Report No. BW 67-2

Volume 1
of 2 Volumes

PRELIMINARY DESIGN REPORT
FULL SIZE STEAM GENERATOR

Vol. 1 - General

to

U.S. Atomic Energy Commission
Chicago Operations Office
Lemont, Illinois

July 1, 1964

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC CONTRACT NO. AT (11-1) - 1280
B&W CONTRACT NO. 610 - 0067

THE BABCOCK & WILCOX CO.
BOILER DIVISION

Barberton, Ohio

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ABSTRACT

The work described in this Report is a portion of the Commission's over-all program on Sodium Components Development. The scope of work under this Contract is:

Phase I

A. Preliminary design of Full-Size Steam Generator.

B. Supporting R&D work.

C. Preliminary Design of 30 MWt Prototype Steam Generator.

Phase II

A. Detail Design of 30 MWt Prototype Steam Generator.

B. Fabrication of 30 MWt Prototype Steam Generator for testing at SCTI, Santa Susana, California.

C. Final Report relating results of testing of Prototype to the design of the Full-Size Steam Generator.

This report is the Design Report on the Preliminary Design of the Full-Size Steam Generator, (Phase I-A above). The Full-Size Steam Generator is of a size that three steam generators will produce steam to drive a 1000 MWe turbine.

This Report is divided into two major parts:

Volume 1 - General

Volume 2 - Stress Analysis

In Volume 1 is a description of the plant steam cycle, the heat transfer data at full and part load, a description of the steam generators, and reduced size copies of some of the arrangement drawings.

In Volume 2 are summarized the results of the ASME Code calculation, the steady state stress analysis, and the transient temperature and stress analysis. A sample calculation showing a typical steady state and transient analysis is included to illustrate the method of solution. To help the reader, the detail calculations are not, in general, included in this Report. These calculations have been assembled into an Appendix which will be sent to those interested upon request.

Large size white prints of all the drawings included in this Report are available and will be sent upon request.

TABLE OF CONTENTS

<u>Note</u> - Stress Analysis is discussed in Volume #2.

1.0 INTRODUCTION:

The United States Atomic Energy Commission has a continuing program of improving the technology in the Atomic Energy Field to demonstrate the production of economical nuclear power. To carry on this program the Commission has programs on fuel element, reactor, and component development. Under component development are included programs on developing sodium pumps, heat exchangers, steam generators, etc. This Contract is one portion of the Commission's overall program on development of steam generators.

The objective of this Contract is to develop a large sodium-heated steam generator of improved design. This steam generator design will be available for use in the Atomic Energy Commission Sodium Reactor Development Program which has the ultimate objective of developing reliable, economical, large central station nuclear power plants. This Contract was received on March 20, 1963, and signed on April 3, 1963.

1.1 Scope of Contract:

The overall scope of work covered under this Contract is as follows:

Phase I.

A. Preliminary Design of Full Size Sodium-Heated Steam Generator.

B. Supporting Research and Development Work.

C. Preliminary Design of 30 MWt Prototype Steam Generator.

Phase II.

A. Detail Design of Prototype Steam Generator.

B. Fabrication of Prototype Steam Generator for Installation and Testing at SCTI, Santa Susana, California.

C. Final Design Report relating the performance of the Prototype Steam Generator to the Design of the Full Size Steam Generator.

This Preliminary Design Report covers the design work under Phase I-A, "Preliminary Design of the Full Size Steam Generator."

1.2 <u>Changes in Scope</u>:

There have been three changes in scope of this Contract affecting the steam generator design. These are as follows:

1. In the original design on which the proposal for this Contract was based, the total heat load was 1000 MWt. For reliability reasons this thermal capacity was divided among three steam generators having a capacity of 333 MWt each. After design work was begun on these steam generators it was learned that the 1000 MWt represented only one loop of a three loop plant. If each loop had three steam generators this would make a total of nine steam generators for the total plant and would add to the cost, but would not increase the reliability of the overall plant. The scope of work under this Contract was modified to describe a steam generator of a size such that three identical steam generators would produce enough steam for 1000 MWe.
2. Another change in scope to raise the steam pressure from

the 2200 psi as specified in the original inquiry to 2400 psi at the turbine. This change brought the steam pressure into agreement with the "preferred standard" steam turbine design conditions common in the industry and will result in a cost saving in the steam turbine.

3. A feedwater temperature of 600F was originally specified for the steam generator. To produce this water temperature a feedwater heater is required that will operate at approximately 1600 psi on the shell side and extract steam from the high pressure turbine casing at approximately 1700 psi. An economic evaluation was made showing the cost of this 1600 psi feedwater heater exceeded the saving in fuel cost made possible by the higher cycle efficiency resulting from using this additional heater. This economic evaluation is included in the Appendix.

   The Contract was modified to lower the feedwater temperature to 530 F, which is a typical feedwater temperature for a 2400 psi steam turbine cycle using eight stages of regenerative feedwater heating.

