{ mm}^3 = 2.33 \text{ ft}^3$$

$$V_{Noz} = \frac{\pi}{4} (18^2 - 16 \frac{7}{8}^2) (4) + \frac{\pi (1.5)}{12} \left\{ (18^2 + 18(20) + 20^2) - (16 \frac{7}{8}^2 + 16 \frac{7}{8} (18 \frac{7}{8}) + 16 \frac{7}{8}^2) \right\}$$

$$+ \left\{ \frac{\pi 14 \frac{1}{2}}{12} (21 \frac{1}{2}^2 + 21 \frac{1}{2} (20) + 20^2) - \frac{\pi (14 \frac{1}{2})^2 (14 \frac{1}{2})}{4} \right\}$$

$$= 1020 \text{ mm}^3 = 0.590 \text{ ft}^3$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{18\frac{7}{8}^2 + 21\frac{1}{2}^2}{2} \right)^{1/2} = 20.23''$$

Assume a $\frac{1}{2}''$ thermal liner (24Cr-1Mo) and $\frac{1}{2}''$ stagnant sodium gap between the flowing sodium and the nozzle for the entire length of the outlet nozzle. In addition, the resistance for the thickest section of the nozzle is assumed to characterize the nozzle for its entire length.

$$\begin{aligned} (UA) &= \frac{2\pi L}{\frac{2}{h(D)_{noz}} + \frac{\ln(OD/ID)_{liner}}{k_{liner}} + \frac{\ln(OD/ID)_{gap}}{k_{gap}} + \frac{\ln(\bar{D}/D_i)}{k_{noz}}} \\ &= \frac{2\pi (18/12)}{\frac{2}{(2225)(\frac{16\frac{1}{8}}{12})} + \frac{\ln(17\frac{7}{8}/16\frac{1}{8})}{16.3} + \frac{\ln(18\frac{7}{8}/17\frac{7}{8})}{42.6} + \frac{\ln(20.23/18\frac{7}{8})}{16.3}} \\ &= 987.0 \frac{\text{Btu}}{\text{hr-}^\circ\text{F}} = 0.2742 \frac{\text{Btu}}{\text{sec-}^\circ\text{F}} \end{aligned}$$

Volumes

$$(V_{Na})_{noz} = 2.33 \text{ ft}^3$$

$$(V_{metal})_{noz} = 0.590 \text{ ft}^3$$

$$(V_{Na})_{plenum} = 36.5 \text{ ft}^3$$

Computations are shown on the figure.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{pV}\right)_{\text{Na plenum}} = \frac{1}{(54.1)(36.5)} = 0.005064 \text{ lbm}^{-1}$$

$$\left[\frac{UA}{(pVC)_{\text{Na}}}\right] = \frac{0.2742}{(478)(1.590)(.136)} = 0.007149 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(pVC)_{\text{Na}}}\right] = \frac{0.2742}{(54.1)(2.33)(.308)} = 0.007063 \text{ sec}^{-1}$$

$$\left(\frac{1}{pV}\right)_{\text{Na NO}_2} = \frac{1}{(54.1)(2.33)} = 0.007933 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{198} = - (0.004485) T_{198} + (0.004485) T_{199}$$

$$\begin{aligned} \dot{T}_{199} = & - (0.008520) T_{199} + (0.008520) T_{198} \\ & + (0.007743) \dot{\omega} T_{218} - (0.007743) \dot{\omega} T_{199} \end{aligned}$$

$$\dot{T}_{200} = (0.0003470) \dot{\omega} T_{199} - (0.0003470) \dot{\omega} T_{200}$$

$$\dot{T}_{201} = (0.0005064) \dot{\omega} T_{243} - (0.0003470) \dot{\omega} T_{200}$$

$$\begin{aligned} \dot{T}_{202} = & (0.007063) T_{202} + (0.007063) T_{203} \\ & + (0.007933) \dot{\omega} T_{201} - (0.007933) \dot{\omega} T_{202} \end{aligned}$$

$$\dot{T}_{203} = - (0.007149) T_{203} + (0.007149) T_{202}$$

$$\dot{\omega} = \text{sodium flow per module} = \dot{\omega}_{76}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

III Water/Steam Inlet AND Outlet Regions

Energy balances for the additional heat exchange between the inlet water and outlet water/steam mixture in the region above the sodium level:

The pressure tube wall is assumed to be an adiabatic boundary.

$$-(UA)'_3 [T_{ANN} - T_{BT}] + \dot{W}_{ANN} h_{ANN,IN} = \dot{W}_{ANN} h_{ANN} + \frac{d}{dt} (PVU)_{ANN}$$

$$(UA)'_3 [T_{ANN} - T_{BT}] - (UA)'_4 [T_{BT} - T_{DC}] = (PVC)_{BT} \frac{dT_{BT}}{dt}$$

$$(UA)'_4 [T_{BT} - T_{DC}] + (\dot{W}P)_{DC,IN} T_{DC} = (\dot{W}P)_{DC} T_{DC} + (PVC_P)_{DC} \frac{dT_{DC}}{dt}$$

Recalling the assumptions made in I. Main Heat Transfer Region, and rearranging into standard format

$$\dot{h}_{ANN} = - \left[\frac{(UA)'_3}{(PV)_{ANN}} \right] T_{ANN} + \left[\frac{(UA)'_3}{(PV)_A} \right] T_{BT} + \left(\frac{\dot{W}}{PV} \right)_A h_{ANN,IN} - \left(\frac{\dot{W}}{PV}_A \right) h_{ANN}$$

$$\dot{T}_{BT} = - \left[\frac{(UA)'_3}{(PVC)_{BT}} + \frac{(UA)'_4}{(PVC)_{BT}} \right] T_{BT} + \left[\frac{(UA)'_3}{(PVC)_{BT}} \right] T_{ANN} + \left[\frac{(UA)'_4}{(PVC)_{BT}} \right] T_{DC}$$

$$\dot{T}_{DC} = - \left[\frac{(UA)'_4}{(PVC_P)_{DC}} \right] T_{DC} + \left[\frac{(UA)'_4}{(PVC_P)_{DC}} \right] T_{BT} + \left(\frac{\dot{W}}{PV} \right)_{DC} \frac{T_{DC,IN}}{IN} - \left(\frac{\dot{W}}{PV} \right)_{DC} T_{DC}$$

In addition, a curve fit of T_{ANN} vs h_{ANN} at a given pressure connects the h_{ANN} node with the corresponding T_{ANN} node.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Energy balances for the inlet and outlet plenums:
The regions are assumed to be bounded by adiabatic walls.

$$(WCp)_w T_{w_{IN}} = (wc_p)_w T_w + (pVCp)_w \frac{dT_w}{dt}$$

$$W_{w/stm} h_{w/stm} = W_{w/stm} h_{w/stm} + \frac{d}{dt}(pVu)_{w/stm}$$

Noting the assumptions made above concerning the water/steam enthalpy and internal energy, and then rearranging the equations into standard format.

$$\dot{T}_w = \left(\frac{w}{pV}\right)_w T_{w_{IN}} - \left(\frac{w}{pV}\right)_w T_w$$

$$\dot{h}_{w/stm} = \left(\frac{w}{pV}\right)_{w/stm} h_{w/stm_{in}} - \left(\frac{w}{pV}\right)_{w/stm} h_{w/stm}$$

The temperature corresponding to $h_{w/stm}$ is obtained from a curve fit $T_{w/stm}$ vs $h_{w/stm}$ for a given pressure.

Energy balance for the inlet nozzle

$$-(UA)[T_{Noz} - T_w] = (pVC)_{Noz} \frac{dT_{Noz}}{dt}$$

$$(UA)[T_{Noz} - T_w] + (wc_p)_w T_{w_{IN}} = (WCp)_w T_w + (pVCp)_w \frac{dT_w}{dt}$$

in standard format

$$\dot{T}_{Noz} = -\left[\frac{(UA)}{(pVC)_{Noz}}\right] T_{Noz} + \left[\frac{(UA)}{(pVC)_{Noz}}\right] T_w$$

$$\dot{T}_w = -\left[\frac{(UA)}{(pVCp)_{Noz}}\right] T_w + \left[\frac{(UA)}{(pVCp)_{Noz}}\right] T_{Noz} + \left(\frac{w}{pV}\right)_w T_{w_{IN}} - \left(\frac{w}{pV}\right)_w T_w$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

and the energy balance for the outlet nozzle

$$-(UA)[T_{noz} - T_{w/stm}] = (pvc)_{noz} \frac{dT_{noz}}{dt}$$

$$(UA)[T_{noz} - T_{w/stm}] + w_{w/stm} h_{w/stm} = w_{w/stm} h_{w/stm} + \frac{d}{dt}(pVu)_{w/stm}$$

Applying the same assumptions as above, and rearranging the equations into standard format

$$\dot{T}_{noz} = -\left[\frac{(UA)}{(pvc)_{noz}}\right] T_{noz} + \left[\frac{(UA)}{(pvc)_{noz}}\right] T_{w/stm}$$

$$\dot{h}_{w/stm} = -\left[\frac{(UA)}{(pV)_{w/stm}}\right] T_{w/stm} + \left[\frac{(UA)}{(pV)_{w/stm}}\right] T_{noz} + \left(\frac{w}{pV}\right)_{w/stm} h_{w/stm} - \left(\frac{w}{pV}\right)_{w/stm} h_{w/stm}$$

$T_{w/stm}$ and $h_{w/stm}$ are connected by a temperature-enthalpy curve fit at a given pressure.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

WATER INLET REGION

$$W_S = 1,390,473 \text{ lbm/hr} = 386.2425 \text{ lbm/sec (design)}$$

Properties are evaluated at pressure and temperature for full load.

$$p = 2663 \text{ psia}, T = 634.5^\circ\text{F} \rightarrow k_w = 0.262 \frac{\text{Btu}}{\text{in-ft}^2\text{ }^\circ\text{F}}, k_{\text{noz}} = 16.3 \frac{\text{Btu}}{\text{in-ft}^2\text{ }^\circ\text{F}}$$

$$\rho_w = 40.32 \frac{\text{lbm}}{\text{ft}^3}, \rho_{\text{noz}} = 482 \frac{\text{lbm}}{\text{ft}^3}$$

$$c_{p_w} = 1.84 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}, c_{\text{noz}} = 0.133 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}$$

$$\mu_s = 0.192 \frac{\text{lbm}}{\text{in}^\circ\text{F}}$$

Heat Transfer coefficient

$$1) G_w = \frac{W}{A} = \frac{1,390,473}{\frac{\pi}{4} (11\frac{1}{4}/12)^2} = 2.014 \times 10^6 \frac{\text{lbm}}{\text{in}^2\text{ }^\circ\text{F}}$$

$$V_w = \frac{G_w}{\rho_w} = \frac{2.014 \times 10^6 / 3600}{40.32} = 13.88 \text{ ft/sec}$$

$$Re_w = \frac{G_w D_c}{\mu_w} = \frac{(2.014 \times 10^6) (11\frac{1}{4}/12)}{0.192} = 9.836 \times 10^6$$

$$Pr_w = \frac{\mu_w c_p}{k_w} = \frac{0.192 (1.84)}{0.262} = 1.35$$

$$h_w = \frac{k_w}{D} [0.023 Re_w^{0.8} Pr_w^{0.4}] = \frac{0.262}{11\frac{1}{4}/12} [0.023 (9.836 \times 10^6)^{0.8} (1.35)^{0.4}]$$

$$= 2847 \frac{\text{Btu}}{\text{in-ft}^2\text{ }^\circ\text{F}} = 0.7909 \frac{\text{Btu}}{\text{sec ft}^2\text{ }^\circ\text{F}}$$

Entrance effects on the heat transfer coefficient are neglected.

2) The average diameter for the nozzle is computed at the thickest section.

RECIRC. Inlet PLENUM

$$V_{H_2O} = \frac{\pi}{4} (47)^2 24 + \frac{\pi}{4} (11\frac{1}{4})^2 (4\frac{3}{4}) = 42100 \text{ m}^3 = 24.4 \text{ ft}^3$$

COMBUSTION ENGINEERING
NUCLEAR POWER DEPARTMENT

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{13\frac{1}{4}^2 + 25\frac{3}{4}^2}{2} \right)^{1/2} = 20.48''$$

Assume a $\frac{1}{4}''$ thermal liner ($2\frac{1}{4}''$ O.D. - I.H.O.) and a $\frac{1}{2}''$ stagnant water gap between the flowing water and the nozzle for the entire length of the inlet nozzle. In addition, the resistance of the thickest section of the nozzle is assumed to characterize the nozzle for its entire length.

$$\begin{aligned} UA &= \frac{2\pi L}{\frac{2}{h_w D_{i,w}} + \frac{\ln(D_o/D_i)_{liner}}{k_{liner}} + \frac{\ln(D_o/D_i)_{gap}}{k_{gap}} + \frac{\ln(\bar{D}/D_i)}{k_{noz}}} \\ &= \frac{2\pi (22/12)}{\frac{2}{(847) \frac{11/4}{12}} + \frac{\ln(25\frac{3}{4}/13\frac{1}{4})}{16.3} + \frac{\ln(13\frac{1}{4}/12\frac{1}{4})}{.262} + \frac{\ln(20.48/13\frac{1}{4})}{16.3}} \\ &= 34.68 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2} = 0.009632 \frac{\text{Btu}}{\text{sec} \cdot \text{ft}^2} \end{aligned}$$

Volumes

$$(V_w)_{Noz} = 1.32 \text{ ft}^3$$

$$(V_{metal})_{noz} = 3.29 \text{ ft}^3$$

$$(V_w)_{plenum} = 24.4 \text{ ft}^3$$

Computations are shown on the figures.

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Coefficients

$$\left(\frac{1}{pV}\right)_{\omega} = \frac{1}{(40.32)(24.4)} = 0.001016 \text{ lbm}^{-1}$$

$$\left[\frac{2A}{(pV)_{\omega}}\right] = \frac{.009632}{(442)(3.79)(.133)} = 0.00004567 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(pV)_{\omega}}\right] = \frac{0.009632}{(40.32)(1.32)(1.89)} = 0.00009836 \text{ sec}^{-1}$$

$$\left(\frac{1}{pV}\right)_{\omega} = \frac{1}{(40.32)(1.32)} = 0.01879 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

STEAM/WATER OUTLET REGION

$$W_s = 1390473 \text{ lbm/hr} = 386.2425 \text{ lbm/sec (design)}$$

Properties are evaluated at pressure and temperature for full load,

$$P_{sat} = 2645 \text{ psia} \Rightarrow T_{sat} = 676.5^\circ \text{F}$$

$$k_f = 0.217 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ \text{F}}; k_g = 0.0536 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ \text{F}}; k_{H_2O} = 16.3 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ \text{F}}$$

$$\rho_f = 33.62 \frac{\text{lbm}}{\text{ft}^3}; \rho_g = 8.545 \frac{\text{lbm}}{\text{ft}^3}; \rho_{H_2O} = 481 \frac{\text{lbm}}{\text{ft}^3}$$

$$C_{p_f} = 3.09 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}}; C_{p_g} = 4.40 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}}; C_{H_2O} = 0.136 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ \text{F}}$$

$$\mu_f = 0.178 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}}; \mu_g = 0.0527 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}}$$

Heat Transfer coefficient

1) The steam/water mixture flows in the nozzle generally under adiabatic conditions. The heat transfer coefficient, under these conditions, represents the potential to transfer heat if temperatures changed. Since boiling is not occurring in the nozzle under design conditions, this heat transfer potential is assumed to be characterized by an annular flow pattern, and the coefficient computed assuming the liquid phase flows alone.

