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ANALOG SIMULATION OF
SODIUM-HEATED STEAM
GENERATOR - A PROGRESS
REPORT

RESEARCH CENTER
REPORT NO. 5132

BY: J. S. IYER

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ANALOG SIMULATION OF SODIUM-HEATED
STEAM GENERATOR - A PROGRESS REPORT

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JANUARY 31, 1967

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THE BABCOCK & WILCOX COMPANY
RESEARCH CENTER
ALLIANCE, OHIO

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ABSTRACT - (Cont'd.)

Results - (Cont'd.)

results of the dynamic model, employing design surface areas, were compared with predicted steady state design performance. The results were found to agree reasonably well.

The dynamic response of the model was then obtained at 100% load using actual installed areas of the prototype. Step perturbations of the following variables were studied:

- a. Feedwater Flow
- b. Feedwater Temperature
- c. Sodium Flow
- d. Sodium Temperature
- e. Intermediate Spray Flow
- f. Spray Temperature

Among others, the responses of the following variables were recorded for each of the above listed perturbations:

- a. Main Steam Flow
- b. Main Steam Temperature
- c. Boiler Outlet Flow
- d. Boiler Outlet Temperature
- e. Sodium Outlet Temperature

Recommendations

The following recommendations can be made:

1. The present model should be converted to a wide-range model by employing the relationships between the flow rates of sodium and water (steam) and their respective heat transfer coefficients.

2. Pressure drop information should be incorporated in the model.

3. Further open-loop responses should be obtained with the above changes and then compared with the results of the testing at the SCTI.

4. The model should be refined to make its performance compatible with the actual performance of the prototype.

5. With the knowledge gained from the refined model, the performance of a single full-size steam generator should be simulated.

6. The dynamic behavior of three full-size steam generators operating in parallel should be modeled and both open- and closed-loop control studies performed on the final simulation.

1.0 INTRODUCTION

The demand for economical power generation has prompted us to seek better heat carriers for heat transfer apparatus. Recent emphasis has been placed on the use of liquid metals as the heat transfer media for nuclear reactors. This is primarily because liquid metals hold promise for large breeder reactors, which will probably be required for the next generation of nuclear power plants.

In a full size plant (~ 1000 MWe) present plans call for the liquid metal to be circulated through three parallel loops to heat the secondary liquid metal in intermediate heat exchangers (IHX). (See Figure 1.1.) The secondary liquid metal is then used to generate steam in a tubular steam generator.

New to the industry is the operation of three parallel systems, IHX plus steam generator. In addition, the dynamic response of liquid metal to liquid metal heat exchangers and liquid metal-heated steam generators will be decidedly faster than the response of fossil fuel-fired heat exchangers. This is due to the high heat transfer coefficients possessed by liquid metals as opposed to the relatively low coefficients of hot gases. Successful control of these systems therefore presents problems not faced before.

The present status of technology is not sufficiently advanced to predict adequately the performance and dynamic behavior of liquid metal systems in parallel arrangements. We have, therefore, felt it necessary to begin solving this problem by formulating a mathematical model of a sodium-heated steam generator. The model attempts to describe the dynamic characteristics of the Babcock & Wilcox 30 MWt Prototype Sodium Heated Steam Generator to be installed at the Sodium Components Testing Installation (SCTI), Canoga Park, California. After conducting tests on the prototype, it should be possible to correct the model so it adequately represents component performance. Our knowledge would be sufficiently advanced at that time to formulate an overall system model including parallel loops for control study and development.

This report presents the progress made during 1966 in developing the model for the 30 MWt steam generator.

2.0 RESULTS

A model having constant heat transfer coefficients at each load has been completely debugged on the analog computer at each of five different load points. The development of the basic system equations that went into the model are included in Appendix A. The scaled and unscaled equations are presented in Appendix B. The wiring diagram for the model is given in Figure 2.1. Potentiometer settings for all loads are in Appendix B.

The steady state results of the dynamic model, employing design surface areas, were compared with predicted steady state design performance. The results were found to agree reasonably well as shown in Table 2.1.

The dynamic response of the model was then obtained at 100% load using actual installed areas of the prototype. Step perturbations of the following variables were studied:

- a. Feedwater Flow (Figures 6.1 and 6.2)
- b. Feedwater Temperature (Figures 6.3 and 6.4)
- c. Sodium Flow (Figures 6.5 and 6.6)
- d. Sodium Inlet Temperature (Figures 6.7 and 6.8)
- e. Intermediate Spray Flow (Figures 6.9, 6.10, and 6.11)
- f. Spray Temperature (Figures 6.12 and 6.13)

As shown on the above listed figures, the responses of the following variables were recorded for each perturbation:

- a. Main Steam Flow
- b. Main Steam Temperature
- c. Boiler Outlet Flow
- d. Boiler Outlet Temperature
- e. Sodium Outlet Temperature

In addition, changes in the respective lengths of the subcooled and saturated zones of the boiler were also recorded.

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3.0 RECOMMENDATIONS

The following recommendations can be made:

1. The present model should be converted to a wide-range model by employing the relationships between the flow rates of sodium and water (steam) and their respective heat transfer coefficients.
2. Pressure drop information should be incorporated in the model.
3. Further open-loop responses should be obtained with the above changes and then compared with the results of the testing at the SCTI.
4. The model should be refined to make its performance compatible with the actual performance of the prototype.
5. With the knowledge gained from the refined model, the performance of a single full-size steam generator should be simulated.
6. The dynamic behavior of three full-size steam generators operating in parallel should be modeled and both open- and closed-loop control studies performed on the final simulation.

4.0 SYSTEM DESCRIPTION

The complete schematic of a full-size nuclear power plant with its main components is shown in Figure 1.1. There are three identical secondary heat exchange circuits and the steam generator forms the final loop in each of these three circuits. The steam generator is heated by sodium from an intermediate heat exchanger (IHX). The IHX provides the heat sink for the reactor.

The SCTI is a 35-MW design capacity fossil-fuel-fired test installation with a primary and secondary system; a sodium-heated steam generator; a pressure-reducing system and desuperheater to simulate the turbine; a condenser; and a feedwater heating system.

The system is designed to impose the same transients on a sodium-to-sodium heat exchanger and on a sodium-heated once-through steam generator that would occur if the equipment were part of a nuclear steam plant.

The detailed steam generator and secondary sodium loops as utilized in a power plant are shown in Figure 4.1. The steam generator is comprised of a single vertical shell housing both the boiler bank and the secondary superheater (Figure 4.2). The sodium flows on the outside of the coils and is contained in an annulus between an outside and an inside metal shroud.

The boiler bank and the superheater are in the form of helical coils, with coils on different radii and several tubes per coil (Figure 4.3). The lower portion of the boiler bank forms the economizer and the upper portion the primary superheater (hereafter designated as superheat region). Between the boiler bank and the secondary superheater (hereafter called the superheater) the steam passes through a single interconnecting pipe wherein spray water can be injected from an intermediate spray control.

The steam generator is a counterflow heat exchanger with sodium flowing vertically downwards and the water rising in the helical coils to the top of different coil radii. Similarly, the superheater has 45 tubes with 5 coils. See Figure 4.3.

For further details on the system description of the Prototype Steam Generator, refer to Babcock & Wilcox Company Report No. BAW-1280-28, Volumes 1 to 4.

5.0 ANALOG MODEL AND ASSUMPTIONS

5.1 Analog Model

The system boundary of the steam generator loop that is simulated on the analog computer is shown in Figure 4.2. Modeling techniques are developed by means of a simplified steam generator that resembles the configuration of the prototype steam generator. For modeling purposes parallel flow circuits are lumped into a single flow path having average conditions.

The model is presently based on a two-dimensional (space and time) approach using lumped parameter techniques (Space-Lumped, Continuous Time Model). It is a model having constant heat transfer coefficients and constant inlet pressure at each operating point. As such, it is only valid for studying small disturbances around the particular load point.

5.1.1 Boiler Section

From Figure 5.1 it is clear that the inside diameter of the boiler tubes varies in the three regions due to different metal wall thicknesses, the outside diameter being fixed. This is not very convenient for analog simulation, especially since the diameter variation is not continuous.

Thus, the first simplification is made by assuming a continuous change in inside diameter with the ID at the two ends of the tube remaining the same as per design data. An equivalent boiler tube was, therefore, assumed. (See Figure 5.3.) This eliminates sudden changes in fluid velocity at the point where the inside diameter changes abruptly. The metal wall thickness and thus the metal mass/foot also vary continuously along the length of the tube.

The sodium cross-sectional flow area, however, is constant throughout the boiler section, and is obtained by assuming a sodium flow path equal to the length of the boiler tube and dividing this length into the sodium volume associated with one tube.

The two fixed boundaries are the ends of the tube designated as 5 and 2. (See Figure 5.3.) Positions of the boundaries 4 and 3 are time dependent. Boundary 4 denotes the transition point from subcooled water to a mixed or saturation region with two-phase flow. Boundary 3 denotes the transition point

from a mixture to a pure vapor. Therefore, the boiler tank is simulated by a variable length model with moving boundaries. The total length of the boiler bank, however, remains fixed.

Even though the sodium does not undergo a change of phase, it too has moving boundaries since the sodium volume associated with a water volume has moving boundaries. The same is applicable for the tube metal wall.

5.1.2 Superheater Section

From Figure 5.2 it is seen that the superheater is a fixed length model with water cross-sectional flow area remaining constant as also the metal wall thickness and sodium flow area. The water in the superheater exists only in one phase and that is as steam throughout the unit.

5.1.3 Interconnecting Pipe and Spray

The total flow from the boiler section passes through a single pipe before entering the superheater. Herein spray water may be injected to control the degree of superheating of the final steam.

5.2 Assumptions

The success of the single-tube generator model studies are dependent on making certain arbitrary assumptions for problem simplification. Thus, we make the following assumptions:

1. No axial heat conduction occurs along the tube walls.
2. The pressure on the sodium side is assumed to be constant throughout the steam generator.
3. The two-phase regime will be assumed to have no slip and, therefore, a mean velocity based on a homogeneous mixture will be used.
4. No heat loss occurs in the interconnecting pipe between boiler exit and superheater inlet.
5. A complete and instantaneous mixing of spray water with boiler water is assumed.

6.0 DISCUSSION

6.1 Feedwater Pump Flow - Figures 6.1 and 6.2

Figures 6.1 and 6.2 show the responses of the sodium-heated steam generator to both a step increase and a step decrease in feedwater pump flow. Because the response for a decrease is much the same as that for an increase, except that all variables behave in the opposite direction, only the increase will be discussed. The reader can note from observing Figure 6.1 that both the boiler outlet flow and the main steam flow increase rapidly initially, then drop off, and finally increase again to a final steady state value. The initial surge in flow is caused by the step increase in flow at the inlet. However, this increase causes a general cooling effect throughout the steam generator which increases the mean fluid density and thus increases the fluid storage of the heat exchanger. This results in a drop in steam flows (leaving boiler and superheater) proportional to the rate of storage. As the rate of storage decreases, the flows then increase to their final values.

If one observes the boiler outlet temperature and the main steam temperature, he will note that these appear to be directly tied to the boiler flow and the main steam flow. Considering the fact that higher steam flows mean lower steam temperatures for the same heat input, this behavior is what would be expected from the actual unit. The outlet sodium temperature from the steam generator shows an initial increase followed by a reversal and finally a net decrease in final value. The final decrease in outlet sodium temperature is expected. However, no explanation is available for the initial rise in outlet temperature.

In observing the responses of the subcooled and saturation lengths, we find some rather interesting characteristics. As would be expected, the subcooled length does increase. This is due to the fact that with the higher flow, more heat must be absorbed in the subcooled region and consequently a greater length is required. The initial decrease in the saturation length is caused by the subcooled region's initial rapid growth into the saturation region. After the end point of the saturation has begun to move, we find that the net overall effect is also an increase in the length of the saturation region.

It should be noted at this point that all variables have leveled out within two minutes of the disturbance. This gives a very good indication that the steam generator is a very rapidly responding system.

6.2 Feedwater Inlet Temperature - Figures 6.3 and 6.4

The responses of the analog model to disturbances in inlet feedwater temperature are somewhat puzzling due to the so-called "see-saw" effect. This effect, a direct result of the space-lumping technique, can cause rapid oscillations about an average point in a given space lump; thus, it is necessary to differentiate between the see-saw oscillations and the actual model response of the steam generator.

The two initial swings in boiler outlet flow and main steam flow appear to be caused by the space-lumping technique and it is only the final increase which seems to be indicative of actual process behavior. If we ignore the first two swings, the reader can note that both flows show a rapid increase and then return to the initial operating flow. This behavior can be explained by realizing that increasing the inlet feedwater temperature causes a general decrease in the amount of storage (lower density) contained within the generator. Thus, the extra flow results from the steam generator losing some of its fluid storage. As the release of stored fluid decreases, the flows then return to their original values.

Much the same can be said for both boiler outlet temperature and main steam temperature, the first initial swings being the result of the modeling technique and only the final swing being of significance. Both temperatures show an initial dip due to the increase in flow; however, as flow returns to its initial value, the boiler outlet temperature and the main steam temperature deviations then cross zero and show a final net increase. This, of course, is due to the higher inlet temperature that we are now feeding our system. As would be expected, the exit sodium temperature also increases due to increases in feedwater temperature.