1.3 Design Objectives:

The full scale steam generator system was designed to meet the following objectives:

1. Produce steam at the lowest cost with due consideration for capitalization and maintenance cost within limitations imposed by the specifications.
2. Achieve a minimum availability factor of 90% computed

on an annual basis, over a design service lifetime of at least 30 years.

3. Provide the basis for the necessary research and development to support the design and fabrication of the Prototype Steam Generator.
4. Minimize mechanical and thermal stresses.
5. Minimize the consequences of accidental mixing of sodium and water or steam due to equipment failure.
6. Easily accessible for maintenance and inspection.

2.0 STEAM PLANT CYCLE:

2.1 Plant Description and Layout:

The 1000 MWe electrical plant will have one reactor and three primary sodium coolant loops. Each of the primary sodium coolant loops shall have an intermediate heat exchanger, a primary sodium pump and associated valves. Connected to the secondary side of each intermediate heat exchanger through secondary sodium piping will be one steam generator, one reheater, one pump, and associated valves and piping. Only the steam generators and reheaters are being designed under this Contract. A sketch, showing a perspective view of one possible arrangement of the steam generators in an electric generation plant, is shown on Figure 1.

Three loops as shown on Figure 2 were chosen for this size plant because it gives the minimum number of loops for good operation.

In a three loop plant two of the loops can carry a major portion of the load if one loop is down for servicing. A number of loops greater than three was not used, since this