This computation may be very inaccurate, but its effects on the overall heat transfer coefficient between the fluid and the nozzle will be small since the nozzle resistance is the dominant component.

$$G_L = \frac{W}{A} (1-x) = \frac{1390473}{\frac{\pi}{4} (13/4/12)^2} (1-0.286) = 1.037 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \cdot \text{hr}}$$

SATURATED STEAM/WATER OUTLET NOZZLE

$$V_{\text{STM/H}_2\text{O}} = \frac{\pi}{4} (13\frac{1}{4})^2 (19\frac{1}{2}) = 2690 \text{ m}^3 = 1.56 \text{ ft}^3$$

$$V_{\text{NOZ}} = \frac{\pi}{4} (25\frac{3}{4})^2 (11) + \left\{ \frac{\pi(5)}{12} (25\frac{3}{4})^2 (16) + \frac{\pi}{4} (13\frac{1}{4})^2 (5) \right\} + \frac{\pi}{4} (16^2 - 13\frac{1}{4}^2) 3\frac{1}{2} = 5490 \text{ m}^3 = 3.17 \text{ ft}^3$$

SATURATED STEAM/WATER OUTLET PLENUM

$$\begin{aligned}
 V_{\text{STM/H}_2\text{O}} &= \frac{\pi}{4} (56\frac{1}{4})^2 48 + \frac{\pi}{4} (56\frac{1}{4}^2 - 48\frac{1}{4}^2) (30) - \left\{ \frac{\pi}{4} (16\frac{1}{2}^2 - 14\frac{3}{4}^2) (8 + \frac{\pi}{4} (16) + 12\frac{1}{4}) \right\} \\
 &\quad - \left\{ \text{Estimate of additional} \right\} \\
 &\quad \left\{ \text{clears in plenum} \right\} \\
 &= 135000 \text{ in}^3 = 78.2 \text{ ft}^3
 \end{aligned}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$Re_L = \frac{G_L D}{\mu_L} = \frac{(1.037 \times 10^6) (13 \frac{3}{4})}{.178} = 6.432 \times 10^6$$

$$Pr_L = \frac{\mu_L C_p}{k_L} = \frac{.178 (3.09)}{.217} = 2.53$$

$$h_L = \frac{k_L}{D} [0.23 Re_L^{.8} Pr_L^{.4}] = \frac{.217}{13 \frac{3}{4} / 12} [0.23 (6.432 \times 10^6)^{.8} (2.53)^{.4}]$$

$$= 1833 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{F}} = 0.5090 \frac{\text{Btu}}{\text{sec} \cdot \text{ft}^2 \cdot \text{F}}$$

2) The average diameter for the nozzle is computed at the thickest section.

$$\bar{D} = \left(\frac{D_1^2 + D_2^2}{2} \right)^{1/2} = \left(\frac{13 \frac{3}{4}^2 + 25 \frac{3}{4}^2}{2} \right)^{1/2} = 20.48''$$

The thermal resistance of the thickest section of the nozzle is assumed to characterize the nozzle for its entire length.

$$UA = \frac{2 \pi L}{\frac{2}{h_{\infty} D_1} + \frac{\ln(\bar{D}/D_1)}{k_{\text{nozzle}}}}$$

$$= \frac{2 \pi (19.5/12)}{\frac{2}{1833 (13 \frac{3}{4} / 12)} + \frac{\ln(20.48/13 \frac{3}{4})}{16.3}}$$

$$= 368.6 \frac{\text{Btu}}{\text{hr} \cdot \text{F}} = 0.1024 \frac{\text{Btu}}{\text{sec} \cdot \text{F}}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Volumes

$$(V_w)_{noz} = 1.56 \text{ ft}^3$$

$$(V_{metal})_{noz} = 3.17 \text{ ft}^3$$

$$(V_w)_{plenum} = 78.2 \text{ ft}^3$$

Computations are shown on the Figures.

Average Density of steam/water mixture

$$\begin{aligned} \bar{\rho} &= \frac{1}{\bar{v}} = \frac{1}{(1-x)v_g + xv_f} = \frac{\rho_g \rho_f}{(1-x)\rho_g + x\rho_f} \\ &= \frac{(33.62)(8.545)}{(0.714)(8.545) + (0.286)(33.62)} = 18.28 \text{ lbm/ft}^3 \end{aligned}$$

Coefficients

$$\left(\frac{1}{\rho V}\right)_{\text{steam/plenum}} = \frac{1}{18.28(78.2)} = 0.0006995 \text{ lbm}^{-1}$$

$$\left[\frac{2A}{(\rho V C)_{noz}}\right] = \frac{0.1024}{(481)(3.17)(.136)} = 0.0004938 \text{ sec}^{-1}$$

$$\left[\frac{2A}{(\rho V)_{w/stm}}\right] = \frac{.1024}{18.28(1.56)} = 0.003591 \frac{\text{Btu/lbm}}{\text{sec}^2 \text{ ft}}$$

$$\left(\frac{1}{\rho V}\right)_{w/stm, noz} = \frac{1}{(18.28)(1.56)} = 0.03507 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

ADDITIONAL HEAT EXCHANGE REGION

$$W_s = 3659.14 \frac{\text{lbm/hr}}{\text{tube}} = 1.016 \frac{\text{lbm/sec}}{\text{tube}} \quad (\text{design})$$

Properties are evaluated at pressure and temperature for full load.

$$P_{\text{sat}} = 2645 \text{ psia} \Rightarrow T_{\text{sat}} = 676.5^\circ\text{F}$$

$$p = 2663 \text{ psia} / T = 634.5^\circ\text{F}$$

$$k_f = 0.217; \quad k_g = 0.536; \quad k_w = 0.262; \quad k_T = 15.6; \quad \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}}$$

$$\rho_f = 33.62; \quad \rho_g = 8.545; \quad \rho_w = 40.32; \quad \rho_T = 480; \quad \frac{\text{lbm/ft}^3}$$

$$C_{p_f} = 3.09; \quad C_{p_g} = 4.40; \quad C_{p_w} = 1.84; \quad C_T = 0.138; \quad \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}$$

$$M_f = 0.178; \quad M_g = 0.0527; \quad M_w = 0.192$$

Heat Transfer Coefficients - Thermal Resistances

1) For 17" (24%) of the additional heat transfer length the outlet steam/water mixture flows obliquely about the bayonet tube assembly (typical heat exchanger shellside flow pattern). For the remaining 54 1/8" the mixture flows in the annuli defined by the pressure tubes and the bayonet tube assemblies. For purposes of calculating a representative heat transfer coefficient the latter flow pattern is assumed for the entire length.

Inaccuracies due to this assumption or assumption made in the actual calculation will have little effect since the thermal resistance of the bayonet tube assembly insulation gap is dominant.

The steam/water mixture is being cooled by the inlet water; consequently condensation is occurring. A lower limit to either boiling or condensing heat transfer coefficients would be calculated if it is assumed

ADDITIONAL HEAT EXCHANGE LENGTH

$$L = 17 + 12\frac{5}{8} + 42 = 71\frac{5}{8}''$$

$$\begin{aligned} d_1 &= 0.501'' ; & d_3 &= 0.701'' ; & d_5 &= 1.156'' \\ d_2 &= 0.581'' ; & d_4 &= 0.781'' ; & d_6 &= 1.500'' \end{aligned}$$

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that the liquid alone flowed.

$$G_L = \frac{W_L}{A} (1-x) = \frac{3659.14}{\frac{\pi (1.156^2 - .761^2)}{4}} (1-.286) = 6.595 \times 10^5$$

$$Re_L = \frac{G_L D}{\mu_L} = \frac{(6.595 \times 10^5) (\frac{1.156 - .761}{12})}{.178} = 1.158 \times 10^5$$

$$Pr_L = \frac{\mu_L c_{pL}}{k_L} = \frac{.178 (3.09)}{.217} = 2.53$$

$$h_L = \frac{k_L}{D_e} [0.23 Re_L^{.8} Pr_L^{.4}] = \frac{.217}{.375/12} [0.23 (1.158 \times 10^5)^{.8} (2.53)^{.4}]$$

$$= 2603 \frac{\text{Btu}}{\text{hr-ft}^2 \text{ } ^\circ\text{F}} = 0.7231 \frac{\text{Btu}}{\text{sec-ft}^2 \text{ } ^\circ\text{F}}$$

$$R_L = \frac{1}{\pi d_4 L h_L} = \frac{1}{\pi (\frac{.781}{12}) (\frac{71.34}{12}) (2603)} = 0.0003148 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

2) Outer Bayonet Tube

$$R_{to} = \frac{\ln(d_4/d_3)}{2\pi k L} = \frac{\ln(.781/.701)}{2\pi (15.6) (\frac{71.34}{12})} = 0.0001847 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

3) Insulation Gap Resistance

$$R_{gap} = \frac{\ln(d_3/d_2)}{2\pi k L} = \frac{\ln(.701/.581)}{2\pi (1.64) (\frac{71.34}{12})} = 0.007823 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

4) Inner Bayonet tube

$$R_{ri} = \frac{\ln(d_2/d_1)}{2\pi k L} = \frac{\ln(.581/.501)}{2\pi (15.6) (\frac{71.34}{12})} = 0.0002532 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

5) Water

$$G_w = \frac{W_w}{A} = \frac{3659.14}{\frac{\pi (1.501^2 - 1.12^2)}{4}} = 2.673 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}$$

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$$V_w = \frac{G_w}{\rho_w} = \frac{2.673 \times 10^6 / 3600}{40.32} = 18.41 \text{ ft}^3/\text{sec}$$

$$Re_w = \frac{G_w D}{\mu_w} = \frac{(2.673 \times 10^6) (\frac{1.301}{12})}{.192} = 5.812 \times 10^5$$

$$Pr_w = \frac{\mu_w C_p}{k_w} = \frac{.192 (184)}{.262} = 1.35$$

$$h_w = \frac{k_w}{D} [0.023 Re_w^{.8} Pr_w^{.4}] = \frac{.262}{.301/12} [0.023 (5.812 \times 10^5)^{.8} (1.35)^{.4}]$$

$$= 6652 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}} = 1.848 \frac{\text{Btu}}{\text{sec-ft}^2\text{-}^\circ\text{F}}$$

$$R_w = \frac{1}{\pi d_y L h_w} = \frac{1}{\pi (\frac{.78}{12}) (\frac{71.56}{12}) 6652} = .0001232 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

$$(UA)_3' = (R_L + R_{B_6} + \frac{R_{B_7}}{2})^{-1} = (.0003148 + .0001847 + \frac{.007873}{2})^{-1}$$

$$= 226.7 \frac{\text{Btu}}{\text{hr-}^\circ\text{F}} = 0.06298 \frac{\text{Btu}}{\text{sec-}^\circ\text{F}}$$

$$(UA)_4' = (\frac{R_{B_7}}{2} + R_{B_8} + R_w)^{-1} = (\frac{.007873}{2} + .0002532 + .0001232)^{-1}$$

$$= 233.2 \frac{\text{Btu}}{\text{hr-}^\circ\text{F}} = 0.06478 \frac{\text{Btu}}{\text{sec-}^\circ\text{F}}$$

Volumes

$$V_{mx} = \frac{\pi}{4} (d_5^2 - d_4^2) L = \frac{\pi}{4} \frac{(1.156^2 - .781^2)}{144} \frac{71.56}{12} = 0.02365 \text{ ft}^3$$

$$V_{BT} = \frac{\pi}{4} [(d_4^2 - d_3^2) + (d_2^2 - d_1^2)] L = \frac{\pi}{4} \left[\frac{(.781^2 - .701^2)}{144} + \frac{(.581^2 - .501^2)}{12} \right] \frac{71.56}{12}$$

$$= .006678 \text{ ft}^3$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$V_w = \frac{\pi}{4} d^2 L = \frac{\pi}{4} \left(\frac{.501}{12} \right)^2 \frac{71.5}{12} = 0.008171 \text{ ft}^3$$

Average density for mixture

$$\bar{\rho} = \frac{P_g P_s}{(1-x)P_g + xP_s} = \frac{33.62(8.545)}{.719(8.545) + .286(33.62)} = 18.28 \frac{\text{lbm}}{\text{ft}^3}$$

Coefficients

$$\left[\frac{(UA)'_s}{(PVC)_{\text{ann}}} \right] = \frac{.06298}{(18.28)(.07365)} = 0.1457 \frac{\text{Btu/lbm}}{\text{sec}^\circ\text{F}}$$

$$\left(\frac{1}{PVC} \right)_{\text{ann}} = \frac{1}{(18.28)(.07365)} = 2.313 \text{ lbm}^{-1}$$

$$\left[\frac{(UA)'_s}{(PVC)_{\text{br}}} \right] = \frac{.06298}{480(.006678)(.138)} = 0.1427 \text{ sec}^{-1}$$

$$\left[\frac{(UA)'_f}{(PVC)_{\text{br}}} \right] = \frac{0.06478}{480(.006678)(.138)} = 0.1464 \text{ sec}^{-1}$$

$$\left[\frac{(UA)'_w}{(PVC)_w} \right] = \frac{.06478}{(40.32)(.008171)(1.84)} = 0.1069 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_w = \frac{1}{(40.32)(.008171)} = 3.035 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{204} = -(0.0004938) T_{204} + (0.0004938) T_{383}$$

$$\dot{h}_{205} = -(0.003591) T_{383} + (0.003591) T_{204} + (0.03507) \dot{w}_w h_{206} - (0.03507) \dot{w}_w h_{205}$$

$$\dot{h}_{206} = (0.0006995) \dot{w}_w h_{207} - (0.0006995) \dot{w}_w h_{206}$$

$$\dot{w}_w = \text{Total water flow per module} = \dot{w}_{83}$$

$$\dot{h}_{207} = -(0.1457) T_{385} + (0.1457) T_{208} + (2.313) \dot{w}_w h_{209} - (2.313) \dot{w}_w h_{207}$$

$$\dot{T}_{208} = -(0.2888) T_{208} + (0.1424) T_{385} + (0.1464) T_{209}$$

$$\dot{T}_{209} = -(0.1069) T_{209} + (0.1069) T_{208} + (3.035) \dot{w}_w T_{210} - (3.035) \dot{w}_w T_{209}$$

$$\dot{w}_w = \text{total water flow per tube} = \dot{w}_{84}$$

$$\dot{T}_{210} = (0.001016) \dot{w}_w T_{211} - (0.001016) \dot{w}_w T_{210}$$

$$\dot{T}_{211} = -(0.00009836) T_{211} + (0.00009836) T_{212} + (0.01879) \dot{w}_w T_{343} - (0.01879) \dot{w}_w T_{211}$$

$$\dot{T}_{212} = -(0.00004567) T_{212} + (0.00004567) T_{211}$$

$$\dot{w}_w = \text{total water flow per module} = \dot{w}_{83}$$

COMBUSTION ENGINEERING

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The nodes representing the temperature of the steam/water mixture in the last annuli node and the evaporator outlet region are connected to the corresponding enthalpy nodes by "flow equations". These equations can be used as appropriate curve fits, i.e. a polynomial in h or a function of time.

In general

$$k = \epsilon_1 \quad ; \quad Z = \bar{T}_{1k1} = \text{nodal value}$$

1) $k < 0$

$$\dot{w} = \epsilon_2 Z + \epsilon_3 Z^2 + \frac{\epsilon_4}{Z} + \frac{\epsilon_5}{Z^2} + \epsilon_6 + \epsilon_7 Z^3 + \epsilon_8 Z^4 + \epsilon_9 Z^5 + \epsilon_{10} Z^6$$

2) $k \geq 0$

$$H = \begin{cases} 0 & k=0 \\ Z & k>0 \end{cases} \quad ; \quad R = \begin{cases} 0, & t \leq 0 \\ \epsilon_3 t + \epsilon_4 t^2, & t > 0 \end{cases}$$

a) $\epsilon_{10} = 0$

$$\dot{w} = H + R + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t + \epsilon_7 t^2)$$

b) $\epsilon_{10} > 0$

$$\dot{w} = \begin{cases} H + \epsilon_{10}, & t_m \leq 0 \\ H + R(t_m^*) + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t_m + \epsilon_7 t_m^2), & t_m > 0 \end{cases}$$

$$t_m = t - (t_s + \epsilon_6) \quad ; \quad t_m^* = \epsilon_9 - t_m$$

The outlet nodes will be at saturated conditions for most of the considered transients. Consequently the temperature nodes depend directly on the pressure. If the pressure is prescribed

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

For the particular transient, the associated saturation temperature is determined. Curve fits in the form of 2(a) or 2(b) would be used. If superheated steam exists in the outlet region, a polynomial curve fit for enthalpy - temperature at a given pressure must be used. Curve fit in the form of (1) above would be employed.