The reader may note here that the subcooled length shows a general decrease. This is not surprising when one realizes that we are now entering our unit with water closer to the saturation point. Therefore, less length is required to

bring this water up to saturation temperature. As the subcooled length of the generator expands into the saturation region, it does cause a momentary decrease in saturation length. However, the overall effect in saturation length is merely a slight increase. The slight increase is caused by the smaller temperature difference between the sodium and the water over which we now transfer heat.

6.3 Sodium Flow - Figures 6.5 and 6.6

As would be expected, increases in sodium flow cause momentary increases in both boiler outlet flow and main steam flow with both of these flows returning to their initial value. This behavior is caused by the release of stored fluid within the heat exchanger due to the higher steam temperature. Both steam temperatures and the outlet sodium temperature increase as expected. A point of interest in these responses is the initial dip in boiler outlet temperature. This dip is brought about by the temporary increase in boiler outlet flow. If one observes the lengths of subcooled and saturation regions, we find that they behave as expected; that is, the higher sodium flow results in shorter regions of subcooling and saturation.

6.4 Sodium Temperature - Figures 6.7 and 6.8

The system response to a step increase in sodium inlet temperature is to shorten the regions of subcooling and saturation and to show a general increase in boiler outlet temperature, main steam temperature and outlet sodium temperature. This behavior is what we would expect in view of what has been said about the previous disturbances. The initial oscillations in steam flows again seem to be a result of the simulation technique and we need only consider the final increase in steam flow and observe the return to original value. This can be explained in terms of fluid storage.

6.5 Spray Flow - Figures 6.9, 6.10, and 6.11

Figures 6.9, 6.10, and 6.11 show the response of our system to various types of disturbances in main steam spray. Figure 6.9 gives the response for a step increase from zero per cent spray to a value of spray flow equal to $7\frac{1}{2}$ per cent of the feedwater flow. The next two figures show an increase and decrease in spray flow equal to $7\frac{1}{2}$ per cent of the feedwater flow when operating from an initial base of $7\frac{1}{2}$ per cent spray. When looking at these three figures, we find that all variables respond in a similar manner. That is, they behave in a

manner consistent with the direction of the disturbance. The exception to this is the outlet sodium temperature which we will comment on later. Looking at the other variables, we find that increasing the spray flow causes a decrease in main steam temperature, as would be expected. The steam flow responses show no final change in the main steam flow, but we find there is a decrease in boiler outlet flow. This is caused by the nature in which spray is used in this unit. The spray flow is taken out of the pump feeding the inlet to the steam generator and inserted in the intermediate pipe between the boiler and the superheater. Consequently, the superheater flow and therefore the main steam flow should show no net change. The only flow that would decrease would be the boiler outlet flow which would be decreased by an amount equal to the spray flow. The main steam flow shows an initial surge due to the step injection of fluid into the superheater entrance, but, as the system levels out, the main steam flow returns to its original value. The boiler outlet flow also shows an initial decrease due to the dropping of its inlet flow but then surges momentarily and finally settles out. The surge is caused by a general heating up in the boiler which results in a release of stored fluid. The boiler outlet flow finally obtains its lower value when the release of stored fluid has subsided.

The reader may be somewhat concerned by the drop in boiler outlet temperature as shown on our responses. This is caused by the location at which we are measuring this temperature. It is actually the steam temperature after spray and, therefore, it is immediately affected by spray. As a result of the spray, there is a step decrease in steam temperature immediately after the spray nozzle. However, the decreased flow in the boiler (caused by by-passing spray around the boiler) results in a gradual temperature rise superimposed on this step decrease. It can be surmised that the boiler outlet temperature before the nozzle increases by observing the responses of the subcooled and saturation lengths. Due to the lower flow, we reach a saturated water condition sooner, and consequently a shorter subcooled length, than we did before the disturbance. The saturation length also becomes shorter because of the lower flow with a slight reversal due to the contraction of the subcooled region. Thus, there is a greater superheat region in the boiler and the net result is an increase in boiler outlet temperature.

When making changes in spray flow, we would expect that a decrease in main steam temperature would be followed with an increase in sodium temperature. That is, when main steam temperature decreases, this indicates less heat absorbed by the steam, and, consequently, would mean less heat released by the sodium which would give us a higher sodium outlet temperature. It is only in Figure 6.10 that we see such a response. The apparent error in Figures 6.9 and 6.11 is not explainable at this time.

6.6 Spray Water Temperature - Figures 6.12 and 6.13

Figures 6.12 and 6.13 show the responses of our system to a step increase and decrease in spray water temperature with spray flow set at $7\frac{1}{2}$ per cent of normal pump flow. Referring to the step increase in Figure 6.12, we note that there is a general overall increase in outlet steam and sodium temperatures as expected.

The boiler outlet temperature shows a step increase due to the step in spray water temperature and then shows a gradual increase as the sodium temperature rises due to the general increase in the system energy level. The main steam temperature also shows an increase as well as the sodium outlet temperature. Because the sodium is now hotter in general throughout the entire heat exchanger, we find that we are able to pass through the subcooled and saturation regions in a shorter length of heat exchanger. Both steam flows, the boiler outlet flow and the main steam flow, show slight increases in value and finally level out to the same values they had initially. This is due to the release of fluid stored within the steam generator.

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TABLES

TABLE 2.1 - COMPARISON OF ANALOG STEADY STATE
SOLUTIONS WITH DESIGN VALUES

		VARIABLE	PERCENT LOAD				
			100	80	60	40	20
INPUTS		Sodium Flow lb/hr	583,500	473,000	352,000	234,000	117,000
		Sodium Inlet Temp. °F	1140	1120	1104	1086	1068
		Feedwater Flow lb/hr	88,750	71,000	53,200	35,500	17,750
		Feedwater Temp. °F	530	505	475	430	370
OUTPUTS	DESIGN	Sodium Outlet Temp. °F	650	627	597	546	493
		Boiler Outlet Temp. °F	750	745	740	735	730
		Superheater Outlet Temp. °F	1050	1050	1050	1050	1050
	ANALOG	Sodium Outlet Temp. °F	649	649	597	535	510
		Boiler Outlet Temp. °F	788	785	814	794	1044
		Superheater Outlet Temp. °F	1075	1076	1107	1072	1074

FIGURES

FIGURE 1.1

A FULL SIZE LIQUID-METAL COOLED NUCLEAR POWER PLANT
(1000 MWe PLANT)

Wiring Diagram - Sodium-Heated Steam Generator

Figure 2.1

(in envelope on back cover)

FIGURE 4.1

DETAIL OF STEAM GENERATOR LOOP

FIGURE 4.2

SCHEMATIC OF STEAM GENERATOR

FIGURE 4.3

COIL NO.	TUBES / COIL
1	4
2	5
3	5
4	5
5	6

COIL NO.	TUBES / COIL
1	8
2	9
3	9
4	9
5	10

BOILER AND SUPERHEATER BUNDLES

FIGURE - 5.1

A TYPICAL BOILER TUBE

FIGURE -5.2 A TYPICAL SUPERHEATER TUBE

FIGURE -5.3 EQUIVALENT SINGLE TUBE BOILER

FIGURE 6.1

FIGURE 6.2

FIGURE 6.3

FIGURE 6.4

FIGURE 6.5

FIGURE 6.6

FIGURE 6.7

FIGURE 6.8

FIGURE 6.9

FIGURE 6.10

FIGURE 6.11

FIGURE 6.12

FIGURE 6.13

LIST OF SYMBOLS

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
W	- Flow rate	lb/sec-tube
L	- Length	ft
ρ	- Density	lb/cu ft
h	- Enthalpy	Btu/lb
	or Local heat transfer coefficient	Btu/sec-F-sq ft
T	- Temperature	F
K	- Volume per unit length	cu ft/ft
U	- Heat transfer coefficient	Btu/sec-F-sq ft
C_p	- Specific heat	Btu/lb-F
V	- Volume	cu ft
A	- Area	sq ft
p	- Perimeter	ft
m	- Mass per unit length	lb/ft
D	- Diameter	in.
d	- Diameter	in.
x	- Location from entrance	ft
MWe	- Megawatts electric	
MWt	- Megawatts thermal	

Subscripts

w	- Water
m	- Tube wall metal
s	- Steam
i	- Location in system, 1, 2, 3, ...

LIST OF SYMBOLS - (Cont'd.)

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
sp	- Spray	
n	- Sodium	
sat	- Saturation	
g	- Saturated steam	
f	- Saturated water	
sH	- Superheater	
sc	- Subcooled	
mwi	- Tube metal to water in ith region	
nmi	- Sodium to tube metal in ith region	

APPENDIX A

DEVELOPMENT OF SYSTEM EQUATIONS

APPENDIX A

DEVELOPMENT OF SYSTEM EQUATIONS

A-1 EXACT SYSTEM EQUATIONS

The simulation is based on the assumption that the system pressure is high enough to neglect any pressure effects on the thermodynamic properties of water, steam and sodium. Also since we are only doing open loop studies, therefore we shall not consider the conservation of momentum.

All subsequent equations are written on a per tube (boiler and superheater) basis.

1.0 BOILER SECTION

1.1 SYSTEM CONSTRAINTS

a. Water Side

Inside diameter at any length x from boiler inlet

$$D_x = 0.736 - 7.399 \times 10^{-4} x \quad (1)$$

where x is in feet and D_x in inches.

Diameters at various regional boundaries

$$D_{w5} = 0.7360 \text{ in.} \quad (2)$$

$$D_{w4} = 0.736 - 7.399 \times 10^{-4} L_{w4} \quad (3)$$

$$D_{w3} = 0.736 - 7.399 \times 10^{-4} L_{w3} \quad (4)$$

$$D_{w2} = 0.736 - 7.399 \times 10^{-4} L_{w2} = 0.637 \text{ in.} \quad (5)$$

$$L_{w4} + L_{w3} + L_{w2} = L_{\text{Total}} \quad (6)$$

b. Metal Wall

Wall thickness at any length x from boiler inlet

$$t_{mx} = \frac{1.00 - D_x}{2} \quad (7)$$

or

$$t_{mx} = 3.699 \times 10^{-4} x + 0.132 \quad (7a)$$

Metal Density

A constant metal density is assumed for all regions.

$$\rho_m = 488 \text{ lb/ft}^3 \quad (8)$$

c. Sodium

Equivalent sodium cross-sectional flow area and equivalent diameter (from Design Data)

$$A_{nb} = 7.1318 \times 10^{-3} \text{ ft}^2 \quad (9)$$

$$D_{nbe} = 1.5193 \text{ in.} \quad (10)$$

These are constants throughout the boiler section for all regions.

1.2 CONSERVATION OF MASS (CONTINUITY)

a. Subcooled Region (Region 4)

$$\text{water side} \quad W_{w5} - W_{w4} = \frac{d}{dt} (V_{w4} \bar{\rho}_{w4}) \quad (11)$$

$$\text{sodium side} \quad W_{n4} - W_{n5} = \frac{d}{dt} (V_{n4} \bar{\rho}_{n4}) \quad (12)$$

b. Saturation Region (Region 3)

$$W_{w4} - W_{w3} = \frac{d}{dt} (V_{w3} \bar{\rho}_{w3}) \quad (13)$$

$$W_{n3} - W_{n4} = \frac{d}{dt} (V_{n3} \bar{\rho}_{n3}) \quad (14)$$

c. Superheat Region (Region 2)

$$W_{w3} - W_{w2} = \frac{d}{dt} (V_{w2} \bar{\rho}_{w2}) \quad (15)$$

$$W_{n2} - W_{n3} = \frac{d}{dt} (V_{n2} \bar{\rho}_{n2}) \quad (16)$$

1.3 CONSERVATION OF ENERGY

The second law of thermodynamics for a control volume system, in the absence of shaft work, electrical and magnetic fields, neglecting kinetic and potential energies reduces to

$$Q - \int_{cs} h_p(\vec{v} \cdot \vec{n}) dA = \frac{d}{dt} \int_{cv} (up) dv \quad (17)$$

This states that the sum of the net heat transported (flow energy) into the system and the net heat transferred into the system (heat flow across the boundary with no mass transfer) is equal to the rate of change of energy stored within the system boundaries. This stored energy may be a gain or loss depending upon the boundary movements.

$$Q = UA\Delta T \quad (18)$$

All heat transfer coefficients U are based on outside diameter of tubes. Hence the heat transfer surface area is also evaluated on the outside diameter basis and since the tube OD is constant the area is a function of length only.

$$A_{ht} = \text{Heat Transfer Area} = 0.2618 L_{wi} \quad (19)$$

where L_{wi} is the length of the region; $i = 2, 3, \text{ or } 4$

With the aid of equations (17), (18) and (19) one can now easily write down the energy equations for the different regions as shown below (assuming $h=u$).

a. Subcooled Region

Water Side

$$W_{w5}h_{w5} - W_{w4}h_{w4} + 0.2618U_{mw4}L_{w4}(\bar{T}_{m4} - \bar{T}_{w4}) = \frac{d}{dt} \{ \bar{\rho}_{w4}V_{w4}\bar{h}_{w4} \} \quad (20)$$

Metal

$$\begin{aligned}
 0.2618U_{nm4}L_{w4}(\bar{T}_{n4}-\bar{T}_{m4}) - 0.2618U_{mw4}L_{w4}(\bar{T}_{m4}-\bar{T}_{w4}) \\
 = C_p \rho_m V_{m4} \frac{d}{dt} (\bar{T}_{m4})
 \end{aligned} \quad (21)$$