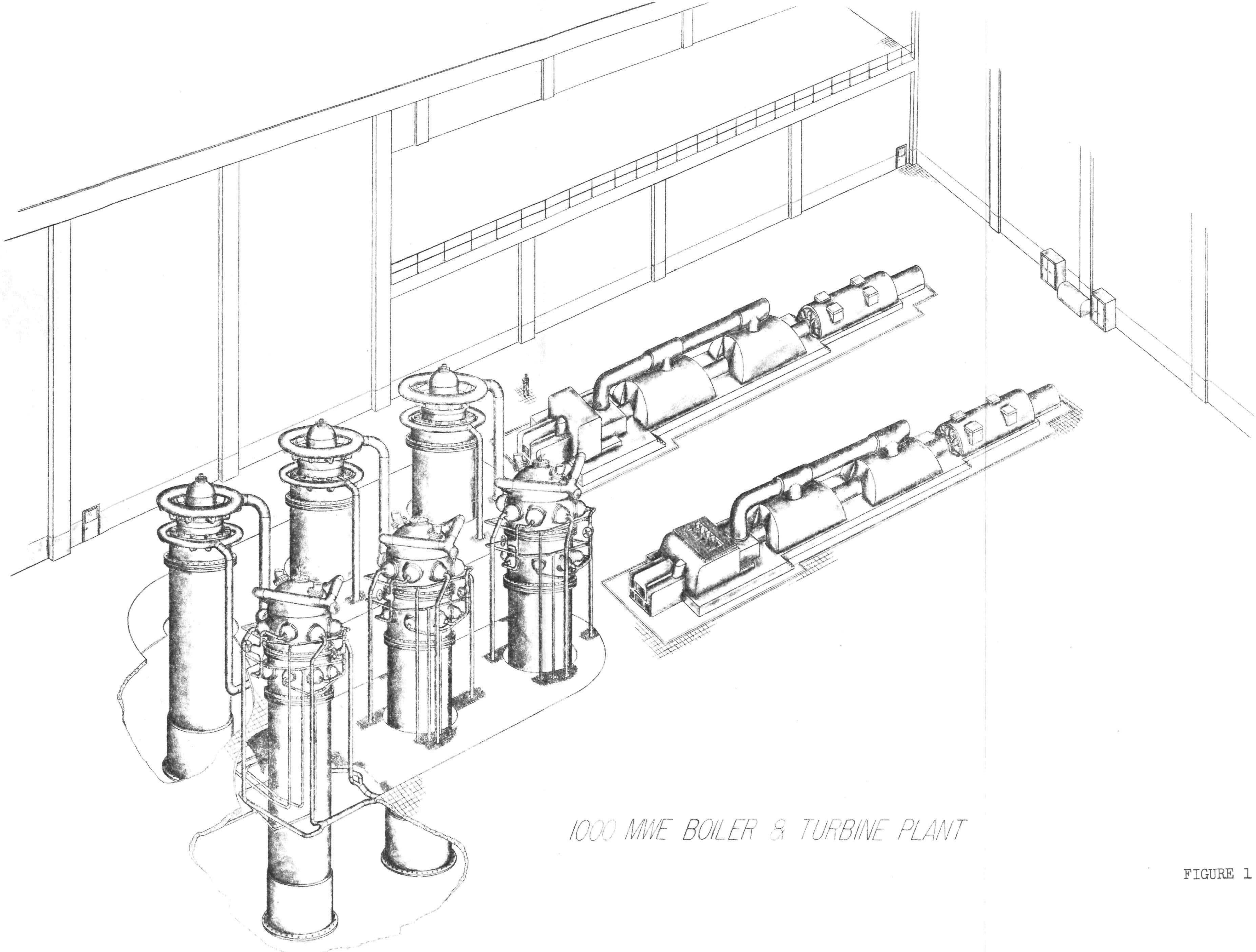


FIGURE 1

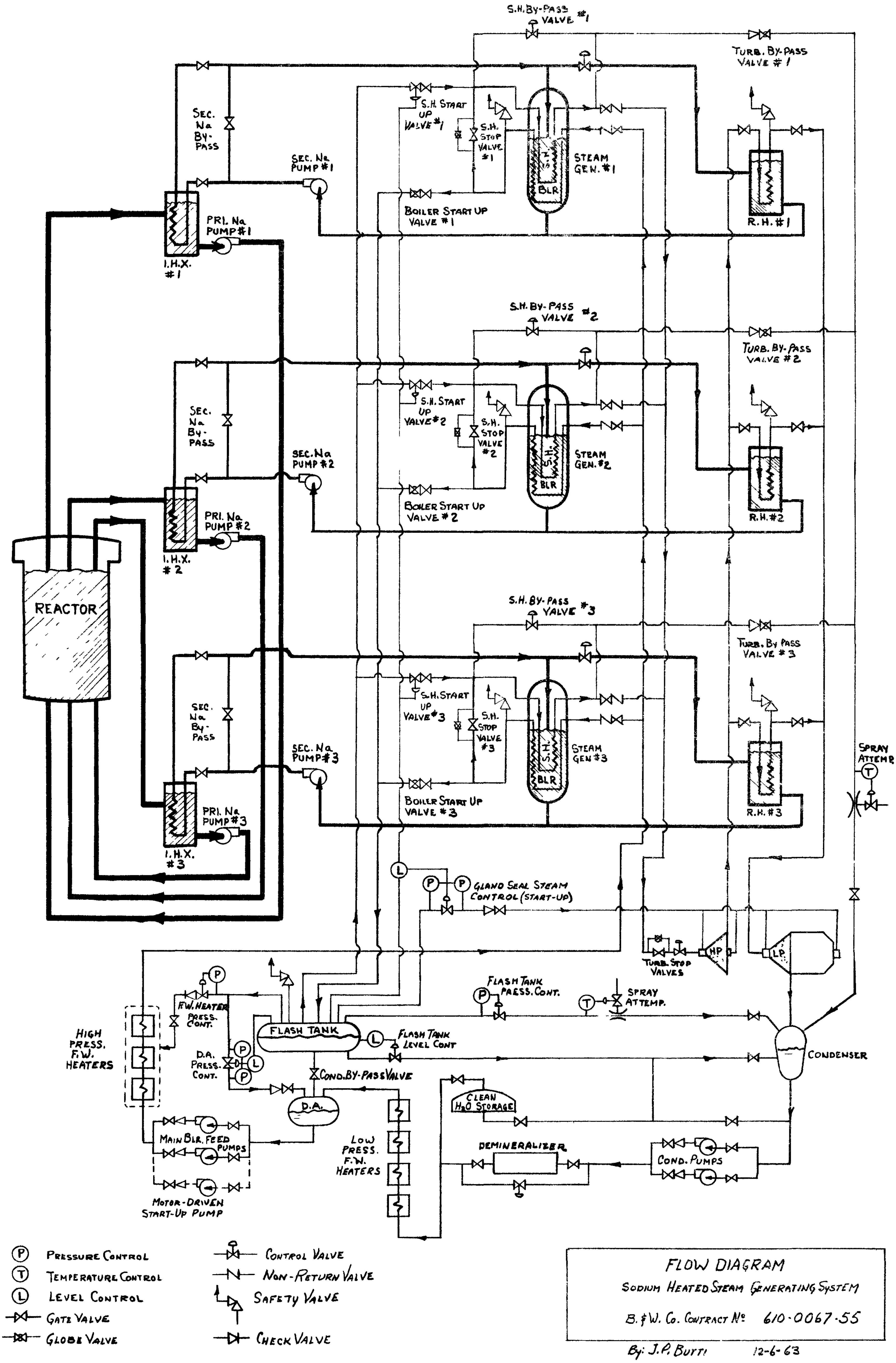

S.H. By-Pass Valve #1
Turb. By-Pass Valve #1
Sec. Na By-Pass
S.H. Start Up Valve #1
S.H. Stop Valve #1
Steam Gen. #1
BLR
Sec. Na Pump #1
Pri. Na Pump #1
I.H.X. #1
Boiler Start Up Valve #1
R.H. #1
S.H. By-Pass Valve #2
Turb. By-Pass Valve #2
S.H. Start Up Valve #2
S.H. Stop Valve #2
Steam Gen. #2
Sec. Na Pump #2
Pri. Na Pump #2
I.H.X. #2
Boiler Start Up Valve #2
R.H. #2
Reactor
S.H. By-Pass Valve #3
Turb. By Pass Valve #3
S.H. Start Up Valve #3
S.H. Stop Valve #3
Steam Gen #3
Sec. Na Pump #3
Pri. Na Pump #3
I.H.X. #3
Boiler Start Up Valve #3
R.H. #3
Spray Attemp.
Gland Seal Steam Control (Start-Up)
Turb. Stop Valves
HP
LP
Flash Tank Press. Cont.
Spray Attemp.
F.W. Heater Press. Cont.
High Press. F.W. Heaters
Flash Tank
Flash Tank Level Cont.
Condenser
D.A. Press. Cont.
Cond. By-Pass Valve
D.A.
Main Blr. Feed Pumps
Motor-Driven Start-Up Pump
Low Press. F.W. Heaters
Clean H_2O Storage
Demineralizer
Cond. Pumps
P Pressure Control
T Temperature Control
L Level Control
Gate Valve
Globe Valve
Control Valve
Non-Return Valve
Safety Valve
Check Valve
Flow Diagram
Sodium Heated Steam Generating System
B.&W. Co. Contract No. 610-0067-55
By: J.P. Burti
12-6-63