For normal transients the pressure will be very near the 100% load operating level and the corresponding saturation temperature is approximately 676.5°F . One of three forms may be used

a) $E_1 = -(\text{connecting node number, } 205, 206, \text{ or } 207)$

$E_6 = 676.5$ all other E 's = 0

b) $E_1 = -369$

all E 's = 0 except one $E = 676.5$

* c) $E_1 = 0$

$E_2 = 676.5$, all other E 's = 0

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$T_{383} = \dot{w}_{54} F_{369} \quad \text{,} \quad \epsilon_1 = -205, -369, \text{ or } 0.$$

$$T_{384} = \dot{w}_{55} F_{369} \quad \text{,} \quad \epsilon_1 = -206, -369, \text{ or } 0.$$

$$T_{385} = \dot{w}_{56} F_{369} \quad \text{,} \quad \epsilon_1 = -207, -369, \text{ or } 0.$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Sodium Piping: SH $\rightarrow$ EV

Energy balance for pipe and sodium nodes

$$-(UA)(T_p - T_{Na}) = (SVC)_p \frac{dT_p}{dt}$$

$$(UA)(T_p - T_{Na}) + (WC_p)_{Na} T_{Na,IN} = (WC_p)_{Na} T_{Na} + (PVC)_{Na} \frac{dT_{Na}}{dt}$$

In standard format

$$\dot{T}_p = - \left[\frac{UA}{(PVC)_p} \right] T_p + \left[\frac{UA}{(PVC)_p} \right] T_{Na}$$

$$\dot{T}_{Na} = - \left[\frac{UA}{(PVC)_{Na}} \right] T_{Na} + \left[\frac{UA}{(PVC)_{Na}} \right] T_p + \left(\frac{W}{PV} \right)_{Na,IN} T_{Na,IN} - \left(\frac{W}{PV} \right)_{Na} T_{Na}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

2 12" standard pipes (24 G-1M₀)

$$D_i = 12.0", \quad D_o = 12.75", \quad L_{dev} = 45.6'$$

$$W_{Na} = 4.353 \times 10^6 / 2 = 2.177 \times 10^6 \text{ lbm/hr} = 604.6 \text{ lbm/sec}$$

Properties are evaluated at temperature for full load.

$$T = 866^\circ F \Rightarrow \begin{aligned} k_{Na} &= 39.6 \frac{\text{Btu}}{\text{hr-ft}^\circ F} & k_p &= 16.3 \frac{\text{Btu}}{\text{hr-ft}^\circ F} \\ \rho_{Na} &= 52.5 \text{ lbm/ft}^3 & \rho_p &= 479 \text{ lbm/ft}^3 \\ C_{pNa} &= 0.303 \frac{\text{Btu}}{\text{lbm}^\circ F} & C_p &= 0.151 \frac{\text{Btu}}{\text{lbm}^\circ F} \\ \mu_{Na} &= 0.605 \text{ lbm/ft-hr} \end{aligned}$$

Three modal sets.

Heat transfer coefficients

$$1) \quad G_{Na} = \frac{W_{Na}}{A} = \frac{2.177 \times 10^6}{\frac{\pi}{4} (1)^2} = 2.771 \times 10^6 \frac{\text{lbm}}{\text{hr-ft}^2}$$

$$V_{Na} = \frac{G}{\rho} = \frac{(2.771 \times 10^6) / 3600}{52.5} = 14.67 \text{ ft/sec}$$

$$Re = \frac{G D_i}{\mu} = \frac{(2.771 \times 10^6) (1)}{0.605} = 4.581 \times 10^6$$

$$Pe = Re \frac{\mu C_p}{k} = (4.581 \times 10^6) \frac{0.605 (0.303)}{39.6} = 21204$$

$$\begin{aligned} h_{Na} &= \frac{k_{Na}}{D_i} \left[5.0 + 0.025 Pe^{0.8} \right] = \frac{39.6}{(1)} \left[5.0 + 0.025 (21204)^{0.8} \right] \\ &= 3061 \frac{\text{Btu}}{\text{hr-ft}^2^\circ F} = 0.8502 \frac{\text{Btu}}{\text{sec-ft}^2^\circ F} \end{aligned}$$

$$2) \quad \bar{D} = \left(\frac{D_o^2 + D_i^2}{2} \right)^{1/2} = \left(\frac{12.75^2 + 12^2}{2} \right)^{1/2} = 12.38"$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$UA = \frac{2\pi L_n}{\frac{2}{h_{wi} D_i} + \frac{\ln(D_o/D_i)}{k_p}} = \frac{2\pi(45.6/3)}{\frac{2}{.85(1)} + \frac{\ln(1238/12)}{16.3/3600}}$$

$$= 10.34 \frac{Btu}{sec \cdot ^\circ F} \text{ per pipe}$$

Volumes

$$V_p = \frac{\pi}{4} (D_o^2 - D_i^2) L_n = \frac{\pi}{4} \frac{(12.75^2 - 12^2)}{144} \frac{45.6}{3} = 1.539 \text{ Ft}^3 \text{ per pipe}$$

$$V_N = \frac{\pi}{4} D_i^2 L_n = \frac{\pi}{4} (1)^2 \frac{45.6}{3} = 11.94 \text{ ft}^3 \text{ per pipe}$$

Coefficients:

$$\left[\frac{UA}{(PV)_p} \right] = \frac{2(10.34)}{(479.2)(1.539)(.151)} = 0.09289 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_{Na}} \right] = \frac{2(10.34)}{52.5[2(11.94)](.303)} = 0.05444 \text{ sec}^{-1}$$

$$\left(\frac{1}{PV} \right)_{Na} = \frac{1}{52.5(11.94)2} = 0.0007976 \text{ min}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{213} = -0.09289 T_{213} + 0.09289 T_{214}$$

$$\dot{T}_{214} = -0.05444 T_{214} + 0.05444 T_{213} + 0.0007976 \dot{\omega} T_{184} - 0.0007976 \dot{\omega} T_{214}$$

$$\dot{T}_{215} = -0.09289 T_{215} + 0.09289 T_{216}$$

$$\dot{T}_{216} = -0.05444 T_{216} + 0.05444 T_{215} + 0.0007976 \dot{\omega} T_{214} - 0.0007976 \dot{\omega} T_{216}$$

$$\dot{T}_{217} = -0.09289 T_{217} + 0.09289 T_{218}$$

$$\dot{T}_{218} = -0.05444 T_{218} + 0.05444 T_{217} + 0.0007976 \dot{\omega} T_{216} - 0.0007976 \dot{\omega} T_{218}$$

$$\dot{\omega} = \text{sodium flow per module} = \dot{\omega}_{76}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Saturated Steam/Water Piping: EV $\rightarrow$ Drum

Energy balances for the pipe and steam/water nodes:

$$-(UA)(T_p - T_{w/stm}) = (PVC)_p \frac{dT_p}{dt}$$

$$(UA)(T_p - T_{w/stm}) + \dot{w}_{w/stm} h_{w/stm} = \dot{w}_p h_{w/stm} + \frac{d}{dt}(P V U)_{w/stm}$$

The following assumptions are made:

$$\frac{dp}{dt} = 0 \quad (\text{implicit, since continuity has not been included in the formulation})$$

$$\frac{dp}{dt} = 0 \Rightarrow \frac{d(\rho v)}{dt} = \frac{d}{dt}(\rho h \cdot p) = \frac{d}{dt}(\rho h)$$

The results of these assumptions are substituted into the energy balances. The equations are then rearranged into standard format.

$$\dot{T}_p = - \left[\frac{(UA)}{(PVC)_p} \right] T_p + \left[\frac{(UA)}{(PVC)_p} \right] T_{w/stm}$$

$$\dot{h}_{w/stm} = - \left[\frac{(UA)}{(P V)_{w/stm}} \right] T_{w/stm} + \left[\frac{(UA)}{(P V)_{w/stm}} \right] T_p + \left(\frac{\dot{w}}{P V} \right)_{w/stm} h_{w/stm} - \left(\frac{\dot{w}}{P V} \right)_{stm} h_{stm}$$

$T_{w/stm}$ and $h_{w/stm}$ are connected by a temperature-enthalpy curve fit for a given pressure.

Combustion Engineering, Inc.

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STEAM/WATER BOILER CIRCULATION SYSTEM FOR ONE OF THREE SECONDARY SODIUM LOOPS

Page No. 1 of 3

Contract No. 7670 Name LMFBR STEAM GENERATOR

HEADERS, PIPING AND MISC. DATA

Quantities indicated are per boiler.

NO	ITEM	NO. REQ'D.	O. D. OR INS. AS NOTED	I. D. OR THICK - INS.	A. S. M. E. SPEC.	DESIGN		NIPPLE DESIGN TEMP. °F	CONNECTIONS
						PRESS. PSIG	TEMP. °F		
1	FW CHECK VALVE	1	10 3/4		SA-				
2	FW STOP VALVE	1	10 3/4		SA-				
3	FW LINE	1	10 3/4	1 1/8 AVG	SA-106C				
4	FW LINES	2	8 5/8	15/16 AVG	SA-106C				
5	STEAM DRUM	1		60 ID	SA-299				2 TO 4 WELD 42'-0"
6	DOWNCOMERS	4	12 3/4	1 3/16 AVG	SA-106C				
7	SUCTION MANIFOLD	1	20	16 ID	SA-515-70				4-12 3/4" 3-20"
8	SUCTION MANIFOLD TO VALVE BENCH	3	20x16		SA-515-70				
9	SUCTION VALVE	3	16x16 x16		SA-				PORT DIA 11 3/4"
10	CIRCULATING PUMP	3			SA-				
11	DISCHARGE VALVE	6	12 5/16 x 12 3/4 x 12 3/4		SA-				PORT DIA 10 3/8"
12	DISCHARGE LINES	6	14	1 3/8 AVG	SA-106C				
13	DISCHARGE MANIFOLD	1	18	14.375 ID	SA-515-70				6-14" 2-18"
14	DISCHARGE LINES TO EVAPORATORS	2	18	15.875 ID	SA-515-70				
					SA-				
					SA-

Remarks

Engineer

1/6

Date 10/19/72 Rev.

Combustion Engineering Inc.

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CE 2000 (12/02)

STEAM/WATER BOILER CIRCULATION SYSTEM FOR ONE OF THREE SECONDARY SODIUM LOOPS

Page No. 20F3

Contract No. 7670 Name LMFBR STEAM GENERATOR

HEADERS, PIPING AND MISC. DATA

Quantities indicated are per boiler.

NO.	ITEM	NO. REQ'D.	O. D. INS.	I. D. OR THICK. INS.	A. S. M. E. SPEC.	DESIGN		NIPPLE DESIGN TEMP. °F	CONNECTIONS
						PRESS. PSIG	TEMP. °F		
15	EVAPORATOR INLET HDR.	1	16	12.75 ID	SA-515-70				2-18" 3-16"
16	EVAPORATOR INLET LINES	3	16	19/16 AVG	SA-106C				
17	EVAPORATOR INLET QUICK CLOSING VALVE	3			SA-				
18	EVAPORATOR	3			SA-				
19	EVAPORATOR MIXTURE OUTLET	3	16	19/16 AVG	SA-106C				
20	EVAPORATOR OUTLET QUICK CLOSING VALVE	3			SA-				
21	EVAPORATOR OUTLET DUMP LINE	3	16	19/16 AVG	SA-106C				
22	EVAPORATOR OUTLET QUICK OPENING VALVE	3			SA-				
23	EVAPORATOR OUTLET LEADS TO DRUM	3	16	19/16 AVG	SA-106C				
24	OUTLET LEAD REDUCER	3	20x16		SA-515-70				
25	MIXTURE DISTRIBUTION BOTTLE	3	20	16 TD	SA-515-70				5"-20
26	MIXTURE DISTRIBUTION LINES	60	5	0.500 HWT	SA-106B				
27	DRUM SAT STEAM OUTLET LINES	18	5	0.500 HWT	SA-106B				
28	SAT STEAM COLLECTION HDR	1	14	11.125 ID	SA-515-70				
					SA-				
					SA-

Remarks

Engineer

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Date 10/12/72 Rev.

Combustion Engineering 'nc.

ENGINEERING DEPT.

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STEAM/WATER BOILER CIRCULATION SYSTEM FOR ONE OF THREE SECONDARY SODIUM LOOPS

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Contract No. 7670 Name LMFBR STEAM GENERATOR

HEADERS, PIPING AND MISC. DATA

Quantities indicated are per boiler.

NO.	ITEM	NO. REQ'D.	O. D. INS.	I. D. OR THICK. - INS.	A. S. M. E. SPEC.	DESIGN		NIPPLE DESIGN TEMP. °F	CONNECTIONS
						PRESS PSIG	TEMP. °F		
29	SH'T'R INLET LEAD SATCHEL HANDLE	2	12 $\frac{3}{4}$	1 $\frac{1}{4}$ AVG	SA-106C				
30	SH'T'R INLET LEAD	1	16	1 $\frac{9}{16}$	SA-106C				
31	SH'T'R INLET LEAD REDUCER	1	22x16		SA-515-70				
32	SH'T'R INLET DISTRIBUTION BOTTLE	1	22	17.375 ID	SA-515-70				
33	SH'T'R INLET LINES	15	5	0.500 HWT	SA-106 B				
34	SUPERHEATER INLET	3	14	1 $\frac{5}{16}$ AVG	SA-106C				
35	SH'T'R INLET QUICK CLOSING VALVE	3			SA-				
36	SUPERHEATER	3			SA-				
37	SH'T'R OUTLET	3	14	10.25 ID	SA-387B				
38	SH'T'R OUTLET QUICK CLOSING VALVE	3			SA-				
39	SH'T'R OUTLET DUMP LINE	3	14	10.25 ID	SA-387B				
40	SH'T'R OUTLET QUICK OPENING VALVE	3			SA-				
41	SH'T'R OUTLET LEAD	3	14	10.25 ID	SA-387B				
42	SH'T'R OUTLET MANIFOLD	1	14	9.75 ID	SA-387B				
43	SH'T'R LEAD SATCHEL HANDLE	2	12 $\frac{3}{4}$	9.25 ID	SA-387B				
44	SH'T'R LEAD	1	16	11.75 ID	SA-387B				

GENERAL NOTES:

1- MATERIALS LISTED ARE SUBJECT TO FURTHER REVIEW.