Sodium

$$W_{n4}h_{n4} - W_{n5}h_{n5} - 0.2618U_{nm4}L_{w4}(\bar{T}_{n4}-\bar{T}_{m4}) = \frac{d}{dt} (\bar{\rho}_{n4}V_{n4}h_{n4}) \quad (22)$$

b. Saturation Region

$$W_{w4}h_{w4} - W_{w3}h_{w3} + 0.2618U_{mw3}L_{w3}(\bar{T}_{m3}-\bar{T}_{w3}) = \frac{d}{dt} (\bar{\rho}_{w3}V_{w3}h_{w3}) \quad (23)$$

$$\begin{aligned}
 0.2618U_{nm3}L_{w3}(\bar{T}_{n3}-\bar{T}_{m3}) - 0.2618U_{mw3}L_{w3}(\bar{T}_{m3}-\bar{T}_{w3}) \\
 = C_p \rho_m V_{m3} \frac{d}{dt} (\bar{T}_{m3})
 \end{aligned} \quad (24)$$

$$W_{n3}h_{n3} - W_{n4}h_{n4} - 0.2618U_{nm3}L_{w3}(\bar{T}_{n3}-\bar{T}_{m3}) = \frac{d}{dt} (\bar{\rho}_{n3}V_{n3}h_{n3}) \quad (25)$$

c. Superheat Region

$$W_{w3}h_{w3} - W_{w2}h_{w2} + 0.2618U_{mw2}L_{w2}(\bar{T}_{m2}-\bar{T}_{w2}) = \frac{d}{dt} (\bar{\rho}_{w2}V_{w2}h_{w2}) \quad (26)$$

$$\begin{aligned}
 0.2618U_{nm2}L_{w2}(\bar{T}_{n2}-\bar{T}_{m2}) - 0.2618U_{mw2}L_{w2}(\bar{T}_{m2}-\bar{T}_{w2}) \\
 = C_p \rho_m V_{m2} \frac{d}{dt} (\bar{T}_{m2})
 \end{aligned} \quad (27)$$

$$W_{n2}h_{n2} - W_{n3}h_{n3} - 0.2618U_{nm2}L_{w2}(\bar{T}_{n2}-\bar{T}_{m2}) = \frac{d}{dt} (\bar{\rho}_{n2}V_{n2}h_{n2}) \quad (28)$$

1.4 AUXILIARY EQUATIONS

A. DIMENSIONAL EQUATIONS

a. Water

Water side volume of a region can be written in terms of an average inside diameter

$$V_{w4} = \frac{\pi}{576} L_{w4} \{0.736 - 3.699 \times 10^{-4} L_{w4}\}^2 \quad (29)$$

$$V_{w3} = \frac{\pi}{576} L_{w3} \{0.736 - 3.699 \times 10^{-4} (L_{w3} + L_{w4})\}^2 \quad (30)$$

$$V_{w2} = V_{total} - V_{w4} - V_{w3} \quad (31)$$

$$V_{total} = \frac{\pi}{576} L_{total} \left\{ \frac{0.736 + 0.637}{2} \right\}^2 \quad (32)$$

b. Metal

An accurate evaluation of the metal volume for the three regions would involve 3 equations with cubic terms in each of them. This would require a lot of non-linear equipment and therefore to simplify the model the metal associated with each region is assumed to be proportional to the length of the region only.

An average metal thickness for the whole boiler section is evaluated from the total volume of metal.

From design data therefore

$$V_{m4} = 2.7924 \times 10^{-3} L_{w4} \quad (33)$$

$$V_{m3} = 2.7924 \times 10^{-3} L_{w3} \quad (34)$$

$$V_{m2} = 2.7924 \times 10^{-3} L_{w2} \quad (35)$$

See Figure 8 for system control volumes.

c. Sodium

$$V_{n4} = 7.1318 \times 10^{-3} L_{w4} \quad (36)$$

$$V_{n3} = 7.1318 \times 10^{-3} L_{w3} \quad (37)$$

$$V_{n2} = 7.1318 \times 10^{-3} L_{w2} \quad (38)$$

B. THERMODYNAMIC PROPERTIES

a. Water Side

The thermodynamic properties of water (steam) were taken from Keenan and Keyes, at 2400 psia pressure. The data was linearized for the analysis. This yields the following equations:

$$\rho_{w5} = 73.4239 - 0.05271 T_{w5} \quad (39)$$

$$\rho_{w4} = \rho_f = 35.714 \text{ lb/ft}^3 \quad (40)$$

$$\bar{\rho}_{w4} = \frac{\rho_{w5} + \rho_{w4}}{2} \quad (41)$$

$$\rho_{w3} = \rho_g = 7.107 \text{ lb/ft}^3 \quad (42)$$

$$\bar{\rho}_{w3} = \frac{\rho_f + \rho_g}{2} = 21.41 \text{ lb/ft}^3 \quad (43)$$

$$\bar{T}_{w2} = 1860.07 - 267.67 \bar{\rho}_{w2} \quad (44)$$

$$h_{w5} = 1.1572 T_{w5} - 89.57 \quad (45)$$

$$h_{w4} = h_f = 718.4 \text{ Btu/lb} \quad (46)$$

$$h_{w3} = h_g = 1101.10 \text{ Btu/lb} \quad (47)$$

$$h_{w2} = 774.173 + 0.6826 T_{w2} \quad (48)$$

$$\bar{h}_{w4} = \frac{h_{w5} + h_{w4}}{2} \quad (49)$$

$$\bar{h}_{w3} = \frac{h_f + h_g}{2} = 909.75 \text{ Btu/lb} \quad (50)$$

$$\bar{h}_{w2} = \frac{h_g + h_{w2}}{2} \quad (51)$$

b. Metal

$$C_{p_m} = 0.130 \text{ Btu/lb}^\circ\text{F} \quad (52)$$

c. Sodium

We assume a constant density for all regions

$$\bar{\rho}_{n2} = \bar{\rho}_{n3} = \bar{\rho}_{n4} = 52.60 \text{ lb/ft}^3 \quad (53)$$

Sodium Enthalpy

$$h_{ni} = 0.3035 T_{ni} \quad (54)$$

$$C_{pn} = 0.3035 \frac{\text{Btu}}{\text{lb}^\circ\text{F}} \quad (55)$$

$$\bar{h}_{ni} = 0.3035 \bar{T}_{ni} \quad (56)$$

C. TEMPERATURES OF REGIONS

a. Water

$$T_{w3} = T_{w4} = T_{\text{sat}} = \bar{T}_{w3} \quad (57)$$

$$\bar{T}_{w4} = \frac{T_{\text{sat}} + T_{w5}}{2} \quad (58)$$

$$\bar{T}_{w2} = \frac{T_{\text{sat}} + T_{w2}}{2} \quad (59)$$

b. Sodium

$$\bar{T}_{n4} = \frac{T_{n4} + T_{n5}}{2} \quad (60)$$

$$\bar{T}_{n3} = \frac{T_{n3} + T_{n4}}{2} \quad (61)$$

$$\bar{T}_{n2} = \frac{T_{n2} + T_{n3}}{2} \quad (62)$$

These (62) equations are sufficient to simulate the boiler section accurately.

2.0 INTERMEDIATE SPRAY CONTROL

The spray is injected in a common pipe through which all the water from the boiler section flows. There are 25 parallel flow channels from the boiler to form the spray pipe flow and 45 parallel flow channels from the spray pipe into the superheater.

2.1 CONTINUITY

$$45W_{w1} = W_{sp1} + 25W_{w2} \quad (63)$$

2.2 ENERGY

$$45W_{w1}h_{w1} = W_{sp1}h_{sp1} + 25W_{w2}h_{w2} \quad (64)$$

2.3 MISCELLANEOUS EQUATION

$$h_{sp} = 1.1572 T_{sp} - 89.57 \quad (65)$$

$$T_{w1} = \frac{(h_{w1} - 774.173)}{0.6826} \quad (66)$$

$$\rho_{sp} = 73.4239 - 0.05271 T_{w5} \quad (67)$$

3.0 SUPERHEATER SECTION

The superheater is a fixed length, constant cross-sectional flow area model. See Figure 6.

3.1 CONSERVATION OF MASS

$$W_{w1} - W_{s1} = \frac{d}{dt} (V_{w1}\bar{\rho}_{w1}) \quad (68)$$

Since we assume constant density for sodium

$$W_{n2}^s = W_{n1} \quad (69)$$

$$25W_{n2} = 45 W_{n2}^s \quad (70)$$

3.2 CONSERVATION OF ENERGY

$$A_{ht} = 0.22907 L_{SH} \text{ (Based on OD)} \quad (71)$$

a. Water

$$\begin{aligned} W_{w1}h_{w1} - W_{s1}h_{s1} + 0.22907L_{SH}[U_{mw1}(\bar{T}_{m1} - \bar{T}_{w1})] \\ = \frac{d}{dt} (V_{w1}\bar{\rho}_{w1}\bar{h}_{w1}) \end{aligned} \quad (72)$$

b. Metal

$$\begin{aligned} 0.22907L_{SH}[U_{nm1}(\bar{T}_{n1} - \bar{T}_{m1})] - 0.22907L_{SH}[U_{mw1}(\bar{T}_{m1} - \bar{T}_{w1})] \\ = C_{p_m} \frac{d}{dt} (\rho_m V_{m1}\bar{T}_{m1}) \end{aligned} \quad (73)$$

c. Sodium

$$\begin{aligned} W_{n1} h_{n1} - W_{n2} h_{n2} &= 0.22907 L_{SH} [U_{nm1} (\bar{T}_{n1} - \bar{T}_{m1})] \\ &= \frac{d}{dt} (\bar{\rho}_{n1} V_{n1} \bar{h}_{n1}) \end{aligned} \quad (74)$$

3.3 AUXILIARY EQUATIONS

A. DIMENSIONAL EQUATIONS

a. Water Side

$$V_{w1} = 2.0361 \times 10^{-3} L_{SH} \quad (75)$$

b. Metal

$$V_{m1} = 2.1397 \times 10^{-3} L_{SH} \quad (76)$$

c. Sodium

$$V_{n1} = 6.3269 \times 10^{-3} L_{SH} \quad (77)$$

B. THERMODYNAMIC PROPERTIES

a. Water

$$\bar{T}_{w1} = 1860.07 - 267.67 \bar{\rho}_{w1} \quad (78)$$

$$h_{s1} = 774.173 + 0.6826 T_{s1} \quad (79)$$

$$\bar{h}_{w1} = 2043.86 - 182.71 \bar{\rho}_{w1} \quad (80)$$

b. Metal

$$C_{p_m} = 0.130 \text{ Btu/lb}^\circ\text{F} \quad (81)$$

$$\bar{\rho}_{m1} = 488 \text{ lb/ft}^3 \quad (82)$$

c. Sodium

$$h_{n1} = 0.3035 T_{n1} \quad (83)$$

$$h_{n2} = 0.3035 T_{n2} \quad (84)$$

$$\bar{h}_{n1} = \frac{h_{n1} + h_{n2}}{2} \quad (85)$$

$$\bar{\rho}_{n1} = 52.60 \text{ lb/ft}^3 \quad (86)$$

C. TEMPERATURES

$$\bar{T}_{w1} = \frac{T_{s1} + T_{sat}}{2} \quad (87)$$

$$\bar{T}_{n1} = \frac{T_{n1} + T_{n2}}{2} \quad (88)$$

Thus equations (1) through (88) represent the thermal behavior of the steam generator from the feedwater inlet to the secondary superheater outlet.

A-2 MODIFIED SYSTEM EQUATIONS

We find after preliminary studies that it is simpler and economical (less analog equipment) to neglect the change in volume due to variable cross-sectional flow area on the water side. Instead we simulate the boiler section by a single tube of uniform inside diameter. The outside diameter, however, remains constant at 1.00 in. The equivalent inside diameter is evaluated from the actual inside volume and total length.

With this assumption, our system has the same volume, metal mass, heat transfer surface area, etc., as the actual prototype. All we have effectively done is to shift the metal mass from the superheat region to subcooled region to give a constant wall tube.

Thus, in essence, we are neglecting effects due to velocity changes. The modified system equations, as simulated on the analog computer, are given on subsequent pages.