FIGURE 2

would have resulted in smaller components and increased cost, with little increase in operating flexibility. The components for a three loop plant approach the limits for shop fabrication and field erection.

2.2 Heat Load and Efficiency:

With a 1000 MWe turbine generator the reactor must produce 7971 x 10^6 Btu/hr. or 2333.5 MWt. For steam conditions of 2400 psig 1050 F/1000 F and 530 F feedwater, the plant efficiency is 42.8% at full load. This is significantly higher than present central stations operating at 2400 psi. In a reactor plant, the increased efficiency is due mainly to the elimination of the heat loss from products of combustion discharged from a conventional stack. A plot of efficiency vs. electrical load is shown on Figure 3.

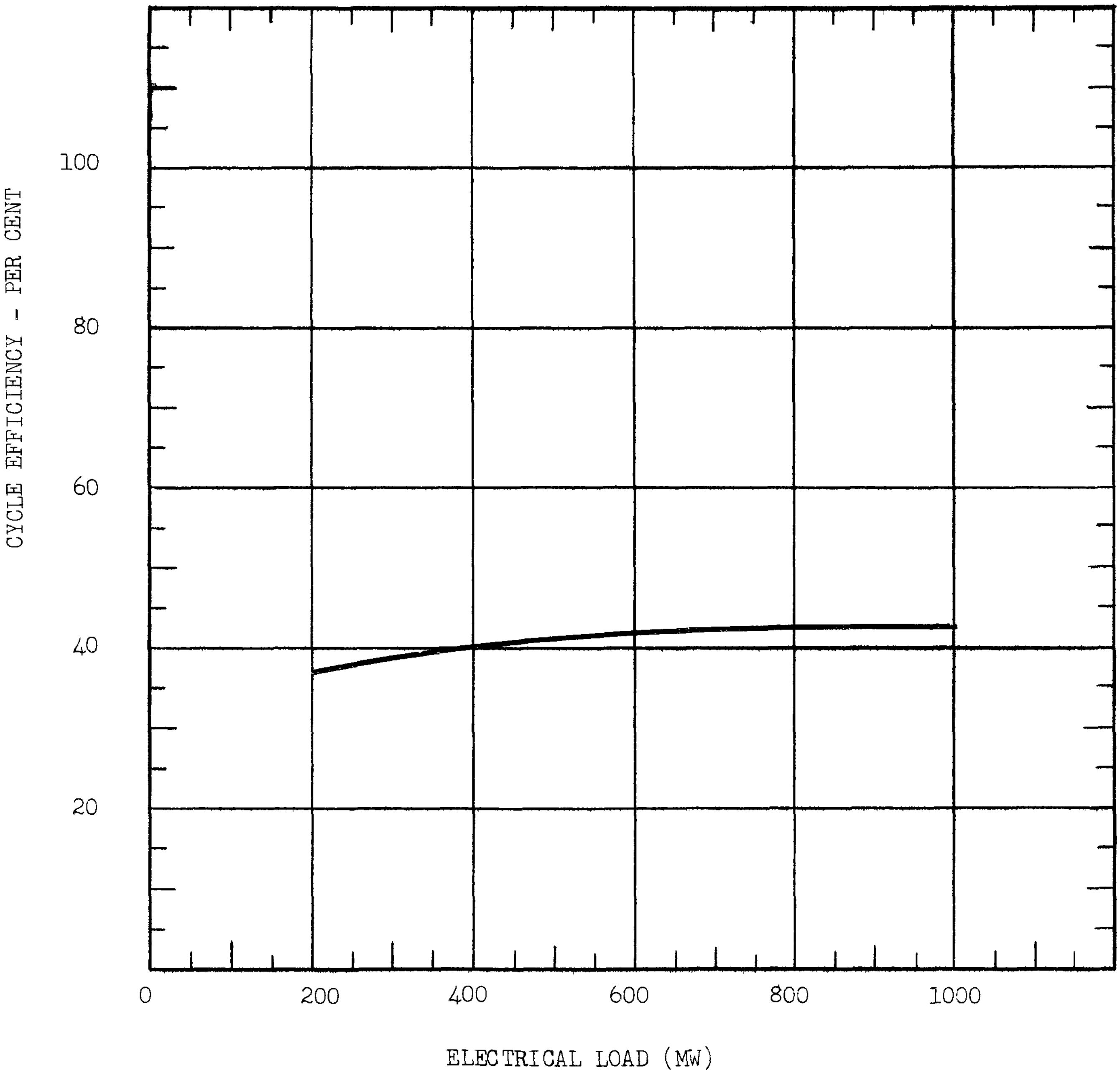
In order to generate 1000 MWe a steam flow of 7.21 x 10^6 lb/hr is required from the steam generators. The reheat steam flow for this full load condition is 5.13 x 10^6 lb/hr.