Remarks _____

Engineer ap

Date

10/19/72

Rev. _____

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\begin{aligned} W_{sim/w} &= 1390473 \text{ lbm/hr Flow per ex module} \\ &= 4171419 \text{ lbm/hr Flow per loop} \end{aligned}$$

Properties are evaluated at pressure and temperature for Full Load.

$$\begin{aligned} P_{sat} &= 2645 \text{ psi} \Rightarrow T_{sat} = 676.5^\circ\text{F} \\ k_f &= 0.218 \frac{\text{BTU}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} ; k_g = 0.0536 \frac{\text{BTU}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} ; k_p = 25.5 \frac{\text{BTU}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}} \\ \rho_f &= 33.61 \frac{\text{lbm}}{\text{ft}^3} ; \rho_g = 8.545 \frac{\text{lbm}}{\text{ft}^3} ; \rho_p = 482 \frac{\text{lbm}}{\text{ft}^3} \\ C_{p_f} &= 3.09 \frac{\text{BTU}}{\text{lbm} \cdot ^\circ\text{F}} ; C_{p_g} = 4.40 \frac{\text{BTU}}{\text{lbm} \cdot ^\circ\text{F}} ; C_p = 0.137 \frac{\text{BTU}}{\text{lbm} \cdot ^\circ\text{F}} \\ \mu_f &= 0.178 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}} ; \mu_g = 0.0527 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}} \\ Pr_f &= 2.53 ; Pr_g = 4.32 \end{aligned}$$

$$\bar{\rho} = \frac{\rho_g \rho_f}{(1-x)\rho_g + x\rho_f} = \frac{33.61(8.545)}{.714(8.545) + .286(33.61)} = 18.28 \frac{\text{lbm}}{\text{ft}^3}$$

3 Nodal sets.

1) 1 set (304 - 305 & 380)

3 Evaporator Outlets - Mixture distribution bottles & Reducers

Outlet: 16" OD, 1 9/16" wall, approximately 16' long
Reducer: 16" $\rightarrow$ 20" OD, approximately 1/2' long
Bottle: 20" OD, 16" ID, approximately 8 3/4' long } assume 9' average length

$$\begin{aligned} V_{metal} &= 3 \left[\frac{\pi}{4} \frac{(16^2 - 12\frac{3}{4}^2)}{144} \right] 16 + 3 \left[\frac{\pi}{4} \frac{(20^2 - 16^2)}{144} \right] 9 \\ &= 2362 + 21.21 = 44.83 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} V_{sim/w} &= 3 \left[\frac{\pi}{4} \left(\frac{12\frac{3}{4}}{12} \right)^2 \right] 16 + 3 \left[\frac{\pi}{4} \left(\frac{16}{12} \right)^2 \right] 9 \\ &= 43.40 + 37.70 = 81.10 \text{ ft}^3 \end{aligned}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Assume that the heat transfer between the steam/water mixture and the pipe is characterized by the flow in the outlet pipes. The mixture flow is, generally, under adiabatic conditions. The heat transfer coefficient, under these circumstances, represents a potential to transfer heat. Since boiling or condensation is not occurring in the pipe under design conditions, this heat transfer potential is assumed to be characterized by a two phase annular flow pattern, and the heat transfer coefficient is computed assuming the liquid phase flows alone.

$$G_L = \frac{W_L}{A} = \frac{4171419}{3 \frac{\pi}{4} \left(\frac{12}{12}\right)^2} (1 - 0.286) = 1.098 \times 10^6 \frac{\text{lbm}}{\text{hr-ft}^2}$$

$$Re_L = \frac{G_L D}{\mu_L} = \frac{(1.098 \times 10^6) \left(\frac{12}{12}\right)}{0.178} = 6.619 \times 10^6$$

$$h_L = \frac{k_L}{D} [0.023 Re_L^{0.8} Pr_L^{0.4}] = \frac{0.215}{12/12} [0.023 (6.619 \times 10^6)^{0.8} (2.53)^{0.4}]$$

$$= 1938 \frac{\text{Btu}}{\text{hr-ft}^2 \cdot ^\circ\text{F}}$$

The average diameters of the pipe sections

$$D_o = \left(\frac{D_o^2 + D_i^2}{2}\right)^{1/2} = \left(\frac{12^2 + 16^2}{2}\right)^{1/2} = 14.52"$$

$$D_H = \left(\frac{86^2 + 10^2}{2}\right)^{1/2} = 18.11"$$

The overall heat transfer coefficient is the sum of the coefficients in the two pipe sections.

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\begin{aligned}
 UA &= \frac{2\pi L_0}{\frac{2}{h D_i} + \frac{\ln(D/D)}{k_r}} + \frac{2\pi L_4}{\frac{2}{h D_i} + \frac{\ln(D/D_4)}{k_r}} \\
 &= \frac{2\pi [3(16)]}{\frac{2}{1938(1274/16)} + \frac{\ln(14.8/1274)}{25.5}} + \frac{2\pi [3(9)]}{\frac{2}{1938(1912)} + \frac{\ln(18.11/16)}{25.5}} \\
 &= 83247 \frac{Btu}{hr \cdot ^\circ F} = 23.12 \frac{Btu}{sec \cdot ^\circ F}
 \end{aligned}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{23.12}{(482)(4483)(.137)} = 1007810 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_{s/w}} \right] = \frac{23.12}{(18.28)(81.10)} = 0.01560 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_{s/w} = \frac{1}{(18.28)(81.10)} = 0.0006745 \text{ lbm}^{-1}$$

2) 2 sets (306-307 & 381 and 308-309 & 382)

3 sets of 20 outlet leads to the separation drum. Each lead has a 5" OD, 1/2" wall, and a typical length of 56' is assumed.

$$V_{\text{metal}} = 3 \left\{ 20 \left[\frac{\pi (5^2 - 4^2)}{4} \right] 28 \right\} = 82.47 \text{ ft}^3$$

$$V_{\text{steam}} = 3 \left\{ 20 \left[\frac{\pi (5^2)}{4} \right] 28 \right\} = 146.6 \text{ ft}^3$$

The heat transfer coefficient for the mixture is computed

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

based on the model described above.

$$G_L = \frac{W_L}{A} = \frac{4171419 (1 - 0.386)}{60 \frac{\pi}{4} \left(\frac{4}{12}\right)^2} = 5.688 \times 10^5 \frac{\text{lbm}}{\text{hr-ft}^2}$$

$$Re_L = \frac{G_L D}{\mu_L} = \frac{(5.688 \times 10^5) \left(\frac{4}{12}\right)}{0.178} = 1.065 \times 10^6$$

$$h_L = \frac{k}{D} [0.023 Re_L^{0.8} Pr_L^{0.4}] = \frac{0.218}{(4/12)} [0.023 (1.065 \times 10^6)^{0.8} (2.53)^{0.4}]$$

$$= 1447 \frac{\text{Btu}}{\text{hr-ft}^2 \cdot ^\circ\text{F}}$$

Position of the pipe node

$$\bar{D} = \left(\frac{D_o^2 + D_i^2}{2} \right)^{1/2} = \left(\frac{4^2 + 5^2}{2} \right)^{1/2} = 4.528''$$

The overall heat transfer coefficient

$$UA = \frac{2 \pi L_{tot}}{\frac{2}{h D_i} + \frac{\ln(D_o/D_i)}{k_p}} = \frac{2 \pi [60(24)]}{\frac{2}{1447(4/12)} + \frac{\ln(4.528/4)}{25.5}}$$

$$= 1172000 \frac{\text{Btu}}{\text{hr} \cdot ^\circ\text{F}} = 325.5 \frac{\text{Btu}}{\text{sec} \cdot ^\circ\text{F}}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{325.5}{(482)(82.47)(.137)} = 0.05977 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PV)_{mix}} \right] = \frac{325.5}{(18.28)(146.6)} = 0.1215 \text{ sec}^{-1}$$

$$\left(\frac{1}{P_V} \right)_{mix} = \frac{1}{(18.28)(146.6)} = 0.0003732 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{304} = - (0.007810) T_{304} + (0.007810) T_{380}$$

$$\dot{h}_{305} = - (0.01560) T_{380} + (0.01560) T_{304} \\ + (0.0006745) \dot{w}_r h_{205} - (0.0006745) \dot{w}_r h_{305}$$

$$\dot{T}_{306} = - (0.05977) T_{306} + (0.05977) T_{381}$$

$$\dot{h}_{307} = - (0.1215) T_{381} + (0.1215) T_{306} \\ + (0.0003732) \dot{w}_r h_{305} - (0.0003732) \dot{w}_r h_{307}$$

$$\dot{T}_{308} = - (0.05977) T_{308} + (0.05977) T_{382}$$

$$\dot{h}_{309} = - (0.1215) T_{382} + (0.1215) T_{308} \\ + (0.0003732) \dot{w}_r h_{307} - (0.0003732) \dot{w}_r h_{309}$$

$$\dot{w}_r = \text{recirc flow per loop} = \dot{w}_{85}$$

COMBUSTION ENGINEERING

NIIICI FAR POWER DEPARTMENT

The nodes representing the temperature of the steam/water mixture in the piping connecting the evaporator with the steam separation drum are connected to the corresponding enthalpy node by "flow equations". These equations can be used as appropriate curve fits, i.e. polynomials in h or a function of time.

In general

$$h_i = \epsilon_i \quad ; \quad Z = F_{|h|} = \text{modal value}$$

1) $k < 0$

$$\omega = \epsilon_2 Z + \epsilon_3 Z^2 + \frac{\epsilon_4}{Z} + \frac{\epsilon_5}{Z^2} + \epsilon_6 + \epsilon_7 Z^3 + \epsilon_8 Z^4 + \epsilon_9 Z^5 + \epsilon_{10} Z^6$$

2) $k > 0$

$$H = \begin{cases} 0, & k=0 \\ Z, & k>0 \end{cases} ; \quad R = \begin{cases} 0, & t \leq 0 \\ \epsilon_3 t + \epsilon_4 t^2, & t > 0 \end{cases}$$

a) $\epsilon_{10} = 0$

$$\omega = H + R + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t + \epsilon_7 t^2)$$

b) $\epsilon_{10} > 0$

$$\omega = \begin{cases} H + \epsilon_{10}, & t_m \leq 0 \\ H + R(t_m^*) + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t_m^* + \epsilon_7 t_m^{*2}), & t_m > 0 \end{cases}$$

$$t_m = t - (t_s + \epsilon_8) ; \quad t_m^* = \epsilon_9 - t_m$$

The pipe nodes will be at saturated conditions for most of the considered transients. Consequently the temperature nodes depend directly on the pressure.

COMBUSTION ENGINEERING

MICRO FAR POWER DEPARTMENT

If the pressure is prescribed for the particular transient, the associated saturation temperature is determined. Curve fits in the form of 2(a) or 2(b) would be used. If superheated steam exists in the outlet region, a polynomial curve fit for enthalpy-temperature at a given pressure must be used. Curve fits in the form of (1) above would be used.

For normal transients the pressure will be very near the full load operating level and the corresponding saturation temperature is approximately 676.5 °F. One of these forms may be used.

a) $E_1 = -$ (correcting mode number, -305, -307, -309)

$E_6 = 676.5$, all other $E_i = 0$

b) $E_1 = -369$

all $E_i = 0$ except one $E = 676.5$

* c) $E_1 = 0$

$E_2 = 676.5$, all other $E_i = 0$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$T_{380} = \dot{w}_{s1} F_{369} ; \quad \epsilon_1 = -305, -369, 0, 0$$

$$T_{381} = \dot{w}_{s2} F_{369} ; \quad \epsilon_1 = +307, -369, 0, 0$$

$$T_{382} = \dot{w}_{s3} F_{369} ; \quad \epsilon_1 = -309, -369, 0, 0$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Saturated Steam Piping: Drum $\rightarrow$ SH

Energy balances for pipe and steam nodes

$$-(UA)(T_p - T_{stm}) = (\rho VC)_p \frac{dT_p}{dt}$$

$$(UA)(T_p - T_{stm}) + \dot{W}_{stm} h_{stm,IN} = \dot{W}_{stm} h_{stm} + \frac{d}{dt}(\rho V u)_{stm}$$

The following assumptions are made:

$$\frac{dp}{dt} = 0 \quad (\text{implicit, since continuity has not been included in the formulation})$$

$$dh = C_p dT$$

$$\frac{dp}{dt} = 0 \Rightarrow \frac{d(\rho u)}{dt} = \frac{d}{dt}(\rho h - p) = \frac{d}{dt}(\rho h)$$

The results of these assumptions are substituted into the energy balances. The equations are then rearranged into standard format

$$\dot{T}_p = -\left[\frac{(UA)}{(\rho VC)_p}\right] T_p + \left[\frac{(UA)}{(\rho VC)_p}\right] T_{stm}$$

$$\dot{T}_{stm} = -\left[\frac{(UA)}{(\rho VC)_{stm}}\right] T_{stm} + \left[\frac{(UA)}{(\rho VC)_{stm}}\right] T_p + \left(\frac{\dot{W}}{\rho V}\right)_{stm,IN} T_{stm} - \left(\frac{\dot{W}}{\rho V}\right)_{stm} T_{stm}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$W_s = 397278 \text{ lbm/hr flow per SH module}$$

$$= 1191834 \text{ lbm/hr flow per loop}$$

Properties are evaluated at pressure and temperature for full load

$$P_{sat} = 2612 \text{ psia} \Rightarrow T = 674.6^\circ\text{F}$$

$$k_s = 0.0531 \frac{\text{Btu}}{\text{ft} \cdot ^\circ\text{F}}, \quad k_p = 25.5 \frac{\text{Btu}}{\text{in} \cdot ^\circ\text{F}}$$

$$\rho_s = 8.325 \frac{\text{lbm}}{\text{ft}^3}, \quad \rho_p = 482 \frac{\text{lbm}}{\text{ft}^3}$$

$$c_{p,s} = 4.28 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}, \quad c_p = 0.137 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}$$

$$\mu_s = 0.0526 \frac{\text{lbm}}{\text{in} \cdot \text{ft}}$$

$$Pr_s = 4.24$$

3 Nodal sets

1) 1 set (333-334)

18 outlet lines from the diam to a collection header. Each line is 5" OD, 1/2" wall, and a typical length of 21' is assumed.

$$V_{\text{metal}} = 18 \left[\frac{\pi}{4} \left(\frac{5^2 - 4^2}{144} \right) \right] 21 = 18.56 \text{ ft}^3$$

$$V_{\text{stm}} = 18 \left[\frac{\pi}{4} \left(\frac{4}{12} \right)^2 \right] 21 = 32.99 \text{ ft}^3$$

The steam heat transfer coefficient

$$G_s = \frac{W_s}{A_s} = \frac{1191834}{18 \frac{\pi}{4} \left(\frac{4}{12} \right)^2} = 7.587 \times 10^5 \frac{\text{lbm}}{\text{in} \cdot \text{ft}^2}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{7.587 \times 10^5 / 3600}{8.325} = 25.32 \text{ ft/sec}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$Re_s = \frac{G_s D}{\mu_s} = \frac{7.587 \times 10^5 \left(\frac{4}{12}\right)}{1.0526} = 4.808 \times 10^6$$

$$h_s = \frac{k_s}{D_c} [0.23 Re_s^{.8} Pr_s^{.4}] = \frac{0.0531}{4/12} [0.23 (4.808 \times 10^6)^{.8} (4.74)^{.4}]$$

$$= 1447 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{of}}$$

position of pipe node

$$\bar{D} = \left(\frac{D_c^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{5^2 + 4^2}{2} \right)^{1/2} = 4.528''$$

The overall heat transfer coefficient

$$UA = \frac{2 \pi L_{tot}}{\frac{2}{h D_c} + \frac{\ln(D_o/D_c)}{k_p}} = \frac{2 \pi [(18)(21)]}{\frac{2}{1447 \left(\frac{4}{12}\right)} + \frac{\ln(4.528/4)}{25.5}}$$

$$= 263600 \frac{\text{Btu}}{\text{hr} \cdot \text{of}} = 73.23 \frac{\text{Btu}}{\text{sec} \cdot \text{of}}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{73.23}{(482)(16.56)(.137)} = 0.05975 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_s} \right] = \frac{73.23}{(8.325)(32.99)(4.74)} = 0.06230 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_s = \frac{1}{(8.325)(32.99)} = 0.003641 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

2) 1 set (335-336)