1.0 BOILER SECTION: VARIABLE LENGTH MODEL

1.1 PHYSICAL CONSTRAINT

a. Waterside $L_{w2} + L_{w3} + L_{w4} = L_{Total}$ (1)

$$\dot{L}_{w2} + \dot{L}_{w3} + \dot{L}_{w4} = 0 \quad (2)$$

$$V_{wi} = K_w L_{wi} \quad (3)$$

Where $K_w = 2.6622 \times 10^{-3} \text{ ft}^2$

Perimeter of 1" O.D. Tube, $P = 0.2618 \text{ ft}$ (4)

b. Metal side $V_{mi} = K_m L_{wi}$ (5)

Where $K_m = 2.7924 \times 10^{-3} \text{ ft}^2$

c. Sodium side $V_{ni} = K_n L_{wi}$ (6)

Where $K_n = 7.1318 \times 10^{-3} \text{ ft}^2$ and

$$i = 2, 3 \text{ or } 4$$

1.2 CONSERVATION EQUATIONS ON WATER-SIDE

$$W_{w5} = W_{\text{pump}} - W_{\text{spray}} \quad (7)$$

NOTE = $W_{\text{spray}} = \frac{W_{\text{spray}}(\text{Total})}{25}$

$$W_{w5} - W_{w4} = K_w \bar{\rho}_{w4} \frac{dL_{w4}}{dt} \quad (8)$$

$$W_{w4} - W_{w3} = K_w \bar{\rho}_{w3} \frac{dL_{w3}}{dt} \quad (9)$$

$$W_{w3} - W_{w2} = K_w \frac{d}{dt} (\bar{\rho}_{w2} L_{w2}) \quad (10)$$

$$\begin{aligned}
 W_{w5} h_{w5} - W_{w4} h_f + 0.2618 U_{mw4} L_{w4} (\bar{T}_{m4} - \bar{T}_{w4}) \\
 = K_w \bar{\epsilon}_{w4} \frac{d}{dt} (L_{w4} \bar{h}_{w4}) \quad (11)
 \end{aligned}$$

$$\begin{aligned}
 W_{w4} h_f - W_{w3} h_g + 0.2618 U_{mw3} L_{w3} (\bar{T}_{m3} - T_{sat}) \\
 = K_w \bar{\epsilon}_{w3} \frac{d}{dt} (L_{w3} \bar{h}_{w3}) \quad (12)
 \end{aligned}$$

$$\begin{aligned}
 W_{w3} h_g - W_{w2} h_{w2} + 0.2618 U_{mw2} L_{w2} (\bar{T}_{m2} - \bar{T}_{w2}) \\
 = K_w \frac{d}{dt} (L_{w2} \bar{\epsilon}_{w2} \bar{h}_{w2}) \quad (13)
 \end{aligned}$$

1.3 CONSERVATION EQUATIONS ON SODIUM-SIDE

$$\text{Density of Sodium } \rho_n = 52.6 \text{ lb/ft}^3 \quad (14)$$

$$W_{n4} - W_{n5} = 0.37513 \frac{dL_{w4}}{dt} \quad (15)$$

$$W_{n3} - W_{n4} = 0.37513 \frac{dL_{w3}}{dt} \quad (16)$$

$$W_{n2} - W_{n3} = 0.37513 \frac{dL_{w2}}{dt} \quad (17)$$

$$\text{Specific heat } C_{pn} = 0.3035 \text{ BTU/lb}^\circ\text{F} \quad (18)$$

$$\begin{aligned}
 W_{n4} h_{n4} - W_{n5} h_{n5} - 0.2618 U_{nm4} L_{w4} (\bar{T}_{n4} - \bar{T}_{m4}) \\
 = 0.1139 \frac{d}{dt} (L_{w4} \bar{T}_{n4}) \quad (19)
 \end{aligned}$$

$$\begin{aligned}
 W_{n3} h_{n3} - W_{n4} h_{n4} - 0.2618 U_{nm3} L_{w3} (\bar{T}_{n3} - \bar{T}_{m3}) \\
 = 0.1139 \frac{d}{dt} (L_{w3} \bar{T}_{n3}) \quad (20)
 \end{aligned}$$

$$W_{n2} h_{n2} - W_{n3} h_{n3} - 0.2618 U_{nm2} L_{w2} (\bar{T}_{n2} - \bar{T}_{m2})$$

$$= 0.1139 \frac{d}{dt} (L_{w2} \bar{T}_{n2}) \quad (21)$$

1.4 CONSERVATION EQUATION ON METAL

$$\text{Specific Heat, } C_{pm} = 0.130 \text{ BTU/lb}^\circ\text{F} \quad (22)$$

$$\text{Density, } \rho_m = 488 \text{ lb/ft}^3 \quad (23)$$

$$(C_{pm} \rho_m V_{mi}) = 0.17715 L_{wi} \quad (24)$$

$$\frac{d\bar{T}_{m4}}{dt} = \frac{U_{nm4}}{0.6767} (\bar{T}_{n4} - \bar{T}_{m4}) - \frac{U_{mw4}}{0.6767} (\bar{T}_{m4} - \bar{T}_{w4}) \quad (25)$$

$$\frac{d\bar{T}_{m3}}{dt} = \frac{U_{nm3}}{0.6767} (\bar{T}_{n3} - \bar{T}_{m3}) - \frac{U_{mw3}}{0.6767} (\bar{T}_{m3} - T_{sat}) \quad (26)$$

$$\frac{d\bar{T}_{m2}}{dt} = \frac{U_{nm2}}{0.6767} (\bar{T}_{n2} - \bar{T}_{m2}) - \frac{U_{mw2}}{0.6767} (\bar{T}_{m2} - \bar{T}_{w2}) \quad (27)$$

1.5 AUXILIARY EQUATIONS

a. Waterside

$$h_{w5} = 1.1572 T_{w5} - 89.57 \quad (28)$$

$$\bar{T}_{w4} = \frac{T_{w5} + T_{sat}}{2} \quad (29)$$

$$h_f = 718.40 \text{ BTU/lb} \quad (30)$$

$$T_{sat} = 662.12^\circ\text{F} \quad (31)$$

$$\bar{\rho}_{w4} = 42.0 \text{ lb/ft}^3 \quad (32)$$

$$\bar{\epsilon}_{w3} = 21.41 \text{ lb/ft}^3 \quad (33)$$

$$\bar{h}_{w4} = \frac{h_{w5} + h_f}{2} \quad (34)$$

$$h_g = 1101.10 \text{ BTU/lb} \quad (35)$$

$$\bar{h}_{w3} = 909.75 \text{ BTU/lb} \quad (36)$$

$$\bar{T}_{w2} = 1860.07 - 267.67 \bar{\epsilon}_{w2} \quad (37)$$

$$h_{w2} = (774.173 - 0.6826 T_{\text{sat}}) + 1.3652 \bar{T}_{w2} \quad (38)$$

$$\bar{h}_{w2} = \frac{h_{w2} + h_g}{2} \quad (39)$$

(b) Sodium side

$$h_{n3} = 2c_{pn} \bar{T}_{n2} - h_{n2} \quad (40)$$

$$h_{n4} = 2c_{pn} \bar{T}_{n3} - h_{n3} \quad (41)$$

$$h_{n5} = 2c_{pn} \bar{T}_{n4} - h_{n4} \quad (42)$$

2.0 INTERMEDIATE SPRAY CONTROL

$$45 W_{w1} = 25 (W_{w2} + W_{sp}) \quad \text{OR}$$

$$1.8 W_{w1} = W_{w2} + W_{sp} \quad (43)$$

$$1.8 W_{w1} h_{w1} = W_{w2} h_{w2} + W_{sp} h_{sp} \quad (44)$$

$$h_{sp} = 1.1572 T_{sp} - 89.57 \quad (45)$$

$$T_{w1} = \frac{(h_{w1} - 774.173)}{0.6826} \quad (46)$$

3.0 SUPERHEATER SECTION - FIXED LENGTH MODEL

3.1 PHYSICAL CONSTRAINT

$$V_{w1} = 2.0361 \times 10^{-3} L_{SH} \quad (47)$$

$$V_{m1} = 2.1397 \times 10^{-3} L_{SH} \quad (48)$$

$$V_{n1} = 6.3269 \times 10^{-3} L_{SH} \quad (49)$$

$$\text{Heat Transfer Surface Area, } A_{ht} = 0.22907 L_{SH} \quad (50)$$

3.2 CONSERVATION EQUATIONS ON WATER SIDE

$$W_{w1} - W_{s1} = V_{w1} \frac{d}{dt} (\bar{P}_{w1}) \quad (51)$$

$$\begin{aligned} W_{w1} h_{w1} - W_{s1} h_{s1} + 0.22907 L_{SH} U_{mw1} (\bar{T}_{m1} - \bar{T}_{w1}) \\ = V_{w1} \frac{d}{dt} (\bar{P}_{w1} \bar{h}_{w1}) \end{aligned} \quad (52)$$

3.3 CONSERVATION EQUATIONS ON METAL

$$(\bar{P}_m V_{m1} c_{pm}) = 0.13574 L_{SH} \quad (53)$$

$$\frac{d\bar{T}_{m1}}{dt} = 1.6896 \left[U_{nm1} (\bar{T}_{n1} - \bar{T}_{m1}) - U_{mw1} (\bar{T}_{m1} - \bar{T}_{w1}) \right] \quad (54)$$

3.4 CONSERVATION EQUATIONS ON SODIUM-SIDE

$$W_{n2}^s = \frac{W_{n2}}{1.8} \quad (55)$$

$$W_{n1} = W_{n2}^s \quad (56)$$

Note: W_{n2} = Flow of sodium per tube in the boiler section.

$$(\bar{F}_n V_{n1} C_{pn}) = 0.101 L_{SH} \quad (57)$$

$$\frac{d\bar{T}_n}{dt} = \frac{W_{n1}(h_{n1} - h_{n2})}{0.101 L_{SH}} - 2.268 V_{n1} (\bar{T}_n - \bar{T}_{m1}) \quad (58)$$

3.5 AUXILIARY EQUATIONS

(a) Sodiumside $h_{n2} = 2C_p \bar{T}_n - h_{n1} \quad (59)$

$$h_{n1} = C_p T_{n1} \quad (60)$$

(b) Waterside

$$\bar{T}_{w1} = 1860.07 - 267.67 \bar{F}_{w1} \quad (61)$$

$$\bar{h}_{w1} = 2043.86 - 182.71 \bar{F}_{w1} \quad (62)$$

$$T_{s1} = 2\bar{T}_{w1} - T_{w1} \quad (63)$$

$$h_{s1} = 774.173 + 0.6826 T_{s1} \quad (64)$$

APPENDIX B
ANALOG SIMULATION

APPENDIX B

ANALOG SIMULATION

The System equations as given in Appendix A are rather too numerous to simulate on the ARC computer. We reduce the number of equations by judicious substitutions and combinations of these equations. This does not change the system being simulated, nor does it imply any additional assumptions. Substitution of fluid mass balance equation into the energy equation was required to get a stable analog model.

The only inputs (need not be constants) or forcing parameters are W_{ni} & T_{ni} on the sodium side, W_{w5} & T_{w5} on the water side and W_{sp} & T_{sp} on the intermediate spray control.

The unscaled equations are given in B-1.

B-1 EQUATIONS FOR SIMULATION (UNSCALED)

The equations are given in the order of solution for ease in identification. One should remember that integration is always preferable on an analog computer, to differentiation. Each of the equations given below solve for the unknowns on the left-hand side.

1.0 BOILER SECTION

1.1 PHYSICAL CONSTRAINT

$$[L_{w2}] = L_{Total} - L_{w3} - L_{w4} \quad (1)$$

$$[\dot{L}_{w2}] = -\dot{L}_{w3} - \dot{L}_{w4} \quad (2)$$

1.2 CONSERVATION EQUATIONS ON WATER SIDE

$$[W_{w5}] = W_p - W_{sp} \quad (3)$$

$$[W_{w4}] = W_{w5} - 2 \left(\frac{K_w}{2} \bar{\rho}_{w4} \dot{L}_{w4} \right) \quad (4)$$

$$\left[W_{w3} - \frac{K_w}{2} \bar{\rho}_{w2} \dot{L}_{w2} \right] = W_{w4} - 2 \left(\frac{K_w}{2} \bar{\rho}_{w3} \dot{L}_{w3} \right) - \frac{K_w}{2} \bar{\rho}_{w2} \dot{L}_{w2} \quad (5)$$

$$[W_{w2}] = (W_{w3} - \frac{K_w}{2} \bar{\rho}_{w2} \dot{L}_{w2}) - \frac{K_w}{2} \bar{\rho}_{w2} \dot{L}_{w2} - 2 \left(\frac{K_w}{2} L_{w2} \frac{d\bar{\rho}_{w2}}{dt} \right) \quad (6)$$

$$\left[\frac{(h_f - h_{w5})}{L_{w4}} \left(\frac{K_w}{2} \bar{\rho}_{w4} \dot{L}_{w4} - W_{w5} \right) \right] = \left(\frac{1.572 K_w \bar{\rho}_{w4}}{2} \right) \frac{dT_{w5}}{dt} - 0.2618 U_{mw4} (\bar{T}_{m4} - T_{w4}) \quad (7)$$

$$\left[(h_f - h_{w5}) \left(\frac{K_w}{2} \bar{\rho}_{w4} \dot{L}_{w4} - W_{w5} \right) \right] = \text{L.H.S. of Eqn. (7)} \times L_{w4} \quad (8)$$

$$\left[\frac{K_w}{2} \bar{\rho}_{w4} \dot{L}_{w4} - W_{w5} \right] = \text{L.H.S. of Eqn. (8)} \div (h_f - h_{w5}) \quad (9)$$

$$\left[\frac{K_w}{2} \bar{\rho}_{w4} \dot{L}_{w4} \right] = \text{L.H.S. of Eqn. (9)} + W_{w5} \quad (10)$$

$$\left[\frac{1}{L_{w3}} \left(\frac{K_w}{2} \bar{\rho}_{w3} \dot{L}_{w3} - W_{w4} \right) \right] = \frac{-0.2618 U_{mw3} (\bar{T}_{m3} - T_{sat})}{(h_g - h_f)} \quad (11)$$

$$\left[\frac{K_w}{2} \bar{\rho}_{w3} \dot{L}_{w3} - W_{w4} \right] = \text{L.H.S. of Eqn. (11)} \times L_{w3} \quad (12)$$

$$\left[\frac{K_w}{2} \bar{\rho}_{w3} \dot{L}_{w3} \right] = \text{L.H.S. of Eqn. (12)} + W_{w4} \quad (13)$$

$$\left[\frac{K_w}{2} \dot{L}_{w2} \bar{\rho}_{w2} \right] = \frac{K_w (\bar{\rho}_{w2})}{2} \times (\dot{L}_{w2}) \quad (14)$$

$$\left[\frac{K_w}{2} \frac{d\bar{\rho}_{w2}}{dt} \right] = \left[\frac{h_{w2} - h_g}{\delta} \right] \left[W_{w3} - \frac{K_w}{2} \bar{\rho}_{w2} \dot{L}_{w2} \right] \frac{1}{L_{w2}} - \frac{0.2618 U_{mw2} (\bar{T}_{m2} - \bar{T}_{w2})}{\delta} \quad (15)$$

$$\left[\frac{K_w}{2} L_{w2} \frac{d\bar{\rho}_{w2}}{dt} \right] = \left[\frac{K_w}{2} \frac{d\bar{\rho}_{w2}}{dt} \right] \times L_{w2} \quad (16)$$