This total steam flow is generated in three steam generators and three reheaters. Full load steam flow per loop is 2.403 x 10^6 lb/hr from the steam generator and 1.71 x 10^6 lb/hr through the reheater.

The difference in steam flow through the steam generators and reheaters is due to steam extracted from the turbine for feedwater heating and for driving the steam driven feedwater pump. The heat load is divided among the three loops. Each loop has a full load capacity of 333.3 MWe or 2657 x 10^6 Btu/hr. Each loop heat load is split with 2330 x 10^6 Btu/hr being transferred in the steam generator and 327 x 10^6 Btu/hr being transferred in the reheater.

FIGURE 3

Efficiency Vs. Electrical Load



2.3 Steam Cycle:

The steam cycle is shown on Figure 4. Normal power plants have a series of feedwater heaters between the condenser and the boiler inlet. These feedwater heaters take water at approximately 100 F and heat it up to between 470 F and 530 F by steam extracted from the turbine. Feedwater leaving the turbine condenser is pumped by a condensate booster pump through four low pressure feedwater heaters to the deaerator. Upon leaving the deaerator, the water pressure is increased by the boiler feed pump and passes through three high pressure feedwater heaters to the steam generator inlets. The heat absorbed by the feedwater in the heaters comes from steam extracted from the turbine at various pressure stages along the turbine. Using the eight heater cycle -- four low pressure heaters, one deaerator and three high pressure heaters -- the water temperature entering the steam generator inlet is 530 F at full load, decreasing to 370 F at 20% load.

Steam leaving the steam generator enters the high pressure stage of the turbine at 2400 psig where it is expanded to a pressure of 525 psig. This lower pressure steam returns to the reheater where it is heated from 655 F to 1000 F and returned to the intermediate and low pressure stages of the turbine. Leaving the low pressure turbine the steam is condensed and the water returns to the feedwater heater cycle.