Collection Header-Satchel Handle-Inlet Lead+ Inlet Distribution Bottle

Header: 14" OD, 11 1/8" ID, 42' long

Handle: 2, 12 3/4" OD, 1 1/4" wall, approximately 15' developed length

LEAD: 16" OD, 1 9/16" wall, approximately 18' developed length

Reducer: 16" → 22" OD, approximately 1/2' long } assume

Bottle: 22" OD, 17 3/8" ID, approximately 6 1/2' long } 7' average length

$$V_{\text{metal}} = \left[\frac{\pi}{4} \frac{(14^2 - 11\frac{1}{8}^2)}{144} \right] 42 + 2 \left[\frac{\pi}{4} \frac{(12\frac{3}{4}^2 - 10\frac{1}{4}^2)}{144} \right] 15' \\ + \left[\frac{\pi}{4} \frac{(16^2 - 12\frac{7}{8}^2)}{144} \right] 18 + \left[\frac{\pi}{4} \frac{(22^2 - 17\frac{3}{8}^2)}{144} \right] 7 \\ = 41.77 \text{ ft}^3$$

$$V_{\text{stem}} = \left[\frac{\pi}{4} \left(\frac{11\frac{1}{8}}{12} \right)^2 \right] 42 + 2 \left[\frac{\pi}{4} \left(\frac{10\frac{1}{4}}{12} \right)^2 \right] 15 + \left[\frac{\pi}{4} \left(\frac{12\frac{7}{8}}{12} \right)^2 \right] 18 \\ + \left[\frac{\pi}{4} \left(\frac{17\frac{3}{8}}{12} \right)^2 \right] 7 \\ = 73.36 \text{ ft}^3$$

The heat transfer coefficient is computed for the flow conditions in the satchel handle. This section has the lower steam velocity and the high film resistance.

$$G_s = \frac{W_s}{A_s} = \frac{1191834}{2 \frac{\pi}{4} \left(\frac{10\frac{1}{4}}{12} \right)^2} = 1.040 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \text{h}}$$

$$V_s = \frac{G_s}{\rho_s} = \frac{1.040 \times 10^6 / 3600}{8.325} = 34.70 \text{ ft/sec}$$

COMBUSTION ENGINEERING

MICHIGAN POWER DEPARTMENT

$$Re_s = \frac{G_s D}{\mu_s} = \frac{(1.040 \times 10^6) \left(\frac{10^{16}}{12}\right)}{0.0526} = 1.689 \times 10^7$$

$$h_s = \frac{k_s}{D} \left[0.023 Re_s^{0.8} Pr_s^{0.4} \right] = \frac{0.0531}{10^{16}/12} \left[0.023 (1.689 \times 10^7)^{0.8} (4.24)^{0.4} \right]$$

$$= 1543 \frac{Btu}{hr \cdot ft^2 \cdot ^\circ F}$$

Nodal position of pipe sections

$$\bar{D}_H = \left(\frac{D_c^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{14^2 + 11^{1/8}^2}{2} \right)^{1/2} = 12.64''$$

$$\bar{D}_{SH} = \left(\frac{12^{3/4}^2 + 10^{1/4}^2}{2} \right)^{1/2} = 11.57''$$

$$\bar{D}_L = \left(\frac{16^2 + 12^{7/8}^2}{2} \right)^{1/2} = 14.52''$$

$$\bar{D}_B = \left(\frac{17^{3/4}^2 + 13^2}{2} \right)^{1/2} = 19.82''$$

The overall heat transfer coefficient is the sum of the overall coefficients in each pipe section.

$$UA = \sum \frac{2\pi L}{\frac{2}{hD_o} + \ln(\bar{D}/D_o) \frac{1}{k_p}} = \frac{2\pi(42)}{\frac{24}{1543(11^{1/8})} + \frac{\ln(12.64/11^{1/8})}{25.5}} + \frac{2\pi[2(30)]}{\frac{24}{1543(10^{1/4})} + \frac{\ln(11.57/10^{1/4})}{25.5}}$$

$$+ \frac{2\pi(18)}{\frac{24}{1543(12^{3/4})} + \frac{\ln(14.52/12^{7/8})}{25.5}} + \frac{2\pi(7)}{\frac{24}{1543(17^{3/4})} + \frac{\ln(19.82/17^{3/4})}{25.5}}$$

$$= 127700 \frac{Btu}{hr \cdot ^\circ F} = 35.47 \frac{Btu}{sec \cdot ^\circ F}$$

Coefficients

$$\left[\frac{UA}{(pvc)_p} \right] = \frac{35.47}{482(41.77)(1.137)} = 0.01286 \text{ sec}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\left[\frac{UA}{(PVC)_s} \right] = \frac{35.47}{(8.325)(73.36)(4.24)} = 0.01370 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_s = \frac{1}{(8.325)(73.36)} = 0.001637 \text{ lbm}^{-1}$$

3) 1 set (337-338)

Inlet lines - Inlet Distribution Bottle & Reducer - Inlets

Lines: 15 5" OD, 1/2" wall, typical developed length = 30'
 Bottle: 3 16" OD, 1 5/16 wall, approximately 4 3/4' long } assume
 Reducer: 3 16" OD → 14" OD, approximately 1/2' long } 5' length
 Inlets: 3 14" OD, 1 5/16 wall approximately 7 1/2' long

$$\begin{aligned} V_{\text{metal}} &= 15 \left[\frac{\pi}{4} \frac{(5^2 - 4^2)}{144} \right] 30 + 3 \left[\frac{\pi}{4} \frac{(16^2 - 12^{7/8^2})}{144} \right] 5 \\ &\quad + 3 \left[\frac{\pi}{4} \frac{(14^2 - 11^{3/8^2})}{144} \right] 7 \frac{1}{2} \\ &= 37.65 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} V_{\text{steam}} &= 15 \left[\frac{\pi}{4} \left(\frac{4}{12} \right)^2 \right] 30 + 3 \left[\frac{\pi}{4} \left(\frac{12^{7/8}}{12} \right)^2 \right] 5 + 3 \left[\frac{\pi}{4} \left(\frac{11^{3/8}}{12} \right)^2 \right] 7 \frac{1}{2} \\ &= 68.71 \text{ ft}^3 \end{aligned}$$

The steam flow heat transfer coefficient is computed for the flow in the 15 inlet lines

$$G_s = \frac{W_s}{A} = \frac{1.191834}{15 \frac{\pi}{4} \left(\frac{4}{12} \right)^2} = 9.104 \times 10^5$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

$$V_s = \frac{Q_s}{P_s} = \frac{9.104 \times 10^5 / 3600}{8.325} = 30.38 \frac{\text{ft}}{\text{sec}}$$

$$Re_s = \frac{Q_s D}{\mu_s} = \frac{(9.104 \times 10^5) (\frac{4}{12})}{0.0526} = 5.770 \times 10^6$$

$$h_s = \frac{k_s}{D} [0.023 Re_s^{.8} Pr_s^{.4}] = \frac{0.0531}{(4/12)} [0.023 (5.770 \times 10^6)^{.8} (4.24)^{.4}]$$

$$= 1674 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot \text{OF}}$$

The nodal position of the pipe sections

$$\bar{D}_L = \left(\frac{D_L^2 + D_0^2}{2} \right)^{1/2} = \left(\frac{4^2 + 5^2}{2} \right)^{1/2} = 4.528''$$

$$\bar{D}_B = \left(\frac{127/8^2 + 14^2}{2} \right)^{1/2} = 14.52''$$

$$\bar{D}_I = \left(\frac{117/8^2 + 14^2}{2} \right)^{1/2} = 12.76''$$

The overall heat transfer coefficient is the sum of the local overall coefficients.

$$UA = \sum \frac{2\pi L}{\frac{2}{h D_o} + \frac{\ln(D_o/D_i)}{k}} = \frac{2\pi [15(30)]}{\frac{24}{1674(4)} + \frac{\ln(4.528/4)}{25.5}} + \frac{2\pi [3(5)]}{\frac{24}{1674(127/8)} + \frac{\ln(14.52/127/8)}{25.5}}$$

$$+ \frac{2\pi [3(74)]}{\frac{24}{1674(117/8)} + \frac{\ln(12.76/117/8)}{25.5}}$$

$$= 375.400 \frac{\text{Btu}}{\text{m}^2 \cdot \text{F}} = 104.3 \frac{\text{Btu}}{\text{sec} \cdot \text{OF}}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{104.3}{782(37.65)(0.137)} = 0.04195 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_s} \right] = \frac{104.3}{(8.325)(68.71)4.28} = 0.04260 \text{ sec}^{-1}$$

$$\left(\frac{1}{PV} \right)_s = \frac{1}{(8.325)(68.71)} = 0.001748 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{333} = -(0.05975) T_{333} + (0.05975) T_{334}$$

$$\begin{aligned} \dot{T}_{334} = & -(0.06230) T_{334} + (0.06230) T_{333} + (0.003641) \dot{\omega}_s T_{362} \\ & - (0.003641) \dot{\omega}_s T_{334} \end{aligned}$$

$$\dot{T}_{335} = -(0.01286) T_{335} + (0.01286) T_{336}$$

$$\begin{aligned} \dot{T}_{336} = & -(0.01370) T_{336} + (0.01370) T_{335} + (0.001637) \dot{\omega}_s T_{334} \\ & - (0.001637) \dot{\omega}_s T_{336} \end{aligned}$$

$$\dot{T}_{337} = -(0.04195) T_{337} + (0.04195) T_{338}$$

$$\begin{aligned} \dot{T}_{338} = & -(0.04260) T_{338} + (0.04260) T_{337} + (0.001748) \dot{\omega}_s T_{336} \\ & - (0.001748) \dot{\omega}_s T_{338} \end{aligned}$$

$$\dot{\omega}_s = \text{steam flow per loop} = \dot{\omega}_{s1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Recirculated Water Piping: Drum $\rightarrow$ Pump; Pump $\rightarrow$ EV

Energy balances for the pipe and water nodes

$$-(UA)(T_p - T_w) = (\rho V C)_p \frac{dT_p}{dt}$$

$$(UA)(T_p - T_w) + (\dot{w}C_p)_w T_{w_{IN}} = (\dot{w}C_p)_w T_w + (\rho V C)_w \frac{dT_w}{dt}$$

In standard format

$$\dot{T}_p = -\left[\frac{(UA)}{(\rho V C)_p}\right] T_p + \left[\frac{(UA)}{(\rho V C)_p}\right] T_w$$

$$\dot{T}_w = -\left[\frac{(UA)}{(\rho V C)_w}\right] T_w + \left[\frac{(UA)}{(\rho V C)_w}\right] T_p + \left(\frac{\dot{w}}{\rho V}\right)_w T_{w_{IN}} - \left(\frac{\dot{w}}{\rho V}\right)_w T_w$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\begin{aligned} W_w &= 1390473 \text{ lbm/hr} \quad \text{Flow per ex module} \\ &= 4171419 \text{ lbm/hr} \quad \text{Flow per loop} \end{aligned}$$

Properties are evaluated at pressure and temperature for full load.

$$P = 2663 \text{ psi}, \quad T = 634.5^\circ\text{F}$$

$$K_w = 0.262 \frac{\text{ft}^4}{\text{lbm} \cdot \text{ft}^2 \cdot \text{F}}, \quad K_p = 26.1 \frac{\text{ft}^4}{\text{lbm} \cdot \text{ft}^2 \cdot \text{F}}$$

$$\rho_w = 40.32 \text{ lbm/ft}^3, \quad \rho_p = 482 \text{ lbm/ft}^3$$

$$C_{pw} = 1.84 \frac{\text{Btu}}{\text{lbm} \cdot \text{F}}, \quad C_p = 0.134 \frac{\text{Btu}}{\text{lbm} \cdot \text{F}}$$

$$\mu_w = 0.192 \text{ lbm/ft} \cdot \text{h}$$

$$Pr_w = 1.35$$

Drum $\rightarrow$ Pump: 2 Nodal sets (310-311 and 312-313)

4 downcomers, $12\frac{3}{4}$ OD, $1\frac{3}{16}$ wall, approximately 68' long.

$$V_{\text{metal}} = 4 \left[\frac{\pi}{4} \frac{(12\frac{3}{4}^2 - 10\frac{3}{8}^2)}{144} \right] 34 = 40.74 \text{ ft}^3$$

$$V_w = 4 \left[\frac{\pi}{4} \left(\frac{10\frac{3}{8}}{12} \right)^2 \right] 34 = 79.84 \text{ ft}^3$$

Heat transfer

$$G_w = \frac{W_w}{A} = \frac{4171419}{4 \frac{\pi}{4} \left(\frac{10\frac{3}{8}}{12} \right)^2} = 1.776 \times 10^6 \frac{\text{lbm}}{\text{ft}^2}$$

$$V_w = \frac{G_w}{\rho_w} = \frac{(1.776 \times 10^6)/3600}{40.32} = 12.24 \text{ ft/sec}$$

$$Re_w = \frac{G_w D}{\mu_w} = \frac{(1.776 \times 10^6) \left(\frac{10\frac{3}{8}}{12} \right)}{0.192} = 7.999 \times 10^6$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$h_w = \frac{k_w}{\delta} [0.023 Re_w^{.8} Pr_w^{.4}] = \frac{.262}{(10^{36}/12)} [0.023 (7.999 \times 10^6)^{.8} (1.35)^{.4}]$$

$$= 2617 \frac{Btu}{m \cdot ft^2 \cdot ^\circ F}$$

The average diameter of the pipes

$$\bar{D} = \left(\frac{D_o^2 + D_i^2}{2} \right)^{1/2} = \left(\frac{10^{3/4}^2 + 12^{3/4}^2}{2} \right)^{1/2} = 11.62''$$

The overall heat transfer coefficient

$$UA = \frac{2\pi L}{\frac{2}{hD} + \frac{\ln(D/D_i)}{R_p}} = \frac{2\pi (34)}{\frac{24}{2617(10^{3/4})} + \frac{\ln(11.62/10^{3/4})}{26.1}}$$

$$= 40860 \frac{Btu}{h \cdot ^\circ F} = 11.35 \frac{Btu}{sec \cdot ^\circ F}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{11.35}{(482) \cancel{40.77} (1.34)} = 0.004316 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_w} \right] = \frac{11.35}{40.32 (79.84) (1.84)} = 0.001916 \text{ sec}^{-1}$$

$$\left(\frac{1}{C_v} \right)_w = \frac{1}{(40.32)(79.84)} = 0.0003106 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$h_w = \frac{k_w}{D} [0.023 Re_w^{.8} Pr_w^{.4}] = \frac{.262}{(1038/12)} [0.023 (7.999 \times 10^6)^{.8} (1.35)^{.4}]$$

$$= 2617 \frac{Btu}{hr \cdot ft^2 \cdot ^\circ F}$$

The average diameter of the pipes

$$\bar{D} = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{10.38^2 + 12.75^2}{2} \right)^{1/2} = 11.62''$$

The overall heat transfer coefficient

$$UA = \frac{2\pi L}{\frac{2}{hD} + \frac{\ln(D/D_i)}{R_p}} = \frac{2\pi (34)}{\frac{2}{2617(1038)} + \frac{\ln(11.62/10.38)}{26.1}}$$

$$= 40880 \frac{Btu}{hr \cdot ^\circ F} = 11.35 \frac{Btu}{sec \cdot ^\circ F}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{11.35}{(482) \cancel{40.77} (1.34)} = 0.004316 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_w} \right] = \frac{11.35}{40.32 (79.84) (1.84)} = 0.001916 \text{ sec}^{-1}$$

$$\left(\frac{1}{C_v} \right)_w = \frac{1}{(40.32)(79.84)} = 0.0003106 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Pump → Evap: 3 Nodal sets

1) 1 Set (339-340)

Discharge lines - Discharge manifold

Lines: 6, 14" OD, 1 3/8" wall, typical length 36'

Manifold: 18" OD, 1 4 3/8" ID, approximately 29' long

$$V_{\text{metal}} = 6 \left[\frac{\pi}{4} \frac{(14^2 - 11\frac{3}{4}^2)}{144} \right] 36 + \left[\frac{\pi}{4} \frac{(18^2 - 14\frac{3}{8}^2)}{144} \right] 29$$

$$= 100.4 \text{ ft}^3$$

$$V_w = 6 \left[\frac{\pi}{4} \left(\frac{11\frac{3}{4}}{12} \right)^2 \right] 36 + \left[\frac{\pi}{4} \left(\frac{14\frac{3}{8}}{12} \right)^2 \right] 29$$

$$= 181.8 \text{ ft}^3$$

Assume the water film coefficient is that computed in the discharge lines.