1.3 CONSERVATION EQUATIONS ON METAL

$$\left[\frac{d\bar{T}_{m4}}{dt} \right] = \frac{U_{nm4}}{0.6767} \bar{T}_{n4} - \left(\frac{U_{nm4} + U_{mw4}}{0.6767} \right) \bar{T}_{m4} + \frac{U_{mw4}}{0.6767} \bar{T}_{w4} \quad (17)$$

$$\left[\frac{d\bar{T}_{m3}}{dt} \right] = \frac{U_{nm3}}{0.6767} \bar{T}_{n3} - \left(\frac{U_{nm3} + U_{mw3}}{0.6767} \right) \bar{T}_{m3} + \frac{U_{mw3}}{0.6767} T_{sat} \quad (18)$$

$$\left[\frac{d\bar{T}_{m2}}{dt} \right] = \frac{U_{nm2}}{0.6767} \bar{T}_{n2} - \left(\frac{U_{nm2} + U_{mw2}}{0.6767} \right) \bar{T}_{m2} + \frac{U_{mw2}}{0.6767} \bar{T}_{w2} \quad (19)$$

1.4 CONSERVATION EQUATIONS ON SODIUM-SIDE

$$\left[\frac{d\bar{T}_{n4}}{dt} \right] = \left(\frac{2W_{n2}}{m_n} + L\dot{w}_4 \right) \left(\frac{h_{n4} - h_{n5}}{2c_{pn}} \right) \frac{1}{Lw_4} - 2.2985 U_{nm4} (\bar{T}_{n4} - \bar{T}_{m4}) \quad (20)$$

$$\left[\frac{d\bar{T}_{n3}}{dt} \right] = \left(\frac{2W_{n2}}{m_n} + L\dot{w}_4 - L\dot{w}_2 \right) \left(\frac{h_{n3} - h_{n4}}{2c_{pn}} \right) \frac{1}{Lw_3} - 2.2985 U_{nm3} (\bar{T}_{n3} - \bar{T}_{m3}) \quad (21)$$

$$\left[\frac{d\bar{T}_{n2}}{dt} \right] = \left(\frac{2W_{n2}}{m_n} - L\dot{w}_2 \right) \left(\frac{h_{n2} - h_{n3}}{2c_{pn}} \right) \frac{1}{Lw_2} - 2.2985 U_{nm2} (\bar{T}_{n2} - \bar{T}_{m2}) \quad (22)$$

1.5 AUXILIARY EQUATIONS

a. Water side

$$[(h_f - h_{w5})] = 807.97 - 1.1572 T_{w5} \quad (23)$$

$$[\bar{T}_{w4}] = \frac{(T_{w5} + T_{sat.})}{2} \quad (24)$$

$$\left[\frac{h_{w2} - h_g}{\delta} \right] = 1.000 - \left(\frac{365.423}{\delta} \right) \bar{P}_{w2} \quad (25)$$

$$[\bar{T}_{w2}] = 1860.07 - 267.67 \bar{P}_{w2} \quad (26)$$

b. Sodium side

$$\left[\frac{h_{n2} - h_{n3}}{2 c_{pn}} \right] = \bar{T}_{n1} - \bar{T}_{n2} - \left(\frac{h_{n1} - h_{n2}}{2 c_{pn}} \right) \quad (27)$$

$$\left[\frac{h_{n3} - h_{n4}}{2 c_{pn}} \right] = \bar{T}_{n2} - \bar{T}_{n3} - \left(\frac{h_{n2} - h_{n3}}{2 c_{pn}} \right) \quad (28)$$

$$\left[\frac{h_{n4} - h_{n5}}{2 c_{pn}} \right] = \bar{T}_{n3} - \bar{T}_{n4} - \left(\frac{h_{n3} - h_{n4}}{2 c_{pn}} \right) \quad (29)$$

2.0 INTERMEDIATE SPRAY CONTROL

$$[1.8 W_{w1}] = W_{w2} + W_{sp} \quad (30)$$

$$\left[\frac{1.8 W_{w1} h_{w1}}{\delta} \right] = W_{w2} \left(\frac{h_{w2} - h_g}{\delta} \right) + W_{w2} \frac{h_g}{\delta} + W_{sp} \frac{h_{sp}}{\delta} \quad (31)$$

$$[h_{w1}] = \delta \left[\frac{1.8 W_{w1} h_{w1}}{\delta} \right] \div [1.8 W_{w1}] \quad (32)$$

$$\left[\frac{h_{sp}}{\delta} \right] = \left(\frac{1.1572}{\delta} \right) T_{sp} - \frac{89.57}{\delta} \quad (33)$$

$$[T_{w1}] = \frac{(h_{w1} - 774.173)}{0.6826} \quad (34)$$

3.0 SUPERHEATER SECTION

3.1 CONSERVATION EQUATIONS ON WATER-SIDE

$$\begin{aligned} \left[(h_{s1} + \beta \bar{P}_{w1} - \alpha) V_{w1} \frac{d\bar{P}_{w1}}{dt} \right] &= \frac{1}{1.8} [1.8 W_{w1} \times h_{s1}] - \frac{\delta}{1.8} \left[1.8 \frac{W_{w1} h_{w1}}{\delta} \right] \\ &\quad - (0.22907 L_{SH}) U_{mw1} (\bar{T}_{m1} - \bar{T}_{w1}) \end{aligned} \quad (35)$$

$$[h_{s1} + \beta \bar{P}_{w1} - \alpha] = h_{s1} + 365.423 \bar{P}_{w1} - 2043.86 \quad (36)$$

$$\left[V_{w1} \frac{d\bar{P}_{w1}}{dt} \right] = \text{L.H.S. of Eqn. (35)} \div (h_{s1} + \beta \bar{P}_{w1} - \alpha) \quad (37)$$

$$[W_{s1}] = \frac{1}{1.8} (1.8 W_{w1}) - V_{w1} \frac{d\bar{P}_{w1}}{dt} \quad (38)$$

3.2 CONSERVATION EQUATION ON METAL

$$\left[\frac{d\bar{T}_{m1}}{dt} \right] = 1.6876 \left[U_{nm1} (\bar{T}_{n1} - \bar{T}_{m1}) - U_{mw1} (\bar{T}_{m1} - \bar{T}_{w1}) \right] \quad (39)$$

3.3 CONSERVATION EQUATION ON SODIUM-SIDE

$$\left[\frac{d\bar{T}_{n1}}{dt} \right] = \left(\frac{0.62651}{L_{SH}} \right) \left[\frac{2W_{n2}}{m_n} \times \left(\frac{h_{n1} - h_{n2}}{2c_{pn}} \right) \right] - 2.268 U_{nm1} (\bar{T}_{n1} - \bar{T}_{m1}) \quad (40)$$

3.4 AUXILIARY EQUATIONS

a. Water side

$$[\bar{T}_{w1}] = 1860.07 - 267.67 \bar{P}_{w1} \quad (41)$$

$$[T_{s1}] = 2 \bar{T}_{w1} - T_{w1} \quad (42)$$

$$[h_{s1}] = 774.173 + 0.6826 T_{s1} \quad (43)$$

b. Sodium side

$$\left[\frac{h_{n1} - h_{n2}}{2c_{pn}} \right] = T_{n1} - \bar{T}_{n1} \quad (44)$$

B-2 EQUATIONS FOR SIMULATION (SCALED)

Table B-1 lists the system variables, the rounded maximum value (RMV) expected during a transient and the analog computer variable.

Table B-II lists parameters that are constants for all load conditions.

Table B-III provides potentiometer settings for all loads when using design areas.

Table B-IV provides potentiometer settings for all loads when using installed areas.

TABLE B-I

RANGE OF VARIABLES

VARIABLE	UNITS	RMV	COMP. VAR	VARIABLE	UNITS	RMV	COMP. VAR
W_{w5}	LB/SEC	10	$\left[\frac{W_{w5}}{10}\right]$	$\left[\frac{hw_2-h_9}{6}\right]$	—	1	$\left[\frac{(hw_2-h_9)}{6}\right]$
W_{w4}	LB/SEC.	10	$\left[\frac{W_{w4}}{10}\right]$	$\bar{T}_{m4}$	°F	2000	$\left[\frac{\bar{T}_{m4}}{2000}\right]$
W_{w3}	LB/SEC.	10	$\left[\frac{W_{w3}}{10}\right]$	$\bar{T}_{m3}$	°F	2000	$\left[\frac{\bar{T}_{m3}}{2000}\right]$
W_{w2}	LB/SEC.	10	$\left[\frac{W_{w2}}{10}\right]$	$\bar{T}_{m2}$	°F	2000	$\left[\frac{\bar{T}_{m2}}{2000}\right]$
L_{w2}	FT.	200	$\left[\frac{L_{w2}}{200}\right]$	$\left[\frac{W_{m2}}{mm}\right]$	FT./SEC.	100	$\left[\frac{W_{m2}}{100mm}\right]$
L_{w3}	FT.	200	$\left[\frac{L_{w3}}{200}\right]$	$\left[\frac{hm_4-hm_5}{4CP}\right]$	°F	10^3	$\left[\frac{hm_4-hm_5}{4000CP}\right]$
L_{w4}	FT.	200	$\left[\frac{L_{w4}}{200}\right]$	$\left[\frac{hm_3-hm_4}{4CP}\right]$	°F	10^3	$\left[\frac{hm_3-hm_4}{4000CP}\right]$
$L\dot{w}_2$	FT./SEC.	200	$\left[\frac{L\dot{w}_2}{200}\right]$	$\left[\frac{hm_2-hm_3}{4CP}\right]$	°F	10^3	$\left[\frac{hm_2-hm_3}{4000CP}\right]$
$L\dot{w}_3$	FT./SEC.	200	$\left[\frac{L\dot{w}_3}{200}\right]$	$\left[\frac{hm_1-hm_2}{4CP}\right]$	°F	10^3	$\left[\frac{hm_1-hm_2}{4000CP}\right]$
$L\dot{w}_4$	FT./SEC.	200	$\left[\frac{L\dot{w}_4}{200}\right]$	T_{m1}	°F	2000	$\left[\frac{T_{m1}}{2000}\right]$
$\bar{e}_{w2}$	LB/FT. ³	10	$\left[\frac{\bar{e}_{w2}}{10}\right]$	$\bar{T}_{m1}$	°F	2000	$\left[\frac{\bar{T}_{m1}}{2000}\right]$
$\dot{\bar{e}}_{w2}$	LB/FT ³ SEC.	10	$\left[\frac{\dot{\bar{e}}_{w2}}{10}\right]$	$\bar{T}_{m1}$	°F	2000	$\left[\frac{\bar{T}_{m1}}{2000}\right]$
(h_f-h_{w5})	BTU/LB	1000	$\left[\frac{(h_f-h_{w5})}{1000}\right]$	$\bar{T}_{w1}$	°F	2000	$\left[\frac{\bar{T}_{w1}}{2000}\right]$
T_{w5}	°F	2000	$\left[\frac{T_{w5}}{2000}\right]$	T_{w1}	°F	2000	$\left[\frac{T_{w1}}{2000}\right]$
$\bar{T}_{w4}$	°F	2000	$\left[\frac{\bar{T}_{w4}}{2000}\right]$	T_{s1}	°F	2000	$\left[\frac{T_{s1}}{2000}\right]$
$T_{SAT.}$	°F	2000	$\left[\frac{T_{SAT.}}{2000}\right]$	T_{SP}	°F	2000	$\left[\frac{T_{SP}}{2000}\right]$
$\bar{T}_{w2}$	°F	2000	$\left[\frac{\bar{T}_{w2}}{2000}\right]$	W_{PUMP}	LB/SEC.	10	$\left[\frac{W_P}{10}\right]$
$\bar{T}_{m4}$	°F	2000	$\left[\frac{\bar{T}_{m4}}{2000}\right]$	W_{SP}	LB/SEC.	10	$\left[\frac{W_{SP}}{10}\right]$
$\bar{T}_{m3}$	°F	2000	$\left[\frac{\bar{T}_{m3}}{2000}\right]$	$\frac{h_{SP}}{8}$	—	1	$\left[\frac{h_{SP}}{8}\right]$
$\bar{T}_{m2}$	°F	2000	$\left[\frac{\bar{T}_{m2}}{2000}\right]$	h_{w1}	BTU/LB	10^4	$\left[\frac{h_{w1}}{10^4}\right]$
$W_{w1}h_{w1}$	BTU/SEC	10^5	$\left[\frac{W_{w1}h_{w1}}{10^5}\right]$	$W_{w1}h_{s1}$	BTU/SEC.	10^5	$\left[\frac{W_{w1}h_{s1}}{10^5}\right]$
W_{s1}	LB/SEC	10	$\left[\frac{W_{s1}}{10}\right]$	$\bar{e}_{w1}$	LB/FT. ³	10	$\left[\frac{\bar{e}_{w1}}{10}\right]$
h_{s1}	BTU/LB	10^4	$\left[\frac{h_{s1}}{10^4}\right]$	$\frac{d\bar{e}_{w1}}{dt}$	LB/FT ³ SEC.	10	$\left[\frac{d\bar{e}_{w1}}{dt}\right]$

TABLE B-II - VALUES OF CONSTANTS

PARA	UNITS	VALUE	PARA	UNITS	VALUE
c_p	BTU/lb °F	0.3035	m_n	lb/ft	0.37513
$\bar{P}_{w4}$	lb/ft ³	42.00	α	BTU/lb	2043.86
$\bar{P}_{w3}$	lb/ft ³	21.41	β	BTU/ft ³	365.423
T_{sat}	°F	662.12	δ	BTU/lb	1761.14
h_g	BTU/lb	1101.10	V_{w1}	ft ³	0.07644*
h_f	BTU/lb	718.40	L_{TOTAL}	ft	119.236* 132.8
$(h_g - h_f)$	BTU/lb	382.70	L_{SH}	ft	37.543* 43.1
K_w	ft ²	2.6622×10^{-3}			

*For design conditions.