2.4 Peak Load:

The steam generator is designed for maximum continous

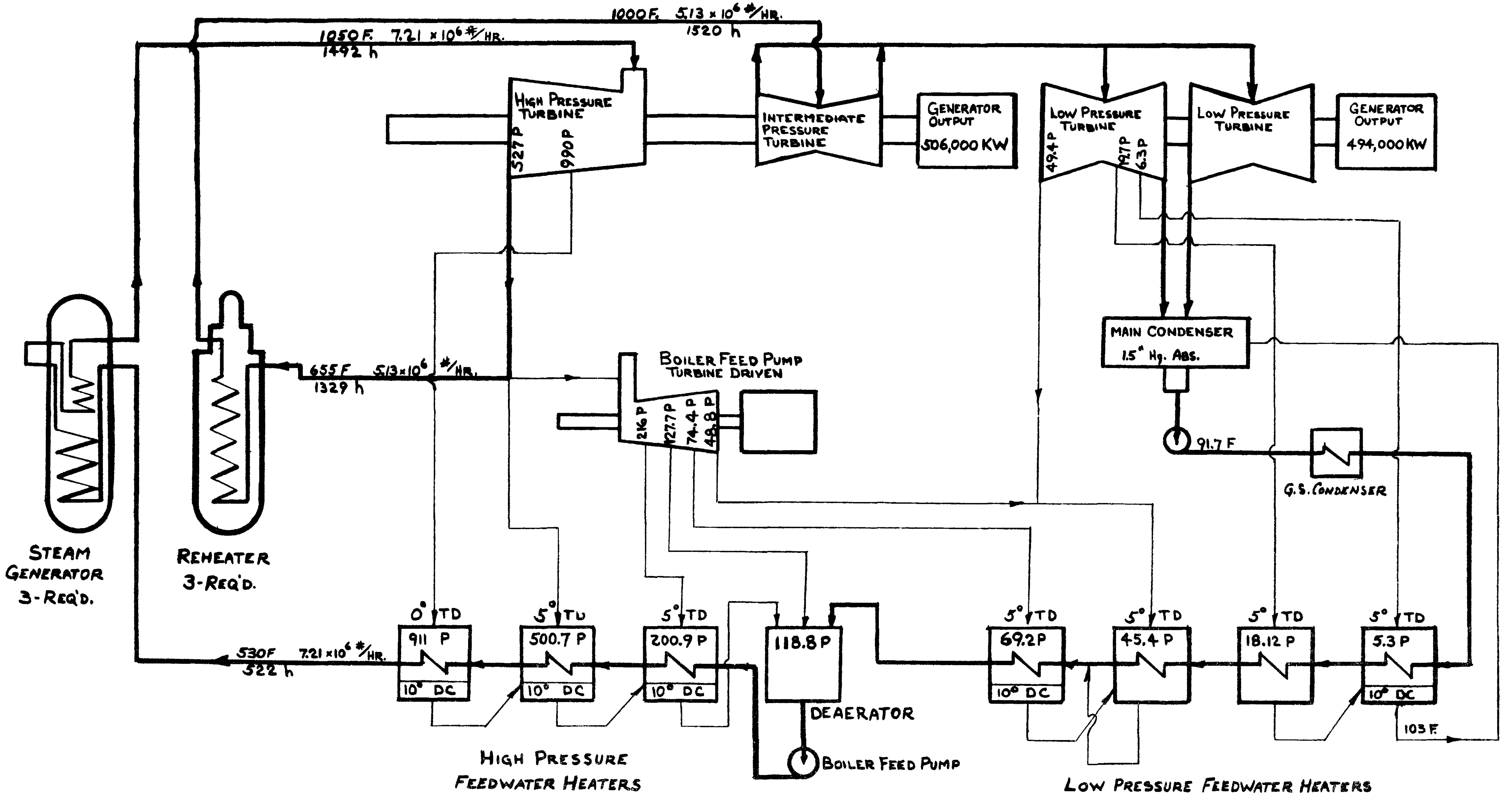


FIGURE 4

STEAM CYCLE DIAGRAM for 1000 MW PLANT

NET PLANT HEAT RATE = 7970 BTU/KW HR

1000 MW TURBINE
2400 P.S.I.G. 1050/1000

BY: J.P. BUTTI 3-17-64
B.&W. Co. No 610-0067-55

load. If additional electrical load is required for peak conditions, changes in steam cycle operation are required.

A normal turbine generator is designed to accept 105% of full load steam flow. Peak conditions can be obtained by:

1. Increasing steam flow to 105% of full load, or
2. Increasing the operating pressure on the steam generator, or
3. Removing the high pressure feedwater heaters from service.

Operation under these conditions is not economical, but will produce the maximum electrical power.

2.5 Secondary Sodium Cycle:

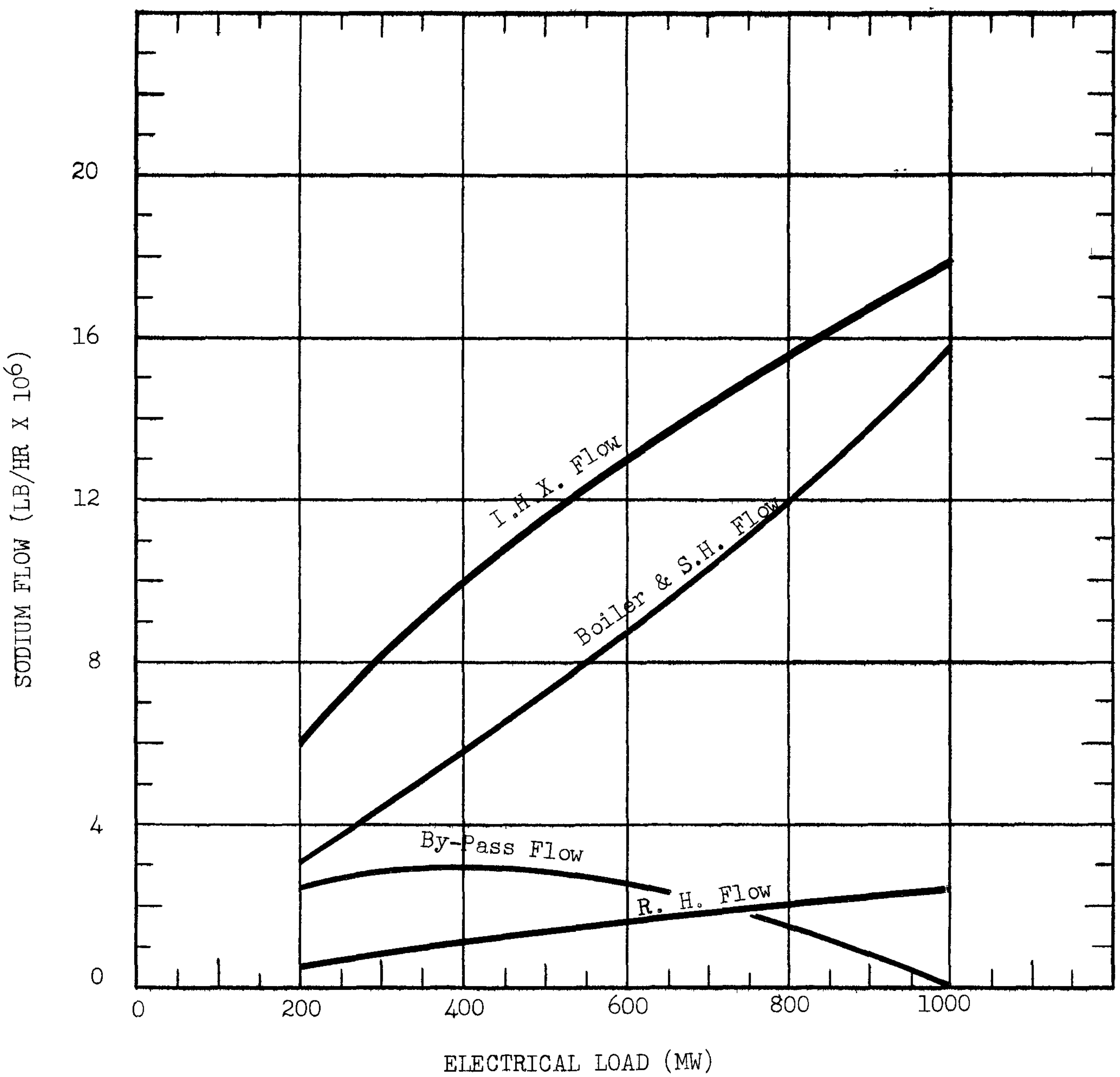
Secondary sodium leaving the IHX at 1140 F and 18.0 x 10^6 lb/hr at full load, flows in a single pipe to the steam plant building. Here the flow divides, with 15.59 x 10^6 lb/hr entering the steam generator and 2.41 x 10^6 lb/hr entering the reheater. After flowing through the boiler and reheater in parallel streams, the sodium is combined in the outlet piping below the reheater and steam generator at an average temperature of 650 F. The sodium then flows in a pipe to the secondary sodium pump and the intermediate heat exchanger. Sodium temperatures and flows for all loads are shown on Figures 5 and 6.