$$G_w = \frac{W_w}{A} = \frac{4171419}{6 \frac{\pi}{4} \left(\frac{11\frac{3}{4}}{12} \right)^2} = 1.007 \times 10^6 \frac{\text{lbm}}{\text{m}^2 \cdot \text{hr}}$$

$$V_w = \frac{G_w}{\rho_w} = \frac{(1.007 \times 10^6) / 3600}{40.32} = 6.939 \text{ ft/sec}$$

$$Re_w = \frac{G_w D}{\mu_w} = \frac{(1.007 \times 10^6) \left(\frac{11\frac{3}{4}}{12} \right)}{.192} = 4.918 \times 10^6$$

$$h_w = \frac{R_w}{D} [0.023 Re_w^{.8} Pr_w^{.4}] = \frac{.262}{(11\frac{3}{4}/12)} [0.023 (4.918 \times 10^6)^{.8} (1.35)^{.4}]$$

$$= 1635 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot ^\circ\text{F}}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

average diameters of the pipe

$$\bar{D}_L = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{18^2 + 14^2}{2} \right)^{1/2} = 12.70''$$

$$D_M = \left(\frac{14^2 + 18^2}{2} \right)^{1/2} = 16.29''$$

The overall heat transfer coefficient is the sum of the local coefficients in the two sections.

$$UA = \sum \frac{2\pi L}{\frac{3}{hD} + \frac{\ln(D_o/D_i)}{k}} = \frac{2\pi [6(36)]}{\frac{24}{1635(11/4)} + \frac{\ln(2.70/1.14)}{26.1}} + \frac{2\pi (24)}{\frac{24}{1635(143/8)} + \frac{\ln(16.29/143/8)}{26.1}}$$

$$= 259500 \frac{\text{Btu}}{\text{hr}^\circ\text{F}} = 72.07 \frac{\text{Btu}}{\text{sec}^\circ\text{F}}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{72.07}{482(100.4)(1.134)} = 0.01111 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_w} \right] = \frac{72.07}{40.32(181.8)(1.84)} = 0.005343 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_w = \frac{1}{(40.32)(181.8)} = 0.001364 \text{ lbm}^{-1}$$

2) 1 set (341-342)

Discharge lines to evaporator inlet headers: 2, 18" OD, 15 7/8" ID, approximately 84.6' long

$$V_{\text{metal}} = 2 \left[\frac{\pi}{4} \left(\frac{18^2 - 15\frac{7}{8}^2}{144} \right) \right] 84.6 = 66.43 \text{ ft}^3$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$U_w = 2 \left[\frac{\pi}{4} \left(\frac{15\frac{7}{8}}{12} \right)^2 \right] 84.6 = 232.6 \text{ ft}^3$$

Heat Transfer coefficient

$$G_w = \frac{W_w}{A} = \frac{4171.419}{2 \frac{\pi}{4} \left(\frac{15\frac{7}{8}}{12} \right)^2} = 1.517 \times 10^6 \frac{\text{lbm}}{\text{m}^2 \cdot \text{ft}^2}$$

$$V_w = \frac{G_w}{\rho_w} = \frac{(1.517 \times 10^6) / 3600}{40.32} = 10.45 \text{ ft/sec}$$

$$Re_w = \frac{G_w D}{\mu_w} = \frac{(1.517 \times 10^6) \left(\frac{15\frac{7}{8}}{12} \right)}{.192} = 1.046 \times 10^7$$

$$h_w = \frac{k_w}{D} [0.23 Re^{.8} Pr^{.4}] = \frac{.262}{(15\frac{7}{8}/12)} [0.23 (1.046 \times 10^7)^{.8} (1.35)^{.4}]$$

$$= 2119 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot \text{°F}}$$

Average diameter of the pipe

$$\bar{D} = \left(\frac{D_o^2 + D_i^2}{2} \right)^{1/2} = \left(\frac{15\frac{7}{8}^2 + 18^2}{2} \right)^{1/2} = 16.97 \text{ ''}$$

The overall heat Transfer coefficient

$$UA = \frac{2\pi L}{\frac{3}{hD} + \frac{\ln(D_i/D_o)}{k}} = \frac{2\pi [2(84.6)]}{\frac{34}{2119(15\frac{7}{8})} + \frac{\ln(16.97/15\frac{7}{8})}{26.1}}$$

$$= 325200 \frac{\text{Btu}}{\text{m}^2 \cdot \text{°F}} = 90.33 \frac{\text{Btu}}{\text{sec} \cdot \text{°F}}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{90.33}{(482)(66.43)(137)} = 0.02105 \text{ sec}^{-1}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$\left[\frac{UA}{(PVC)_w} \right] = \frac{90.33}{(40.32)(232.6)(1.84)} = 0.005235 \text{ sec}^{-1}$$

$$\left(\frac{1}{PV} \right)_w = \frac{1}{(40.32)(232.6)} = 0.001066 \text{ lbm}^{-1}$$

3) 1 set (343-344)

Evaporator Inlet Header - Evaporator inlet lines

Header: 16" OD, 12^{3/4}" ID, approximately 35' long

Lines: 3, 16" OD, 1^{9/16}" wall, approximately 24^{1/2}' long

$$V_m = \left[\frac{\pi}{4} \frac{(16^2 - 12^{3/4^2})}{144} \right] (35) + 3 \left[\frac{\pi}{4} \frac{(16^2 - 12^{7/8^2})}{144} \right] 24\frac{1}{2}$$

$$= 54.01 \text{ ft}^3$$

$$V_w = \left[\frac{\pi}{4} \left(\frac{12^{3/4}}{12} \right)^2 \right] (35) + 3 \left[\frac{\pi}{4} \left(\frac{12^{7/8}}{12} \right)^2 \right] 24\frac{1}{2}$$

$$= 97.48$$

Heat transfer coefficient

$$G_w = \frac{w_w}{A} = \frac{4171419}{3 \left[\frac{\pi}{4} \left(\frac{12^{7/8}}{12} \right)^2 \right]} = 1.538 \times 10^6 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}$$

$$V_w = \frac{G_w}{\rho_w} = \frac{1.538 \times 10^6 / 3600}{40.32} = 10.60 \text{ ft/sec}$$

$$Re_w = \frac{G_w D}{\mu_w} = \frac{1.538 \times 10^6 \left(\frac{12^{7/8}}{12} \right)}{1.92} = 8.594 \times 10^6$$

$$h_w = \frac{k_w}{D} [0.23 Re_w^{0.8} Pr_w^{0.4}] = \frac{0.262}{(12^{7/8}/12)} [0.23 (8.594 \times 10^6)^{0.8} (1.35)^{0.4}]$$

$$= 2233 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

Average diameter of the two sections

$$\bar{D}_H = \left(\frac{D_1^2 + D_2^2}{2} \right)^{1/2} = \left(\frac{12\frac{3}{4}^2 + 16^2}{2} \right)^{1/2} = 14.47''$$

$$\bar{D}_L = \left(\frac{12\frac{7}{8}^2 + 11\frac{1}{2}^2}{2} \right)^{1/2} = 14.52''$$

The overall coefficient is the sum of the two local coefficients.

$$UA = \sum \frac{2\pi L}{\frac{2}{hD} + \frac{\ln(D/D)}{k}} = \frac{2\pi (35)}{\frac{2}{2233(12\frac{3}{4})} + \frac{\ln(14.47/12\frac{3}{4})}{26.1}} + \frac{2\pi [3(24\frac{1}{2})]}{\frac{2}{2233(11\frac{1}{2})} + \frac{\ln(14.52/11\frac{1}{2})}{26.1}}$$

$$= 123500 \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2} = 34.31 \frac{\text{Btu}}{\text{sec} \cdot \text{ft}^2}$$

Coefficients

$$\left[\frac{UA}{(PVC)_p} \right] = \frac{34.31}{(482)(54.01)(1.34)} = .009835 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(PVC)_o} \right] = \frac{34.31}{(40.32)(97.48)(1.84)} = .004744 \text{ sec}^{-1}$$

$$\left(\frac{1}{PVC} \right)_o = \frac{1}{(40.32)(97.48)} = .0002544 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{310} = -(0.001916) T_{310} + (0.001916) T_{310} + (0.0003106) \dot{\omega}_n T_{363} - (0.0003106) \dot{\omega}_n T_{310}$$

$$\dot{T}_{311} = -(0.004316) T_{311} + (0.004316) T_{310}$$

$$\dot{T}_{312} = -(0.001916) T_{312} + (0.001916) T_{313} + (0.0003106) \dot{\omega}_n T_{310} - (0.0003106) \dot{\omega}_n T_{312}$$

$$\dot{T}_{313} = -(0.004316) T_{313} + (0.004316) T_{312}$$

$$\dot{T}_{339} = -(0.005343) T_{339} + (0.005343) T_{340} + (0.0001364) \dot{\omega}_n T_{310} - (0.0001364) \dot{\omega}_n T_{339}$$

$$\dot{T}_{340} = -(0.01111) T_{340} + (0.01111) T_{339}$$

$$\dot{T}_{341} = -(0.005235) T_{341} + (0.005235) T_{342} + (0.0001066) \dot{\omega}_n T_{339} - (0.0001066) \dot{\omega}_n T_{341}$$

$$\dot{T}_{342} = -(0.02105) T_{342} + (0.02105) T_{341}$$

$$\dot{T}_{343} = -(0.004744) T_{343} + (0.004744) T_{344} + (0.0002544) \dot{\omega}_n T_{341} - (0.0002544) \dot{\omega}_n T_{343}$$

$$\dot{T}_{344} = -(0.009835) T_{344} + (0.009835) T_{343}$$

$$\dot{\omega}_n = \text{total recirc flow per loop} = \dot{\omega}_{RS}$$

COMBUSTION ENGINEERING

NIICI FAR POWER DEPARTMENT

RECIRCULATION PUMP

Energy balance for the water within the pump:
The water is assumed to be bounded by adiabatic walls.

$$(\dot{w}c_p)_w T_{w_{in}} = (\dot{w}c_p)_w T_w + (\rho V c_p)_w \frac{dT_w}{dt}$$

In standard format

$$\dot{T}_w = \left(\frac{\dot{w}}{\rho V}\right)_w T_{w_{in}} - \left(\frac{\dot{w}}{\rho V}\right)_w T_w$$

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

$$W_w = 1390473 \text{ lbm/hr flow per module}$$

$$= 4171419 \text{ lbm/hr flow per loop}$$

Properties are evaluated at pressure and temperature for full load.

$$P = 2663 \text{ psi}, T = 634.5 \text{ } ^\circ\text{F}$$

$$k_w = .262 \text{ Btu/in-}^{\circ}\text{F}; k_p = 26.1 \text{ Btu/in-}^{\circ}\text{F}$$

$$\rho_w = 40.32 \text{ lbm/hr}; \rho_r = 482 \text{ lbm/hr}$$

$$c_{p,w} = 1.84 \text{ Btu/lbm-}^{\circ}\text{F}; c_p = .134 \text{ Btu/lbm-}^{\circ}\text{F}$$

$$\mu_w = .192 \text{ lbm/hr}$$

$$Pr_w = 1.35$$

Pump - includes suction manifold $\rightarrow$ valves, inlet lines.

A gross estimate of the total volume (pump plus additional items) is assumed to be

$$V_{\text{water}} = 50 \text{ ft}^3$$

Coefficient

$$\left(\frac{1}{cV}\right)_w = \frac{1}{(40.32)(50)} = .0004960 \text{ lbm}^{-1}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Summary

$$\dot{T}_{115} = (1.0004960)\dot{w}_r T_{312} - (1.0004960)\dot{w}_r T_{115}$$

$$\dot{w}_r = \text{recirc flow per loop} = \dot{w}_{85}$$

COMBUSTION ENGINEERING

NUCLEAR POWER DEPARTMENT

Drum

The drum receives a steam/water mixture from the pipe, separates the two phases, and mixes the separated water with the feedwater.

Steam quality

$$X = \left(\frac{1}{h_{fg}} \right) h_{wstm} - \left(\frac{h_f}{h_{fg}} \right)$$

where h_f , h_g , $h_{fg} = h_g - h_f$, the specific enthalpies of the saturated states, depend on the drum operating pressure.

The separated steam flow and the separated water flow are

$$\dot{W}_{stm} = \dot{W}_r X = \dot{W}_{stm}$$

$$\dot{W}_w = \dot{W}_r (1 - X) = \dot{W}_w$$

During a transient the hydraulic conditions downstream of the drum dictate the instantaneous demand for steam flow. If the steam production is insufficient, the drum pressure would drop thus causing flashing of steam in the section connecting the evaporator and the drum and in the evaporator itself. This hydraulic model of the drum has not been included in the thermal transient model. Instead, the feedwater flow and drum pressure as functions of time

COMBUSTION ENGINEERING NUCLEAR POWER DEPARTMENT

provided in the series of curve defining the transients were assumed applicable. In addition the steam flow was assumed to be the same as the feedwater flow, and the separated water flow was computed from this.

P, W_s, W_{seal} assumed

$$W_w = W_r - W_s$$

The thermodynamic properties T_{sat}, h_f, h_g were assume to adjust to the new pressure level instantaneously. The ratio of w_s to w_r at any time should give the quality at that time. Since the pressure curve was assumed and the drum hydraulic adjustment assumed a priori, it is not expected that quality calculation to agree. The calculations of x, W_w, W_s , described above, based on exit enthalpy are still performed, but they are not used in any further calculations.

The energy balances for the upper portion of the drum (i.e. that part which is above the nominal waterlevel):

$$-(UA) [T_{\text{Dr}} - T_{\text{stm}}] = (PVC)_{\text{Dr}} \frac{dT_{\text{Dr}}}{dt}$$

$$(UA) [T_{\text{Dr}} - T_{\text{stm}}] + W_{\text{stm}} h_{\text{stm}} = W_{\text{stm}} h_{\text{stm}} + \frac{d}{dt}(P V U)$$

COMBUSTION ENGINEERING

NIIICI FAR POWER DEPARTMENT

The following assumptions are made:

$$\frac{dp}{dt} \approx 0 \quad (\text{implicit, since continuity has not been included in the formulation})$$

$$\frac{dp}{dt} \approx 0 \Rightarrow \frac{d}{dt}(pu) = \frac{d}{dt}(ph - p) = \frac{d(ph)}{dt}$$

Combining these assumptions with the energy balances and rearranging the equations into standard format

$$\dot{T}_{Dr} = - \left[\frac{UA}{(pV)_{Dr}} \right] T_{Dr} + \left[\frac{UA}{(pV)_{Dr}} \right] T_{stm}$$

$$\dot{h}_{stm} = - \left[\frac{UA}{(pV)_{stm}} \right] T_{stm} + \left[\frac{UA}{(pV)_{stm}} \right] T_{Dr} + \left(\frac{1}{pV} \right)_{stm} \dot{w}_{stm} H_g - \left(\frac{1}{pV} \right) \dot{w}_s h_{stm}$$

Similarly, for the lower portion of the drum

$$-(UA)[T_{Dr} - T_w] = (pV)_{Dr} \frac{dT_{Dr}}{dt}$$

$$(UA)[T_{Dr} - T_w] + \dot{w}_w h_{w,w} + \dot{w}_f h_{feed} = \dot{w}_{oc} h_w + \frac{d}{dt}(pV_u)$$

Noting the above assumptions and rearranging

$$\dot{T}_{Dr} = - \left[\frac{UA}{(pV)_{Dr}} \right] T_{Dr} + \left[\frac{UA}{(pV)_{Dr}} \right] T_w$$

$$\dot{h}_w = - \left[\frac{UA}{(pV)_w} \right] T_w + \left[\frac{UA}{(pV)_w} \right] T_{Dr} + \left(\frac{1}{pV} \right)_w \dot{w}_w H_g + \left(\frac{1}{pV} \right) \dot{w}_{feed} h_{feed} - \left(\frac{1}{pV} \right) \dot{w}_{oc} h_w$$

In addition T_w, h_w and T_{stm}, h_{stm} are connected by curve fits for the given operating pressure.