SCALED EQUATIONS

1.0 BOILER SECTION

1.1 PHYSICAL CONSTRAINT

$$\left[\frac{L_{W2}}{200} \right] = \frac{L_{Total}}{200} - \frac{L_{W3}}{200} - \frac{L_{W4}}{200} \quad (1)$$

$$\left[\frac{\dot{L}_{W2}}{200} \right] = - \frac{1}{(10 K_w \bar{\rho}_{w3})} \left[10 K_w \bar{\rho}_{w3} \frac{\dot{L}_{W3}}{200} \right] - \frac{1}{(10 K_w \bar{\rho}_{w4})} \left[10 K_w \bar{\rho}_{w4} \frac{\dot{L}_{W4}}{200} \right] \quad (2)$$

1.2 CONSERVATION EQUATIONS FOR WATER-SIDE

$$\left[\frac{W_{W5}}{10} \right] = \left[\frac{W_p}{10} \right] - \left[\frac{W_{Sp}}{10} \right] \quad (3)$$

$$\left[\frac{W_{W4}}{10} \right] = \left[\frac{W_{W5}}{10} \right] - 2 \left[10 K_w \bar{\rho}_{w4} \frac{\dot{L}_{W4}}{200} \right] \quad (4)$$

$$\left[\frac{W_{W3}}{10} - 100 K_w \frac{\bar{\rho}_{w2} \dot{L}_{W2}}{2000} \right] = \left[\frac{W_{W4}}{10} \right] - 2 \left[10 K_w \bar{\rho}_{w3} \frac{\dot{L}_{W3}}{200} \right] - \left[100 K_w \frac{\bar{\rho}_{w2} \dot{L}_{W2}}{2000} \right] \quad (5)$$

$$\left[\frac{W_{W2}}{10} \right] = \left[\frac{W_{W3}}{10} - 100 K_w \frac{\bar{\rho}_{w2} \dot{L}_{W2}}{2000} \right] - \left[100 K_w \frac{\bar{\rho}_{w2} \dot{L}_{W2}}{2000} \right] - 2 \left[100 K_w \frac{L_{W2}}{200} \frac{d \bar{\rho}_{w2}/10}{dt} \right] \quad (6)$$

$$\left[\frac{\left(\frac{h_g - h_{w5}}{10} \right) \left[10 K_w \bar{\rho}_{w4} \frac{\dot{L}_{W4}}{200} \right]}{\left[\frac{L_{W4}}{200} \right]} \right] = (23.144 K_w \bar{\rho}_{w4}) \left[\frac{dT_{w5}/2000}{dt} \right] - (10.472 U_{mw4}) \left[\frac{\bar{T}_{m4}}{2000} - \frac{\bar{T}_{W4}}{2000} \right] \quad (7)$$

$$\left[\frac{h_f - h_{w5}}{10^3} \right] \left[10 \text{ Kw } \bar{\rho}_{w4} \frac{\dot{L}_{w4}}{200} - \frac{w_{w5}}{10} \right] = \text{L.H.S. of Eqn. (7)} \times \left[\frac{L_{w4}}{200} \right] \quad (8)$$

$$\left[10 \text{ Kw } \bar{\rho}_{w4} \frac{\dot{L}_{w4}}{200} - \frac{w_{w5}}{10} \right] = \text{L.H.S. of (8)} \div \left[\frac{h_f - h_{w5}}{10^3} \right] \quad (9)$$

$$\left[10 \text{ Kw } \bar{\rho}_{w4} \frac{\dot{L}_{w4}}{200} \right] = \text{L.H.S. of (9)} + \left[\frac{w_{w5}}{10} \right] \quad (10)$$

$$\left[\frac{10 \text{ Kw } \bar{\rho}_{w3} \frac{\dot{L}_{w3}}{200} - \frac{w_{w4}}{10}}{\left[\frac{L_{w3}}{200} \right]} \right] = - \left(\frac{1.0472 U_{mw3} \times 10^4}{(h_g - h_f)} \right) \left[\frac{\bar{T}_{m3}}{2000} - \frac{T_{sat}}{2000} \right] \quad (11)$$

$$\left[10 \text{ Kw } \bar{\rho}_{w3} \frac{\dot{L}_{w3}}{200} - \frac{w_{w4}}{10} \right] = \text{L.H.S. of (11)} \times \left[\frac{L_{w3}}{200} \right] \quad (12)$$

$$\left[10 \text{ Kw } \bar{\rho}_{w3} \frac{\dot{L}_{w3}}{200} \right] = \text{L.H.S. of (12)} + \left[\frac{w_{w4}}{10} \right] \quad (13)$$

$$\left[\frac{100 \text{ Kw } \bar{\rho}_{w2} \dot{L}_{w2}}{2000} \right] = (100 \text{ Kw}) \left[\frac{\bar{\rho}_{w2}}{10} \right] \times \left[\frac{L_{w2}}{200} \right] \quad (14)$$

$$\left[100 \text{ Kw } \frac{d\bar{\rho}_{w2}/10}{dt} \right] = \left(\frac{h_{w2} - h_g}{\delta} \right) \left[\frac{w_{w3}}{10} - \frac{100 \text{ Kw } \bar{\rho}_{w2} \dot{L}_{w2}}{2000} \right] \left[\frac{200}{L_{w2}} \right] - \left(\frac{1.0472 U_{mw2}}{\delta} \right) \left[\frac{\bar{T}_{m2}}{2000} - \frac{\bar{T}_{w2}}{2000} \right] \quad (15)$$

$$\left[100 K_w \frac{L_{w2}}{200} \frac{d \bar{\epsilon}_{w2/10}}{dt} \right] = \left[100 K_w \frac{d \bar{\epsilon}_{w2/10}}{dt} \right] \times \left[\frac{L_{w2}}{200} \right] \quad (16)$$

1.3 CONSERVATION EQUATIONS ON METAL

$$\begin{aligned} \left[\frac{d \bar{T}_{m4}/2000}{dt} \right] &= \frac{U_{nm4}}{0.6767} \left[\frac{\bar{T}_{n4}}{2000} \right] - \left(\frac{U_{nm4} + U_{mw4}}{0.6767} \right) \left[\frac{\bar{T}_{m4}}{2000} \right] \\ &\quad + \frac{U_{mw4}}{0.6767} \left[\frac{\bar{T}_{w4}}{2000} \right] \end{aligned} \quad (17)$$

$$\begin{aligned} \left[\frac{d \bar{T}_{m3}/2000}{dt} \right] &= \frac{U_{nm3}}{0.6767} \left[\frac{\bar{T}_{n3}}{2000} \right] - \left(\frac{U_{nm3} + U_{mw3}}{0.6767} \right) \left[\frac{\bar{T}_{m3}}{2000} \right] \\ &\quad + \left(\frac{U_{mw3} T_{sat}}{0.6767 \cdot 2000} \right) \end{aligned} \quad (18)$$

$$\begin{aligned} \left[\frac{d \bar{T}_{m2}/2000}{dt} \right] &= \frac{U_{nm2}}{0.6767} \left[\frac{\bar{T}_{n2}}{2000} \right] - \left(\frac{U_{nm2} + U_{mw3}}{0.6767} \right) \left[\frac{\bar{T}_{m2}}{2000} \right] \\ &\quad - \frac{U_{mw2}}{0.6767} \left[\frac{\bar{T}_{w2}}{2000} \right] \end{aligned} \quad (19)$$

1.4 CONSERVATION EQUATIONS ON SODIUM-SIDE

$$\begin{aligned} \left[\frac{d \bar{T}_{n4}/2000}{dt} \right] &= \left[\frac{W_{n2}}{100 m_n} + \frac{L_{w4}}{200} \right] \left[\frac{h_{n4} - h_{n5}}{4000 c_{pn}} \right] \left[\frac{200}{L_{w4}} \right] \\ &\quad - 2.2985 U_{nm4} \left[\frac{\bar{T}_{n4}}{2000} - \frac{\bar{T}_{m4}}{2000} \right] \end{aligned} \quad (20)$$

$$\left[\frac{d\bar{T}_{m3}/2000}{dt} \right] = \left[\frac{W_{n2}}{100m_n} + \frac{L\dot{w}_4}{200} - \frac{L\dot{w}_2}{200} \right] \left[\frac{h_{n3} - h_{n4}}{4000 c_{p_n}} \right] \left[\frac{200}{L_{w3}} \right] - 2.2985 U_{nm3} \left[\frac{\bar{T}_{n3}}{2000} - \frac{\bar{T}_{m3}}{2000} \right] \quad (21)$$

$$\left[\frac{d\bar{T}_{n2}/2000}{dt} \right] = \left[\frac{W_{n2}}{100m_n} - \frac{L\dot{w}_2}{200} \right] \left[\frac{h_{n2} - h_{n3}}{4000 c_{p_n}} \right] \left[\frac{200}{L_{w2}} \right] - 2.2985 U_{nm2} \left[\frac{\bar{T}_{n2}}{2000} - \frac{\bar{T}_{m2}}{2000} \right] \quad (22)$$

1.5 AUXILIARY EQUATIONS

a. Waterside

$$\left[\frac{h_f - h_{w5}}{10^3} \right] = 0.8080 - 2.3144 \left[\frac{T_{w5}}{2000} \right] \quad (23)$$

$$\left[\frac{\bar{T}_{w4}}{2000} \right] = \frac{1}{2} \left[\left[\frac{T_{w5}}{2000} \right] + \left[\frac{T_{sat}}{2000} \right] \right] \quad (24)$$

$$\left[\frac{h_{w2} - h_g}{\delta} \right] = 1.000 - \left(\frac{365.423 \times 10}{\delta} \right) \left[\frac{\bar{S}_{w2}}{10} \right] \quad (25)$$

$$\left[\frac{\bar{T}_{w2}}{2000} \right] = 0.9300 - 1.3384 \left[\frac{\bar{S}_{w2}}{10} \right] \quad (26)$$

b. Sodiumside

$$\left[\frac{h_{n2} - h_{n3}}{4000 c_{pn}} \right] = \left[\frac{\bar{T}_{n1}}{2000} \right] - \left[\frac{\bar{T}_{n2}}{2000} \right] - \left[\frac{h_{n1} - h_{n2}}{4000 c_{pn}} \right] \quad (27)$$

$$\left[\frac{h_{n3} - h_{n4}}{4000 c_{pn}} \right] = \left[\frac{\bar{T}_{n2}}{2000} \right] - \left[\frac{\bar{T}_{n3}}{2000} \right] - \left[\frac{h_{n2} - h_{n3}}{4000 c_{pn}} \right] \quad (28)$$

$$\left[\frac{h_{n4} - h_{n5}}{4000 c_{pn}} \right] = \left[\frac{\bar{T}_{n3}}{2000} \right] - \left[\frac{\bar{T}_{n4}}{2000} \right] - \left[\frac{h_{n3} - h_{n4}}{4000 c_{pn}} \right] \quad (29)$$

2.0 INTERMEDIATE SPRAY CONTROL

$$\left[\frac{1.8 W_{w1}}{10} \right] = \left[\frac{W_{w2}}{10} \right] + \left[\frac{W_{sp}}{10} \right] \quad (30)$$

$$\left[\frac{1.8 W_{w1} h_{w1}}{10 \delta} \right] = \left[\frac{W_{w2}}{10} \right] \left[\frac{h_{w2} - h_g}{\delta} \right] + \left(\frac{h_g}{\delta} \right) \left[\frac{W_{w2}}{10} \right] + \left[\frac{W_{sp}}{10} \right] \left[\frac{h_{sp}}{\delta} \right] \quad (31)$$

$$\left[\frac{h_{sp}}{\delta} \right] = \left(\frac{2314.4}{\delta} \right) \left[\frac{T_{sp}}{2000} \right] - \left(\frac{89.57}{\delta} \right) \quad (32)$$

$$\left[\frac{h_{w1}}{104} \right] = \left(\frac{\delta}{104} \right) \left[\frac{1.8 W_{w1} h_{w1}}{10 \delta} \right] \div \left[\frac{1.8 W_{w1}}{10} \right] \quad (33)$$

$$\left[\frac{T_{w1}}{2000} \right] = \frac{5}{0.6826} \left[\frac{h_{w1}}{104} \right] - 0.5671 \quad (34)$$