2.6 Steam Generator - Reheater Arrangement:

In the early stages of the design, consideration was given to several arrangements of the steam generator. Figure 7 shows the superheater section, boiler section and reheater in separate pressure shells, each with its own

FIGURE 5

Sodium Flow Vs. Load



SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

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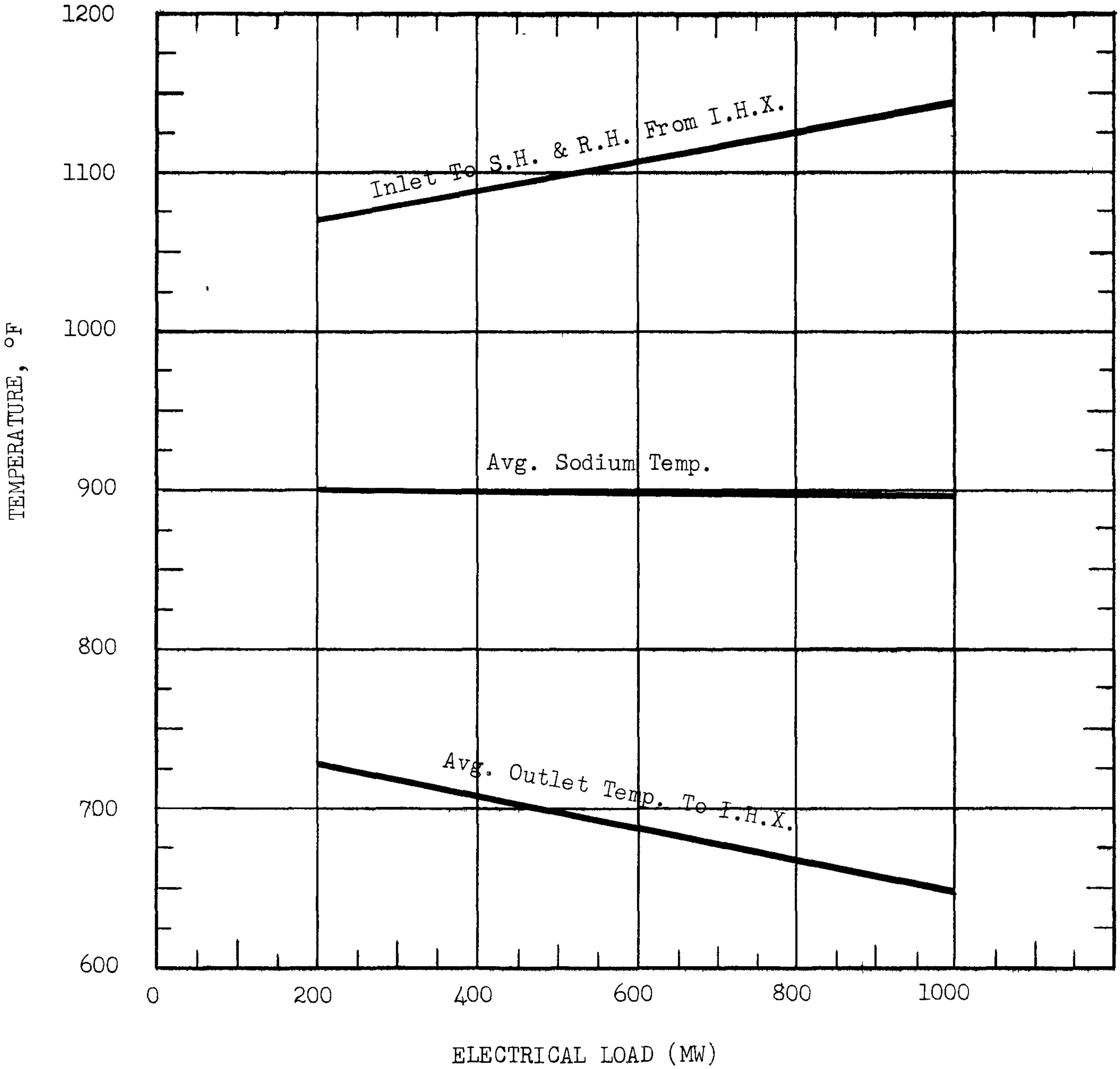
FIGURE 6