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$$\begin{aligned} W_r &= 1390473 \text{ lbm/hr per module} \\ &= 4171419 \text{ lbm/hr per loop} \end{aligned} \left. \vphantom{\begin{aligned} W_r &= 1390473 \text{ lbm/hr per module} \\ &= 4171419 \text{ lbm/hr per loop} \end{aligned}} \right\} \text{recirc flow}$$

$$\begin{aligned} W_s &= 397278 \text{ lbm/hr per module} \\ &= 1191834 \text{ lbm/hr per loop} \end{aligned} \left. \vphantom{\begin{aligned} W_s &= 397278 \text{ lbm/hr per module} \\ &= 1191834 \text{ lbm/hr per loop} \end{aligned}} \right\} \text{steam and feedwater flow}$$

Properties are evaluated at pressure and temperature for full load.

$$P_{\text{sat}} = 2645 \text{ psia}; T_{\text{sat}} = 676.5^\circ\text{F}$$

$$k_g = 0.0537 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}}; k_m = 25.8 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}}; h_{\text{feed}} = 442.9 \frac{\text{Btu}}{\text{lbm}}; k_w = 0.262 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}}$$

$$S_g = 8.545 \frac{\text{lbm}}{\text{ft}^3}; S_{\text{on}} = 462 \frac{\text{lbm}}{\text{ft}^3}; C_p = 0.963; \rho_w = 40.32 \frac{\text{lbm}}{\text{ft}^3}$$

$$C_{p_g} = 4.40 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}; C_{\text{on}} = .137 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}; C_{p_w} = 1.84 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}$$

$$\mu_g = 0.0527 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}}; \mu_w = .192 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}}$$

$$P_{r_g} = 4.32; P_{r_w} = 1.35$$

$$\begin{aligned} h_f &= 750.2 \frac{\text{Btu}}{\text{lbm}} \\ h_g &= 1076.6 \frac{\text{Btu}}{\text{lbm}} \end{aligned} \left. \vphantom{\begin{aligned} h_f &= 750.2 \frac{\text{Btu}}{\text{lbm}} \\ h_g &= 1076.6 \frac{\text{Btu}}{\text{lbm}} \end{aligned}} \right\} h_{fg} = 326.4 \frac{\text{Btu}}{\text{lbm}}$$

$$T = 460^\circ\text{F}$$

$$T = 634.5^\circ\text{F}$$

$$h_{\text{feed}} = 442.9 \frac{\text{Btu}}{\text{lbm}}; k_w = 0.262 \frac{\text{Btu}}{\text{in} \cdot \text{ft} \cdot ^\circ\text{F}}$$

$$C_p = 0.963; \rho_w = 40.32 \frac{\text{lbm}}{\text{ft}^3}$$

$$C_{p_w} = 1.84 \frac{\text{Btu}}{\text{lbm} \cdot ^\circ\text{F}}$$

$$\mu_w = .192 \frac{\text{lbm}}{\text{ft} \cdot \text{hr}}$$

$$P_{r_w} = 1.35$$

The drum has a 60" ID, 6 3/4" wall, and it is 42' long with hemispherical end caps. The water level is nominally 0.8' below the center horizontal plane. The internal structure of the drum is not considered.

$$V_{\text{total}} = \frac{\pi}{4} \frac{(13\frac{1}{2}^2 - 60^2)}{144} 42 + \frac{4}{3} \pi \frac{(36\frac{3}{4}^3 - 30^3)}{1728} = 467.7 \text{ ft}^3$$

$$V_{\text{total internal}} = \frac{\pi}{4} \left(\frac{60}{12}\right)^2 \cdot \frac{42}{2} + \frac{4}{3} \pi \left(\frac{30}{12}\right)^3 = 890.1 \text{ ft}^3$$

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$$V_{\text{Below level}} = \left\{ R^2 \cos^{-1} \left(\frac{R-h}{R} \right) - (R-h) \sqrt{2Rh - h^2} \right\} L + \left\{ \frac{\pi}{6} (6Rh^2 - 2h^3) \right\}$$

$$V_{\text{BL OD}} = \left\{ \left(\frac{36.34}{12} \right)^2 \cos^{-1} \left(\frac{36.34 - 2.26}{36.34} \right) - \left(\frac{36.34 - 2.26}{12} \right) \sqrt{2 \left(\frac{36.34}{12} \right) (2.26) - (2.26)^2} \right\} 42$$

$$+ \left\{ \frac{\pi}{6} \left[6 \left(\frac{36.34}{12} \right) (2.26)^2 - 2 (2.26)^3 \right] \right\}$$

$$= 451.8 \text{ ft}^3$$

$$V_{\text{BL ID}} = \left\{ \left(\frac{30}{12} \right)^2 \cos^{-1} \left(\frac{30 - 1.7}{30} \right) - \left(\frac{30 - 1.7}{12} \right) \sqrt{2 \left(\frac{30}{12} \right) (1.7) - (1.7)^2} \right\} 42$$

$$+ \left\{ \frac{\pi}{6} \left[6 \left(\frac{30}{12} \right) (1.7)^2 - 2 (1.7)^3 \right] \right\}$$

$$= 264.8 \text{ ft}^3$$

$$(V_{\text{metal}})_{\text{Lower Drum}} = V_{\text{BL OD}} - V_{\text{BL ID}} = 451.8 - 264.8 = 187.0 \text{ ft}^3$$

$$(V_{\text{metal}})_{\text{Upper Drum}} = V_{\text{metal TOT}} - V_{\text{metal Lower Drum}} = 467.7 - 187.0 = 280.7 \text{ ft}^3$$

$$(V_{\text{water}}) = V_{\text{BL ID}} = 264.8 \text{ ft}^3$$

$$(V_{\text{steam}}) = V_{\text{Total Internal}} - V_{\text{BL ID}} = 890.1 - 264.8 = 625.3 \text{ ft}^3$$

The heat transfer area is the wetted area. The total wetted area is the total inside surface area of the drum.

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$$A_{TOT} = \pi D_c L + \pi D^2 = \pi (5) (42) + \pi (5)^2$$

$$= 738.3 \text{ ft}^2$$

The area wetted by the water

$$A_w = D \left\{ \cos^{-1} \left(\frac{R-h}{R} \right) \right\} L + \pi D h = (5) \left\{ \cos^{-1} (.32) \right\} 42 + \pi (5) (1.7)$$

$$= 288.2 \text{ ft}^2$$

The area wetted by the steam

$$A_{sm} = A_T - A_w = 738.3 - 288.2 = 450.1 \text{ ft}^2$$

The radial position of the Drum node is

$$D = \left(\frac{D_i^2 + D_o^2}{2} \right)^{1/2} = \left(\frac{60^2 + 73.5^2}{2} \right)^{1/2} = 67.09''$$

The thermal resistance of the drum can be written as

$$R = \frac{D_c}{2k} \frac{\ln(D/D_c)}{A_{wetted}}$$

cylindrical geometry
is assumed characteristic!

So

$$R_{stm} = \frac{5}{2(25.8)} \frac{\ln(67.09/60)}{450.1} = .00002398 \frac{\text{hr} \cdot \text{ft}^2}{\text{Btu}}$$

$$R_w = \frac{5}{2(25.8)} \frac{\ln(67.09/60)}{288.2} = .00003747 \frac{\text{hr} \cdot \text{ft}^2}{\text{Btu}}$$

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Heat Transfer Coefficient

The heat transfer coefficients for the water-drum and for the steam-drum interactions are computed assuming natural convection. The correlations for horizontal plates recommended by McAdams will be used. These should yield high thermal resistances which is considered conservative since there will be a minimum of moderation of a transient between the evaporator and superheater.

In addition assume for calculational purposes the following quantity

$$\beta_{\text{stm}} = 0.01 \text{ } ^\circ\text{F}^{-1} ; \beta_{\text{water}} = 0.005 \text{ } ^\circ\text{F}^{-1} ; \Delta T = 1^\circ\text{F}$$

$$L = 2.0', \text{ characteristic length, an average width of the water level}$$

$$Gr = \frac{\rho^2 g \beta \Delta T L^3}{\mu^2}$$

$$Gr_{\text{stm}} = \frac{(8.575)^2 (4.17 \times 10^{-8}) (0.01)}{(1.0527)^2} (1) (2)^3 ; Gr_{\text{water}} = \frac{(30.32)^2 (4.17 \times 10^{-8}) (0.005)}{(0.192)^2} (1) (2)^3$$

$$= 8.77 \times 10^{-4} \quad = 7.36 \times 10^{-4}$$

$$h_{\text{stm}} = \frac{k_s}{L} (1.27) (Gr Pr)^{1/5}$$

$$= \frac{0.537}{2} (1.27) [(8.77 \times 10^{-4}) (4.32)]^{1/5}$$

$$= 10.1 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot ^\circ\text{F}}$$

$$h_u = \frac{k_u}{L} (1.14) (Gr Pr)^{1/5}$$

$$= \frac{0.262}{2} (1.14) [(7.36 \times 10^{-4}) (1.35)]^{1/5}$$

$$= 18.3 \frac{\text{Btu}}{\text{m}^2 \cdot \text{ft}^2 \cdot ^\circ\text{F}}$$

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Finally the overall coefficient is given by

$$UA = \frac{1.0}{\frac{1}{hA} + R}$$

$$(UA)_{sm} = \frac{1.0}{\frac{1}{(10.1)(450.1)} + 0.00002398} = 4099 \frac{\text{BTU}}{\text{hr}^\circ\text{F}} = 1.139 \frac{\text{BTU}}{\text{sec}^\circ\text{F}}$$

$$(UA)_w = \frac{1.0}{\frac{1}{(18.3)(288.2)} + 0.00003747} = 4404 \frac{\text{BTU}}{\text{hr}^\circ\text{F}} = 1.223 \frac{\text{BTU}}{\text{sec}^\circ\text{F}}$$

Coefficients

a) upper drum

$$\left[\frac{UA}{(pvc)_{or}} \right] = \frac{1.139}{(482)(280.7)(.137)} = 0.00006145 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(pvc)_{sm}} \right] = \frac{1.139}{(8.545)(625.3)} = 0.0002132 \frac{\text{BTU/lbm}}{\text{sec}^\circ\text{F}}$$

$$\left(\frac{1}{pv} \right) = \frac{1.0}{(8.545)(625.3)} = 0.0001872 \text{ lbm}^{-1}$$

b) Lower drum

$$\left[\frac{UA}{(pvc)_{or}} \right] = \frac{1.223}{(482)(187.0)(.137)} = 0.00009904 \text{ sec}^{-1}$$

$$\left[\frac{UA}{(pvc)_w} \right] = \frac{1.223}{(40.32)(264.8)} = 0.0001145 \frac{\text{BTU/lbm}}{\text{sec}^\circ\text{F}}$$

$$\left(\frac{\Sigma p}{pv} \right) = \frac{0.963}{(40.32)(264.8)} = 0.00009020 \frac{\text{BTU/lbm}}{\text{lbm}^\circ\text{F}}$$

$$\left(\frac{1}{pv} \right) = \frac{1.0}{(40.32)(264.8)} = 0.00009366 \text{ lbm}^{-1}$$

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Summary

$$\dot{h}_{48} = -(0.0002132) T_{362} + (0.0002132) T_{49} \\ + (0.0001872) \dot{w}_s H_{356} - (0.0001872) \dot{w}_s h_{48}$$

$$\dot{T}_{49} = -(0.00006145) T_{49} + (0.00006145) T_{362}$$

$$\dot{h}_{50} = -(0.0001145) T_{363} + (0.0001145) T_{51} \\ + (0.00007366) \dot{w}_{\text{feed}} h_{\text{feed}} - (0.00009366) \dot{w}_w H_{357} \\ - (0.00009366) \dot{w}_r h_{50}$$

$$\dot{T}_{51} = -(0.00009904) T_{51} + (0.00009904) T_{363}$$

$$\dot{w}_s = \text{steam flow per loop} = \dot{w}_{81}$$

$$\dot{w}_{\text{feed}} = \text{feedwater flow per loop} = \dot{w}_{82}$$

$$\dot{w}_r = \text{total recirculated flow per loop} = \dot{w}_{85}$$

$$H_{356} = \text{saturated vapor enthalpy} = h_g = \dot{w}_{86}$$

$$H_{357} = \text{saturated liquid enthalpy} = h_f = \dot{w}_{87}$$

$$\dot{w}_w = \text{separated water flow per loop} = \dot{w}_{47}$$

The algebraic equations for the saturation enthalpies are

$$H_{356} = (1.0) \dot{w}_{86} F_{369} \quad ; \quad F_{369} = 1.0$$

$$H_{357} = (1.0) \dot{w}_{87} F_{369}$$

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The algebraic nodes for the drum

$$X_{368} = (1.0) \left(\frac{1}{h_{fg}} \right) h_{309} - (1.0) \left(\frac{h_E}{h_{fg}} \right) \bar{F}_{369} \quad ; \quad \bar{F}_{369} = 1.0$$

$$\dot{W}_{367} = (1.0) \dot{w}_r X_{368}$$

$$\dot{W}_{366} = (1.0) \dot{w}_r \bar{F}_{369} - (1.0) \dot{w}_r X_{368}$$

$$h_{365} = (1.0) \dot{w}_{enth} F_{369}$$

$\left(\frac{1}{h_{fg}} \right) =$ reciprocal of the difference in saturation enthalpies
 $= \dot{w}_{gr}$

$\left(\frac{h_E}{h_{fg}} \right) =$ ratio of the saturated liquid enthalpy to the
 difference in saturation enthalpies
 $= \dot{w}_{gg}$

$\dot{w}_r =$ total recirculation flow per loop $= \dot{w}_{gs}$

$\dot{w}_{enth} =$ feedwater enthalpy history $= \dot{w}_{75}$

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The nodes representing the temperature of the steam and water in the drum are connected to the corresponding enthalpy node by "flow equations". These equations can be used as appropriate curve fits, i.e. polynomials in h or as a function of time.

In general

$$k = \epsilon_1, \quad Z = \bar{h}_k = \text{nodal value}$$

1) $k < 0$

$$\dot{w} = \epsilon_2 Z + \epsilon_3 Z^2 + \frac{\epsilon_4}{Z} + \frac{\epsilon_5}{Z^2} + \epsilon_6 + \epsilon_7 Z^3 + \epsilon_8 Z^4 + \epsilon_9 Z^5 + \epsilon_{10} Z^6$$

2) $k \geq 0$

$$H = \begin{cases} 0, & k=0 \\ Z, & k>0 \end{cases} \quad R = \begin{cases} 0, & t \leq 0 \\ \epsilon_3 t + \epsilon_4 t^2, & t > 0 \end{cases}$$

a) $\epsilon_{10} = 0$

$$\dot{w} = H + R + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t + \epsilon_7 t^2)$$

b) $\epsilon_{10} > 0$

$$\dot{w} = \begin{cases} H + \epsilon_{10}, & t_m \leq 0 \\ H + R(t_m^*) + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t_m + \epsilon_7 t_m^2), & t_m > 0 \end{cases}$$

$$t_m = t - (t_s + \epsilon_8) \quad ; \quad t_m^* = \epsilon_9 - t_m$$

The steam node will be at saturated conditions for most of the considered transients. Consequently the temperature nodes depend directly on the pressure. If the pressure is prescribed for the particular transient, the associated saturation temperature is determined. Curve fits in the

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Form 2(a) or 2(b) would be used. For normal transients the pressure will be very near the full load operating level and the corresponding saturation temperature is approximately 676.5°F . One of the following forms may be used.

a) $\epsilon_1 = -48$

$\epsilon_6 = 676.5$, all other ϵ 's = 0

b) $\epsilon_1 = -369$

all ϵ 's = 0 except one $\epsilon = 676.5$

*c) $\epsilon_1 = 0$

$\epsilon_2 = 676.5$, all other ϵ 's = 0

For stringent conditions that deviate from the above, special considerations must be made.