3.0 SUPERHEATER SECTION

3.1 CONSERVATION EQUATION ON WATER SIDE

$$\left[\frac{(h_{s1} + \beta \bar{P}_{w1} - \alpha)}{10^4} (10 V_{w1} \frac{d\bar{P}_{w1}/10}{dt}) \right] = \frac{10}{1.8} \left[1.8 \frac{W_{w1}}{10} \times \frac{h_{s1}}{10^4} \right] - \left(\frac{10 \delta}{1.8 \times 10^4} \right) \left[1.8 \frac{W_{w1} h_{w1}}{10 \delta} \right] \\ - (4.5814 \times 10^{-2} L_{SH}) U_{mw1} \left[\frac{\bar{T}_{m1}}{2000} - \frac{\bar{T}_{w1}}{2000} \right] \quad (35)$$

$$\left[\frac{h_{s1} + \beta \bar{P}_{w1} - \alpha}{10^4} \right] = \left[\frac{h_{s1}}{10^4} \right] + 0.3654 \left[\frac{\bar{P}_{w1}}{10} \right] - 0.2044 \quad (36)$$

$$\left[10 V_{w1} \frac{d\bar{P}_{w1}/10}{dt} \right] = \text{L.H.S. of (35)} \div \left[\frac{h_{s1} + \beta \bar{P}_{w1} - \alpha}{10^4} \right] \quad (37)$$

$$\left[\frac{W_{s1}}{10} \right] = 0.5556 \left[1.8 \frac{W_{w1}}{10} \right] - \frac{1}{10} \left[10 V_{w1} \frac{d\bar{P}_{w1}/10}{dt} \right] \quad (38)$$

3.2 CONSERVATION EQUATION ON METAL

$$\left[\frac{d\bar{T}_{m1}/2000}{dt} \right] = (1.6876 U_{nm1}) \left[\frac{\bar{T}_{\eta 1}}{2000} \right] - (1.6876 (U_{nm1} + U_{mw1})) \left[\frac{\bar{T}_{m1}}{2000} \right] \\ + (1.6876 U_{mw1}) \left[\frac{\bar{T}_{w1}}{2000} \right] \quad (39)$$

3.3 CONSERVATION EQUATION ON SODIUM SIDE

$$\left[\frac{d\bar{T}_{n1}/2000}{dt} \right] = \left(\frac{125.302}{L_{SH}} \right) \left[\frac{W_{n2}}{100m_n} \times \frac{(h_{n1} - h_{n2})}{4000 \text{ cp}} \right] - (2.2680 U_{nm1}) \left[\frac{\bar{T}_{n1}}{2000} - \frac{\bar{T}_{m1}}{2000} \right] \quad (40)$$

3.4 AUXILIARY EQUATIONS

a. WATER SIDE

$$\left[\frac{\bar{T}_{w1}}{2000} \right] = 0.9300 - 1.3384 \left[\frac{\bar{q}_{w1}}{10} \right] \quad (41)$$

$$\left[\frac{T_{s1}}{2000} \right] = 2 \left[\frac{\bar{T}_{w1}}{2000} \right] - \left[\frac{\bar{T}_{w1}}{2000} \right] \quad (42)$$

$$\left[\frac{h_{s1}}{104} \right] = 0.0744 + 0.13652 \left[\frac{T_{s1}}{2000} \right] \quad (43)$$

b. SODIUM SIDE

$$\left[\frac{h_{n1} - h_{n2}}{4000 \text{ cp}} \right] = \left[\frac{T_{n1}}{2000} \right] - \left[\frac{\bar{T}_{n1}}{2000} \right] \quad (44)$$

TABLE B-III - POT. SETTINGS* (DESIGN AREAS)

POT. NO.	LOAD %				
	100	80	60	40	20
P00	0.5556				
Q00	0.0010				
P01	0.1308				
Q01	0.3500				
P02	0.1338				
Q02	0.9300				
P03	0.3654				
Q03	0.1729	0.1401	0.1043	0.0693	0.0347
P04	0.5556				
Q04	0.5000				
P05	0.1009	0.0983	0.0947	0.0903	0.0871
Q05	0.1009	0.0983	0.0947	0.0903	0.0871
P06	0.9230	0.8831	0.8368	0.7687	0.7019
Q06	0.7505	0.7311	0.7047	0.6715	0.6482
P07	0.1758	0.1549	0.1347	0.0991	0.0545
Q07	0.1758	0.1549	0.1347	0.0991	0.0545
P08	0.1365				
Q08	0.0774				
P09	0.3338				
Q09	0.5700	0.5610	0.5520	0.5430	0.5340

*Settings are given only for those Pots. requiring a change from one load to another.

TABLE B-III (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P10	0.5000				
Q10	0.4500				
P11	0.3750				
Q11	0.3500				
P12	0.1086	0.0875	0.0739	0.0514	0.0201
Q12	0.2120	0.1898	0.1637	0.1326	0.0949
P13	0.2255	0.2102	0.1905	0.1641	0.1268
Q13	0.2255	0.2102	0.1905	0.1641	0.1268
P14	0.1725	0.1520	0.1322	0.0992	0.0535
Q14	0.5300				
P15	0.5000				
Q15	0.3250				
P16	0.1078	0.1047	0.1004	0.0946	0.0915
Q16	0.1078	0.1047	0.1004	0.0946	0.0915
P17	0.8944				
Q17	0.8944				
P18	0.3000				
Q18	0.3182	0.2966	0.2688	0.2315	0.1790
P19	0.6928	0.6727	0.6454	0.6079	0.5882
Q19	0.1011	0.0969	0.0914	0.0839	0.0767

TABLE B-III (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P20	0.1078	0.1047	0.1004	0.0946	0.0915
Q20	0.1078	0.1047	0.1004	0.0946	0.0915
P21	0.9048	0.8625	0.8091	0.7405	0.6831
Q21	0.6928	0.6727	0.6454	0.6079	0.5882
P22	0.8530	0.7636	0.6586	0.5335	0.3818
Q22	0.2650	0.2525	0.2375	0.2150	0.1850
P23	0.0986	0.0789	0.0591	0.0394	0.0197
Q23	0.0074	0.0079	0.0044	0.0037	0.0020
P24	0.3311				
Q24	--	--	--	--	--
P25	0.1078	0.1047	0.1004	0.0946	0.0915
Q25	0.1078	0.1047	0.1004	0.0946	0.0915
P26	0.1021	0.0937	0.0869	0.0763	0.0649
Q26	0.6928	0.6727	0.6454	0.6079	0.5882
P27	0.2314				
Q27	0.8080				
P28	0.6072	0.4890	0.4132	0.2874	0.1125
Q28	0.2011	0.1619	0.1369	0.0952	0.0373
P29	0.1755				
Q29	0.9784				

TABLE B-III (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P30	0.4000				
Q30	0.8530	0.7636	0.6586	0.5335	0.3818
P31	0.1000				
Q31	0.2044				
P32	0.2075				
Q32	0.1338				
P33	0.9300				
Q33	0.1755				
P35	0.0750				
P36	0.5962				
P41	0.2662				
P42	0.1761				
Q42	0.6252				
P43	0.2662				
Q43	0.3756				
P44	0.7325				
Q44	0.5671				
P45	0.1314				
Q45	0.0509				
P46	0.2650	0.2525	0.2375	0.2150	0.1850

TABLE B-IV - POT. SETTINGS* (INSTALLED AREAS)

POT. NO.	LOAD %				
	100	80	60	40	20
P00	0.5556				
Q00	0.0010				
P01	0.1140				
Q01	0.3500				
P02	0.1338				
Q02	0.9300				
P03	0.3654				
Q03	0.1729	0.1401	0.1043	0.0693	0.0347
P04	0.5556				
Q04	0.5000				
P05	0.1009	0.0983	0.0947	0.0903	0.0871
Q05	0.1009	0.0983	0.0947	0.0903	0.0871
P06	0.9230	0.8831	0.8368	0.7687	0.7019
Q06	0.7505	0.7311	0.7047	0.6715	0.6482
P07	0.2018	0.1778	0.1546	0.1137	0.0626
Q07	0.2018	0.1778	0.1546	0.1137	0.0626
P08	0.1365				
Q08	0.0774				
P09	0.2907				
Q09	0.5700	0.5610	0.5520	0.5430	0.5340

*Settings are given only for those Pots. requiring a change from one load to another.

TABLE B-IV (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P30	0.4000				
Q30	0.8530	0.7636	0.6586	0.5335	0.3818
P31	0.1000				
Q31	0.2044				
P32	0.2075				
Q32	0.1338				
P33	0.9300				
Q33	0.1755				
P35	0.0750				
P36	0.6690				
P41	0.2662				
P42	0.1761				
Q42	0.6252				
P43	0.2662				
Q43	0.3756				
P44	0.7325				
Q44	0.5671				
P45	0.1314				
Q45	0.0509				
P46	0.2650	0.2525	0.2375	0.2150	0.1850

TABLE B-IV (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P20	0.1078	0.1047	0.1004	0.0946	0.0915
Q20	0.1078	0.1047	0.1004	0.0946	0.0915
P21	0.9048	0.8625	0.8091	0.7405	0.6831
Q21	0.6928	0.6727	0.6454	0.6079	0.5882
P22	0.8530	0.7636	0.6586	0.5335	0.3818
Q22	0.2650	0.2525	0.2375	0.2150	0.1850
P23	0.0986	0.0789	0.0591	0.0394	0.0197
Q23	0.0074	0.0079	0.0044	0.0037	0.0020
P24	0.3311				
Q24	--	--	--	--	--
P25	0.1078	0.1047	0.1004	0.0946	0.0915
Q25	0.1078	0.1047	0.1004	0.0946	0.0915
P26	0.1021	0.0937	0.0869	0.0763	0.0649
Q26	0.6928	0.6727	0.6454	0.6079	0.5882
P27	0.2314				
Q27	0.8080				
P28	0.6072	0.4890	0.4132	0.2874	0.1125
Q28	0.2011	0.1619	0.1369	0.0952	0.0373
P29	0.1755				
Q29	0.9784				

TABLE B-IV (Continued)

POT. NO.	LOAD %				
	100	80	60	40	20
P10	0.5000				
Q10	0.4500				
P11	0.3750				
Q11	0.3500				
P12	0.1086	0.0875	0.0739	0.0514	0.0201
Q12	0.2120	0.1898	0.1637	0.1326	0.0949
P13	0.2255	0.2102	0.1905	0.1641	0.1268
Q13	0.2255	0.2102	0.1905	0.1641	0.1268
P14	0.1725	0.1520	0.1322	0.0992	0.0535
Q14	0.5300				
P15	0.5000				
Q15	0.3250				
P16	0.1078	0.1047	0.1004	0.0946	0.0915
Q16	0.1078	0.1047	0.1004	0.0946	0.0915
P17	0.8944				
Q17	0.8944				
P18	0.3000				
Q18	0.3182	0.2966	0.2688	0.2315	0.1790
P19	0.6928	0.6727	0.6454	0.6079	0.5882
Q19	0.1011	0.0969	0.0914	0.0839	0.0767

APPENDIX C
PROTOTYPE DESIGN DATA

APPENDIX C

PROTOTYPE DESIGN DATA

C-1 SYSTEMS DATA

(Based on the analog equivalent tube using the prototype design data) All the data is evaluated on a per tube basis and is as per installed in the prototype.

1.0 BOILER SECTION

1.1 Water Side

Length of Tube, L_{total}	133.80 ft
No. of Tubes, N_b	25
Equivalent Diameter, D_{wbe}	0.6986 inch
Flow Area, K_w	$2.6622 \times 10^{-3} \text{ft}^2$
Volume of Tube, V_{total}	0.3562ft^3
Outside Diameter, D_o	1.00 inch

1.2 Metal

Wall Thickness, t_m	0.1507 inch
Area, K_m	$2.7924 \times 10^{-3} \text{ft}^2$
Mass, m_m	1.3627 lbs/ft

1.3 Sodium Side

Equivalent Diameter, D_{nbe}	1.5193 inch
Flow Area, K_n	$7.1318 \times 10^{-3} \text{ft}^2$
Mass, m_N	0.37513 lb/ft

1.4 Miscellaneous

The heat transfer surface areas are based on outside diameter since the heat transfer coefficients are based on the outside diameter.

Heat Transfer Area, A_{ht}	$0.2618 \text{ft}^2/\text{ft}$

2.0 SUPERHEATER SECTION

2.1 Water Side

Length of Tube, L_{Total}	43.1 ft
No. of Tubes N_s	45
Inside Diameter, D_i	0.611 inch
Outside Diameter, D_o	0.875 inch
Flow Area, A_{cross}	$2.0361 \times 10^{-3} \text{ ft}^2$
Volume of Tube, V_w	$8.7756 \times 10^{-2} \text{ ft}^3$

2.2 Metal

Wall Thickness, t_m	0.132 inch (0.120" MW)
Volume, V_m	$9.222 \times 10^{-2} \text{ ft}^3$
Mass, M_m	45.0 lbs.