The water node will be at a subcooled condition. The temperature will be a function of enthalpy for a given pressure. Curve fit in the form (1) is used.

The selected pressure is 2645 psia which is the pressure at the exit of the main heat transfer region of the evaporator and very nearly the pressure in the drum. The effect due to pressure variation will be small since properties of compressed water are a weak function of pressure.

The values of temperature-enthalpy were

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obtained from the GE Mark II steam tables (curve fits to Keenan & Keyes steam tables). GE Mark II program POLFIT was then used to obtain the coefficients for a polynomial curve fit.

$$T = -(247.953) + (2.06166)h - (1.10304 \times 10^{-3})h^2$$

valid for $T \leq T_{sat}$

Consequently

$$C_1 = -50$$

$$C_2 = 2.06166$$

$$C_3 = -1.10304 \times 10^{-3}$$

$$C_4 = 0$$

$$C_5 = 0$$

$$C_6 = -247.953$$

$$C_7 = 0$$

$$C_8 = 0$$

$$C_9 = 0$$

$$C_{10} = 0$$

In CEROS format the T mode is equated to the product of the flow equation with the unity mode.

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Summary

$$T_{362} = (1.0) W_{R2} F_{369} ; \quad \epsilon_1 = -48, -369, 070$$

$$T_{363} = (1.0) W_{13} F_{369} ; \quad \epsilon_1 = -50$$

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The curve defining each transient were rendered into approximate analytical form using the functions available in the CEROS flow equations. The time varying form of these equations are as follows:

$$\epsilon_1 (\text{integral}) \geq 0 \Rightarrow Z = F_{\epsilon_1} \begin{matrix} (\text{nodal}) \\ (\text{value}) \end{matrix} = 0 \quad \text{if } \epsilon_1 = 0$$

$$H = \begin{cases} 0, & \epsilon_1 = 0 \\ Z, & \epsilon_1 > 0 \end{cases}$$

$$R(t) = \begin{cases} 0, & t \leq 0 \\ \epsilon_3 t + \epsilon_4 t^2, & t > 0 \end{cases}$$

a) $\epsilon_{10} = 0$

$$\dot{\omega} = H + R(\bar{t}) + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t + \epsilon_7 t^2)$$

$$\bar{t} = t + \epsilon_9 \quad ; \quad \epsilon_8 = 0$$

b) $\epsilon_{10} > 0$

$$\dot{\omega} = \begin{cases} H + \epsilon_{10} & t_s \leq 0 \text{ and } t_m \leq 0 \\ H + R(t_m^*) + \epsilon_2 + \epsilon_5 \exp(\epsilon_6 t + \epsilon_7 t^2) & \end{cases}$$

$$t_m = t - (t_s + \epsilon_8) \quad t_s \text{ defined during CEROS run.}$$

$$t_m^* = t_m + \epsilon_9$$

The 10 ϵ 's completely define these flow equations. In order to simulate a particular transient curve the ϵ 's are specialized to a curve fit.

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Steady State values for flow equations.

$\dot{w}_{50}, \dot{w}_{57} \rightarrow \dot{w}_{71}, \dot{w}_{73}$ are curve fits connecting temperature and enthalpy nodes. These will not be changed during the transient.

$$\dot{w}_{47} = \dot{w}_w = 821.3$$

$$\dot{w}_{51} = \dot{w}_{52} = \dot{w}_{53} = \dot{w}_{54} = \dot{w}_{55} = \dot{w}_{56} = \dot{w}_{72} = T_{x1} = 676.5$$

$$\dot{w}_{74} = T_{in} = 960$$

$$\dot{w}_{75} = h_{feed} = 442.9$$

$$\dot{w}_{76} = \dot{w}_{wa} \text{ per module} = 1209$$

$$\dot{w}_{77} = \dot{w}_{wa} \text{ per SH tube} = 8.061$$

$$\dot{w}_{78} = \dot{w}_{wa} \text{ per EV tube} = 3.182$$

$$\dot{w}_{79} = \dot{w}_s \text{ per module} = 112.6$$

$$\dot{w}_{80} = \dot{w}_s \text{ per SH tube} = 0.7504$$

$$\dot{w}_{81} = \dot{w}_s \text{ per loop} = 337.7$$

$$\dot{w}_{82} = \dot{w}_{feed} \text{ per loop} = 337.7$$

$$\dot{w}_{83} = \dot{w}_r \text{ per module} = 386.2$$

$$\dot{w}_{84} = \dot{w}_r \text{ per EV tube} = 1.016$$

$$\dot{w}_{85} = \dot{w}_r \text{ per loop} = 1159$$

$$\dot{w}_{86} = \dot{h}_g = 1076.6$$

$$\dot{w}_{87} = \dot{h}_f = 750.2$$

$$\dot{w}_{88} = 1/\dot{h}_{fg} = 0.003064$$

$$\dot{w}_{89} = \dot{h}_f/\dot{h}_{fg} = 2.298$$

In all the above equations G_2 = particular value, all other G 's are 0.

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1) Normal Scram

$$T_{Na} = 960 + 0.20 t$$

$$\omega_{74}: \epsilon_2 = 960, \epsilon_3 = 0.20, \text{ all others } 0.$$

$$h_{feed} = 442.9$$

$$\omega_{75}: \epsilon_2 = 442.9, \text{ all others } 0.$$

same as steady state

$$\omega_{Na} = 0.95 e^{-0.09005t} + 0.05 \quad (\text{normalized})$$

$$\omega_{76}: \epsilon_2 = 60.45, \epsilon_5 = 1149, \epsilon_6 = -0.09005$$

$$\omega_{77}: \epsilon_2 = 0.4031, \epsilon_5 = 7.568, \epsilon_6 = -0.09005$$

$$\omega_{78}: \epsilon_2 = 0.1591, \epsilon_5 = 3.0229, \epsilon_6 = -0.09005$$

$$\omega_s = \omega_{feed} = 0.96 e^{-0.06539t} + 0.04 \quad (\text{normalized})$$

$$\omega_{79}: \epsilon_2 = 4.503, \epsilon_5 = 108.1, \epsilon_6 = -0.06539$$

$$\omega_{80}: \epsilon_2 = 0.03002, \epsilon_5 = 0.7204, \epsilon_6 = -0.06539$$

$$\omega_{81}: \epsilon_2 = 13.508, \epsilon_5 = 324.2, \epsilon_6 = -0.06539$$

$$\omega_{82}: \epsilon_2 = 13.508, \epsilon_5 = 324.2, \epsilon_6 = -0.06539$$

$$\omega_w = 1145.5 - 324.2 e^{-0.06539t}$$

$$\omega_{47}: \epsilon_2 = 1145.5, \epsilon_5 = -324.2, \epsilon_6 = -0.06539$$

$$P(t) = 2447 + 198 e^{-0.1333t}$$

Assuming an immediate adjustment to equilibrium and using the 1969 ASME Steam

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tables, the following analytical expressions for T_{sot} , h_f , h_g , h_{fg} are obtained.

$$T_{sot} = 664.9 + 11.6 e^{-0.1333t}$$

$$\dot{w}_{s1} \rightarrow \dot{w}_{s6} : E_2 = 664.9, E_5 = 11.6, E_6 = -0.1333 \text{ and } \dot{w}_{72}$$

$$h_g = 1099 - 22.4 e^{-0.1333t}$$

$$\dot{w}_{86} : E_2 = 1099, E_5 = -22.4, E_6 = -0.1333$$

$$h_f = 724.9 + 25.3 e^{-0.1333t}$$

$$\dot{w}_{87} : E_2 = 724.9, E_5 = 25.3, E_6 = -0.1333$$

$$1/h_{fg} = 0.002673 + 0.0003910 e^{-0.1333t}$$

$$\dot{w}_{88} : E_2 = 0.002673, E_5 = 0.0003910, E_6 = -0.1333$$

$$h_{hfg} = 1.938 + 0.360 e^{-0.1333t}$$

$$\dot{w}_{89} : E_2 = 1.938, E_5 = 0.360, E_6 = -0.1333$$

All other flow equations constant at their steady state values.

2) Seizure of one Secondary Pump with Scream

This transient is identical with normal Scream with the following exceptions.

$$T_{IN} = 960$$

$$\dot{w}_{74} : E_2 = 960, \text{ (same as steady state)}$$

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$$\omega_{Na} = 0.95 e^{-0.1689t} + 0.05$$

$$\omega_{76}: \epsilon_2 = 60.45, \epsilon_5 = 1.49, \epsilon_6 = -0.1689$$

$$\omega_{77}: \epsilon_2 = 0.4031, \epsilon_5 = 7.568, \epsilon_6 = -0.1689$$

$$\omega_{78}: \epsilon_2 = 0.1591, \epsilon_5 = 3.0229, \epsilon_6 = -0.1689$$

3) Single primary pump seizure with scram

This transient is identical with normal Scram with the following single exception.

$$T_{Na} = \begin{cases} 960 & 0 \leq t \leq 100 \\ 960 - 2.87t & 100 \leq t \leq 200 \\ 673 & t \geq 200 \end{cases}$$

In order to implement this 2 flow equations are needed. ω_{49} is added to the already used ω_{74} .

$$T_{Na} = F_{364} = (1.0)\omega_{74} F_{369} + (1.0)\omega_{49} F_{369}; F_{369} = 1.0$$

is the new algebraic equation required. Node 220 which represents time is also added. Provision for a "Reactor Scram" at ~~100~~ are made; this will define $t_s = 100$.

$$\omega_{74}: \epsilon_2 = 960, \epsilon_3 = -2.87, \epsilon_0 = 960$$

$$\omega_{49}: \epsilon_3 = 2.87, \epsilon_8 = 100, \epsilon_{10} = 1.0 \times 10^{-6} \text{ (a very small + number for getting control needs)}$$

ω_{74} is a ramp down delayed by $t_s = 100$ sec. ω_{49} is a ramp ~~up~~ delayed by $t_s + t_s = 200$ sec. Consequently after 200 sec the two ramps add to cancel further changes in T_{Na} .

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4) Loss of one Circulation pump

One pump goes off line in 3 seconds and the flow reduces to 66%. A 15 second delay at 66% flow is assumed, and then the standby pump cuts in. The flow returns to 100% in 12 seconds. All other flow equations remaining at the 100% load steady state.

$$W_r = \begin{cases} 1 - 0.1133t & 0 \leq t \leq 3 \\ 0.66 & 3 \leq t \leq 18 \\ 0.66 + 0.02833t & 18 \leq t \leq 30 \\ 1.0 & t \geq 30 \end{cases}$$

For ease of implementation node 355 is added and coupled to 4 new flow equations 41, 42, 43, 44. This will give the normalized circulation flow. Flow equations 83, 84, 85 are coupled to 355 with the appropriate constant to adjust the flow to module, evaporator tube, and loop levels. In addition node 220, representing time is coupled to the "Reactn Schem" option to define $t_s = 0$.

$$F_{355} = (1.0)W_{41} F_{369} + (1.0)W_{42} F_{369} + (1.0)W_{43} F_{369} + (1.0)W_{44} F_{369}$$

where $F_{369} \equiv 1$.

$$\begin{aligned} W_{41}: & \quad E_2 = 1.0, \quad E_3 = -0.1133, \quad E_{10} = 1.0 \times 10^{-8} \\ W_{42}: & \quad E_3 = 0.1133, \quad E_8 = 3.0, \quad E_{10} = 1.0 \times 10^{-8} \\ W_{43}: & \quad E_3 = 0.02833, \quad E_8 = 18.0, \quad E_{10} = 1.0 \times 10^{-8} \\ W_{44}: & \quad E_3 = -0.02833, \quad E_8 = 30.0, \quad E_{10} = 1.0 \times 10^{-8} \end{aligned}$$

small +
number is
required
in option
control

At the appropriate delay times, 6 new flow equations are introduced to counteract previous changes or to effect new changes.

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$$W_{83}: E_1 = -355; E_2 = 386.2$$

$$W_{84}: E_1 = -355; E_2 = 1.016$$

$$W_{85}: E_1 = -355; E_2 = 1159$$

E_1 is selected as -355 , for option control and 355 for coupling to the appropriate mode.

5) Power ramp from 100% load to 40% load.

Mode 220 representing time is coupled to the "Reactn Scram" option to define $t_s = 0$.

$$T_{Na} = \begin{cases} 960 - 0.03t & t \leq 1200 \\ 924 & t > 1200 \end{cases}$$

An additional flow equation is required

$$T_{in} = F_{364} = (1.0) W_{74} F_{369} + (1.0) W_{49} F_{369}$$

$$W_{74}: E_2 = 960, E_3 = -0.03, E_{10} = 1.0 \times 10^{-8} *$$

$$W_{49}: E_3 = 0.03, E_8 = 1200, E_{10} = 1.0 \times 10^{-8} *$$

$$N_{reed} = \begin{cases} 442.9 - 0.08008t & t \leq 1200 \\ 346.4 & t > 1200 \end{cases}$$

An additional flow equation is required

$$h_{reed} = F_{365} = (1.0) W_{75} F_{369} + (1.0) W_{48} F_{369}$$

$$W_{75}: E_2 = 442.9, E_3 = -0.08008, E_{10} = 1.0 \times 10^{-8} *$$

$$W_{48}: E_3 = 0.08008, E_8 = 1200, E_{10} = 1.0 \times 10^{-8} *$$

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$$w_s = w_{\text{seed}} = \begin{cases} 1 - 0.000525t & t \leq 1200 \\ 0.37 & t > 1200 \end{cases}$$

Node 355 is added to compute the normalized value of w_s, w_{seed} . This value is coupled into the appropriate flow equation with the correct scale factor.

$$F_{355} = (1.0) w_{45} F_{369} + (1.0) w_{44} F_{369}$$

$$w_{44}: \quad E_2 = 1.0, \quad E_3 = 0.000525, \quad E_{10} = 1.0 \times 10^{-8}$$

$$w_{45}: \quad E_3 = 0.000525, \quad E_6 = 1200, \quad E_{10} = 1.0 \times 10^{-8}$$

and

$$w_{79}: \quad E_1 = -355, \quad E_2 = 112.6$$

$$w_{80}: \quad E_2 = -355, \quad E_1 = 0.7504$$

$$w_{81}: \quad E_1 = -355, \quad E_2 = 337.7$$

$$w_{82}: \quad E_1 = -355, \quad E_2 = 337.7$$

E_1 is selected as -355 for option control and proper coupling to node.

$$w_w = \begin{cases} 821.3 + 0.1773t & t \leq 1200 \\ 1034.0 & t > 1200 \end{cases}$$

Node 50 must be coupled to both flow equations defining w_w .

$$h_{50} = F_{50} = \dots + (1.0) w_{47} F_{357} + (1.0) w_{46} F_{357}$$

$$F_{357} = h_g$$

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$$W_{46}: E_2 = 821.3, E_3 = 0.1773, E_{10} = 1.0 \times 10^{-8} *$$

$$W_{47}: E_3 = -0.1773, E_8 = 1200, E_{10} = 1.0 \times 10^{-8} *$$

$$W_{49} = \begin{cases} 1.0 - 0.0005042t & t \leq 1200 \\ 0.395 & t > 1200 \end{cases}$$

Node 354 adds the two square flow equations. Then the sodium flow is coupled into the proper equations with appropriate scale factors

$$W_{49} = F_{354} = (1.0) W_{42} F_{369} + (1.0) W_{43} F_{369}$$

$$W_{42}: E_2 = 1.0, E_3 = -0.0005042, E_{10} = 1.0 \times 10^{-8} *$$

$$W_{43}: E_3 = 0.0005042, E_8 = 1200, E_{10} = 1.0 \times 10^{-8} *$$

and

$$W_{76}: E_1 = -354, E_2 = 1209$$

$$W_{77}: E_1 = -354, E_2 = 8.061$$

$$W_{78}: E_1 = -354, E_3 = 3.182$$

* $E_{10} = 1.0 \times 10^{-8}$ is used for option control only.