2.3 Sodium Side

Equivalent Diameter, D_{nse}	1.3877 inch
Flow Area, A_n	$6.3269 \times 10^{-3} \text{ ft}^2$
Volume, V_n	$2.7269 \times 10^{-1} \text{ ft}^3$
Mass, M_n	14.343 lbs.

2.4 Miscellaneous

Heat Transfer Area, A_{ht} (Based on outside diameter)	9.873 ft^2

C-2 HEAT TRANSFER COEFFICIENTS (THEORETICAL)

In this section the actual heat transfer Film Coefficients on both the sodium and the water side are evaluated from correlations available from the literature.

In the analog simulation these coefficients are combined with the metal resistance and are given in C-3.

1.0 SODIUM SIDE

There are two correlations in the literature to determine the heat transfer coefficient from sodium to metal. These are:

$$N_u = \frac{U_{nm} D_h}{12K} = 0.212 (D_h R_e P_r)^{0.6} \quad (1)$$

$$N_u = \frac{U_{nm} D_h}{12K} = 4.03 + 0.228 (P_e)^{0.67} \quad (2)$$

and

where N_u is the Nusselts number

$$P_r, \text{ Prandtl No.} = C_p \frac{\mu}{k}$$

$$R_e, \text{ Reynolds No.} = \frac{D_h}{12} \frac{W}{A_{\text{cross}}} \frac{1}{\mu}$$

$$P_e = \text{Peclet's No.} = \left\{ \frac{D_o}{12\mu} \frac{W}{A} \right\} \left\{ \frac{C_p \mu}{k} \right\} = (R_e \cdot P_r)$$

D_h = Hydraulic Diameter, inches

D_o = Outside Diameter, inches

W = Total Sodium Flow, lbs/hr

A = Total Sodium Flow Area, ft^2

A_{cross} = Equivalent Cross Flow Area/Tube, ft^2

k = Thermal Conductivity of Sodium, $\text{Btu}/\text{ft}^2 \text{ hr}^\circ\text{F}/\text{ft}$

μ = Viscosity, $\text{lb}/\text{hr}\cdot\text{ft}$

C_p = Specific Heat, $\text{Btu}/\text{lb } ^\circ\text{F}$

h_{nm} = Heat Transfer Coefficient on sodium side, $\frac{\text{Btu}}{\text{ft}^2 \text{ hr}^\circ\text{F}}$

Assuming the thermal properties are constant, then equations (1) and (2) both yield h_{nm} as a function of W only.

Equation 1 is from the Liquid-Metals Handbook Sodium-NaK Supplement, 1st, July 1955 issued by the AEC - Department of the Navy, Washington, D.C.

Equation 2 is from the B&W Report No. BAW-1280-28.

The heat transfer coefficients are assumed to be constant for all regions in the Boiler Section, on the sodium side.

Figure C-1 gives the heat transfer coefficient on the sodium side as a function of sodium flow for both the Boiler and the Superheater Sections, based on Correlation (1). (See Table C-I).

TABLE C-I

HEAT TRANSFER COEFFICIENTS ON SODIUM SIDE

BASED ON NA-NAK SUPPLEMENT CORRELATION

(Btu/hr ft² °F)

<u>LOAD %</u>	<u>W/W⁰</u>	<u>BOILER</u>	<u>SUPERHEATER</u>
100	1.0000	8711	6325
80	0.8812	7676	5574
60	0.7384	6432	4670
40	0.5778	5033	3654
20	0.4771	4156	3018

2.0 WATER SIDE

There are distinct regions of heat transfer mechanisms on the water side and a different correlation is used in each region.

2.1 Boiler Section

a. Subcooled Region

The correlation used is the well known Colburn equation for forced convection:

$$h_{sc} = 0.023 \frac{k}{D_h} (R_e)^{0.8} (P_r)^{0.4} \quad (3)$$

$$h_{mw4} = h_{sc} * \frac{D_h}{D_o} \quad (4)$$

These are given in Table C-II and Figure C-2.

b. Saturation Region

The heat transfer mechanism in the saturated region consists of nucleate boiling superimposed with forced convection and in the downstream region it is by Film Boiling.

Assuming DNB (Departure from Nucleate Boiling) occurs at about 70% steam quality, we may write an overall heat transfer coefficient for the saturation region as follows:

$$U_{mw3} = h_{sat} = 0.7 h_{nb} + 0.3 h_{FB} + h_{FC} \quad (5)$$

where h_{nb} = Nucleate Boiling heat transfer coefficient
based on entire length and O.D.

h_{FB} = Film Boiling heat transfer coefficient
also based on entire length and O.D.

h_{FC} = Forced convection heat transfer coefficient.

1. Nucleate Boiling

$$\frac{h_{nb}}{h_{nb}^o} = \left\{ \frac{\Delta T_f}{\Delta T_f^o} \right\}^2 \quad (6)$$

$$\text{and } h_{nb}^o = C (T_f^o)^2 \quad (7)$$

$$C = \frac{\mu h_{fg}}{\sqrt{\frac{\sigma}{\rho_f - \rho_g}}} \left\{ \frac{C_p}{0.013 h_{fg} (P_r)^{1.7}} \right\}^3 \quad (8)$$

$$\Delta T_f^o = \frac{60 \left[\frac{Q^o}{A_{ht} \times 10^6} \right]^{0.25}}{P/900} \quad (9)$$

e

where Q^o = Heat Flux, Btu/hr

P = Pressure, psia

A_{ht} = Heat Transfer Surface Area, ft^2

h_{fg} = Heat of Vaporization of Water, Btu/lb

σ = Surface Tension, lb/ft

C_p = Sp. Heat of Liquid, Btu/lb $^{\circ}$ F

From (6) and (9) we can write

$$h_{nb} = h_{nb}^o \left\{ \frac{Q}{Q^o} \right\}^{\frac{1}{2}} \quad (10)$$

2. Film Boiling

A modified Colburn equation is used for the film boiling heat transfer evaluation:

$$h_{FB} = \frac{1}{2} \frac{0.023k}{D_o/12} \{P_r\}^{0.4} (R_e)^{0.8} \quad (11)$$

3. Forced Convection

The Colburn correlation is used for the forced convection heat transfer

$$h_{FC} = \frac{0.023k}{D_o/12} (P_r)^{0.4} (R_e)^{0.8} \quad (12)$$

Thus from (10), (11) and (12), substitution into (5) yields

$$h_{sat} = h_{mw3} = 0.7 h_{nb}^o (Q/Q^o) + 0.3 h_{FB}^o \left(\frac{W}{W^o} \right)^{0.8} + h_{FC}^o \left(\frac{W}{W^o} \right)^{0.8} \quad (13)$$

These are given in Table C-III and also plotted in Figure C-3.

c. Superheat Region

We use the following correlation in the superheat region

$$h_{SH} = 0.019 \frac{k}{D_{h/12}} (R_e)^{0.8} (P_r)^{0.4} \quad (14)$$

$$h_{mw2} = h_{SH} \frac{D_o}{D_h} \quad (15)$$

See Table C-IV and Figure C-2.

2.2 Superheater Section

A single heat transfer coefficient is adequate representation of the heat transfer phenomena in the Superheater section.

The correlation is the same as given in equation (14) except that the properties are now evaluated at an average temperature in the superheater. (See Table C-V and Figure C-4).

$$h_{mw1} = h_{SH} * \frac{D_o}{D_h} \text{ (superheater)} \quad (16)$$

TABLE C-II
HEAT TRANSFER COEFFICIENT ON WATER SIDE
SUBCOOLED REGION (Btu/hr ft²°F)

<u>LOAD %</u>	<u>W/W^o</u>	<u>h_{sc}</u>	<u>h_{mw4}</u>
100	1.0000	3026	2227
80	0.8000	2532	1864
60	0.5994	2009	1479
40	0.4000	1458	1073
20	0.2000	835	615

TABLE C-III

HEAT TRANSFER COEFFICIENT ON WATER SIDE

SATURATION REGION (Btu/hr ft²°F)

$$C = 92.32 \text{ (see Equation 8)}$$

$$h_{nb}^o = 8638 \text{ Btu/hr ft}^2\text{°F}; \Delta T_f^o = 9.67\text{°F}$$

$$P = 2400 \text{ psia}$$

$$Q/Q^o = \% \text{ Load of full load}$$

$$h_{FB}^o = 1270 \text{ Btu/hr ft}^2\text{°F}$$

$$h_{FC}^o = 2540 \text{ Btu/hr ft}^2\text{°F}$$

$$h_{sat} = h_{mw3} = 6047 \left(\frac{Q}{Q^o} \right)^{1/2} + 2921 \left(\frac{W}{W^o} \right)^{0.8} \quad (\text{From Equation 13})$$

<u>LOAD</u> <u>Q/Q^o</u>	<u>W/W^o</u>	<u>U_{mw3}</u>
1.000	1.0000	8968
0.800	0.8000	7852
0.600	0.5994	6624
0.400	0.4000	5232
0.200	0.2001	3510

TABLE C-IV

HEAT TRANSFER COEFFICIENT ON WATER SIDE

SUPERHEAT REGION (Btu/hr ft²°F)

<u>LOAD %</u>	<u>W/W^o</u>	<u>h_{SH}</u>	<u>h_{mw2}</u>
100	1.000	1434	913
80	0.8000	1200	764
60	0.5994	952	606
40	0.4000	691	440
20	0.2001	396	252

TABLE C-V

HEAT TRANSFER COEFFICIENT ON WATER SIDE

SUPERHEATER SECTION (Btu/hr ft² °F)

<u>LOAD %</u>	<u>W/W⁰</u>	<u>h_{SH}</u>	<u>h_{mw1}</u>
100	1.0000	824	575
80	0.8000	690	482
60	0.5994	547	382
40	0.4000	397	277
20	0.2001	227	158

C-3 ANALOG MODEL HEAT TRANSFER COEFFICIENTS

In the analog model the heat transfer coefficients used are from bulk fluid to mean metal for both on the sodium and the water side.

The metal volume is equally distributed to sodium and water side for evaluating the metal resistance.

C-3-a SUPERHEATER

Outside diameter, $d_o = 0.875$ inch

Inside diameter, $d_i = 0.611$ inch

Mean diameter, $d_m = 0.754$ inch

A: SODIUM SIDE

The overall heat transfer coefficient is given by

$$\frac{1}{U_{nml}} = \frac{1}{h_{nml}} + \frac{t_n}{12k} \quad (1)$$

where:

k = Thermal conductivity of Superheater tube metal, Btu/hr ft² °F

$$t_n = \frac{d_o}{2} \ln \frac{d_o}{d_m} = 0.0650 \text{ inch}$$

h_{nml} = Heat Transfer Film coefficient as given in Section C-2.

Equation (1) reduces to

$$\frac{1}{U_{nml}} = \frac{1}{h_{nml}} + 1.5093 \quad (1a)$$

B: Water Side

Similarly on the water side we have

$$\frac{1}{U_{mw1}} = \frac{1}{h_{mw1}} + \frac{t_w}{12k} + \frac{1}{C} \quad (2)$$

where:

$$t_w = \frac{d_o}{2} \ln \frac{d_m}{d_i} = 0.0923 \text{ inch}$$

C = Fouling allowance (3333 Btu/hr ft² °F)

h_{mw1} = Film coefficient based on O.D. as given in Section C-2.

Thus on the water side the Equation (2) reduces to

$$\frac{1}{U_{mw1}} = \frac{1}{h_{mw1}} + 3.223 \quad (2a)$$

C-3-b BOILER

Outside diameter, $d_o = 1.000$ inch

Inside diameter, $d_i = 0.6986$ inch

Mean diameter, $d_m = 0.8625$ inch

$t_h = 0.0740$ inch

$t_w = 0.1055$ inch

A: SODIUM SIDE

As in the previous case

$$\frac{1}{U_{nmi}} = \frac{1}{h_{nmi}} + 1.3662 \quad (3)$$

where

$i = 2, 3, \text{ or } 4$ for the three boiler regions

B: WATER SIDE:

$$\frac{1}{U_{mwi}} = \frac{1}{h_{mwi}} + 3.0277 \quad (4)$$

where

$i = 2, 3, \text{ or } 4$

These heat transfer coefficients are tabulated as a function of load in Table C-

TABLE C-VI - HEAT TRANSFER COEFFICIENTS*
(BTU/Sec ft² °F)

LOAD · %	SODIUM - METAL		METAL - WATER			
	V _{nm1}	V _{nm2} , V _{nm3} & V _{nm4}	V _{mw1}	V _{mw2}	V _{mw3}	V _{mw4}
100	0.44474	0.46882	0.10219	0.14346	0.22189	0.21532
80	0.43324	0.45525	0.09004	0.12843	0.17868	0.20073
60	0.41759	0.43674	0.07829	0.11077	0.15100	0.18190
40	0.39790	0.41137	0.05760	0.08972	0.10502	0.15667
20	0.38410	0.39804	0.03168	0.06422	0.04112	0.12110

*Note: These are overall heat transfer coefficients as explained in Appendix C-3

FIGURE C-1

HEAT TRANSFER COEFFICIENT ON WATER SIDE (BOILER)
(Based on Outside Diameter)

FIGURE C-2

FIGURE C-3

FIGURE C-4