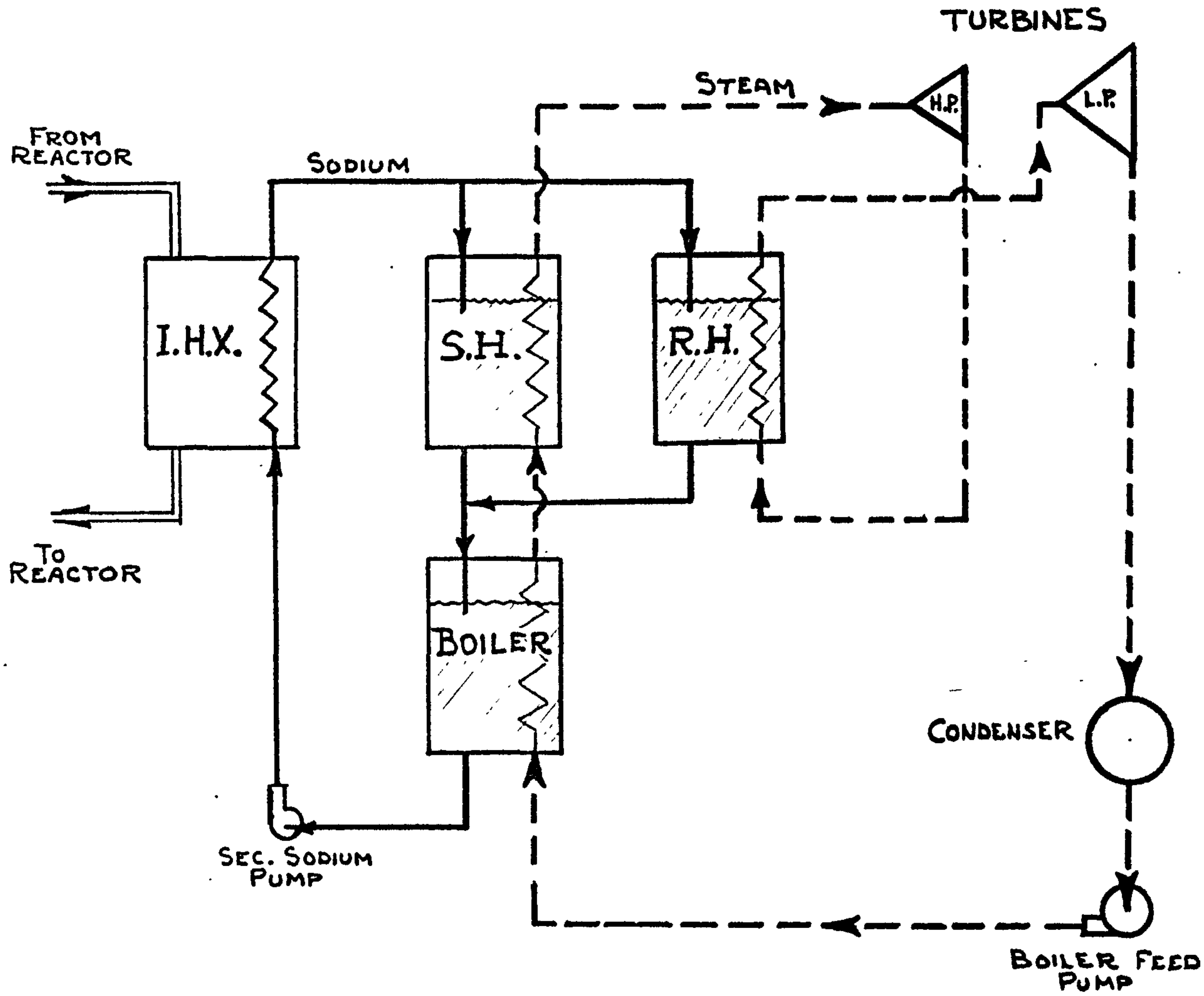
Sodium Temperature Vs. Load



cover gas volume. The reheater and superheater had parallel sodium flow paths which joined to take all the sodium flow through the boiler.

Figure 8 shows the arrangement used for this design. The superheater and boiler sections are in one shell. This eliminates the extra pressure vessel with its cover gas space, and the necessity of trying to control three separate sodium levels. The reheater and steam generator (boiler and superheater sections) are in parallel flow, since this internal steam generator design did not permit any acceptable method of introducing the reheat sodium flow to the boiler tube bundle. This condition resulted in the LMTD of the reheater decreasing from 216 F to 76 F with a corresponding increase in reheater heat transfer surface.

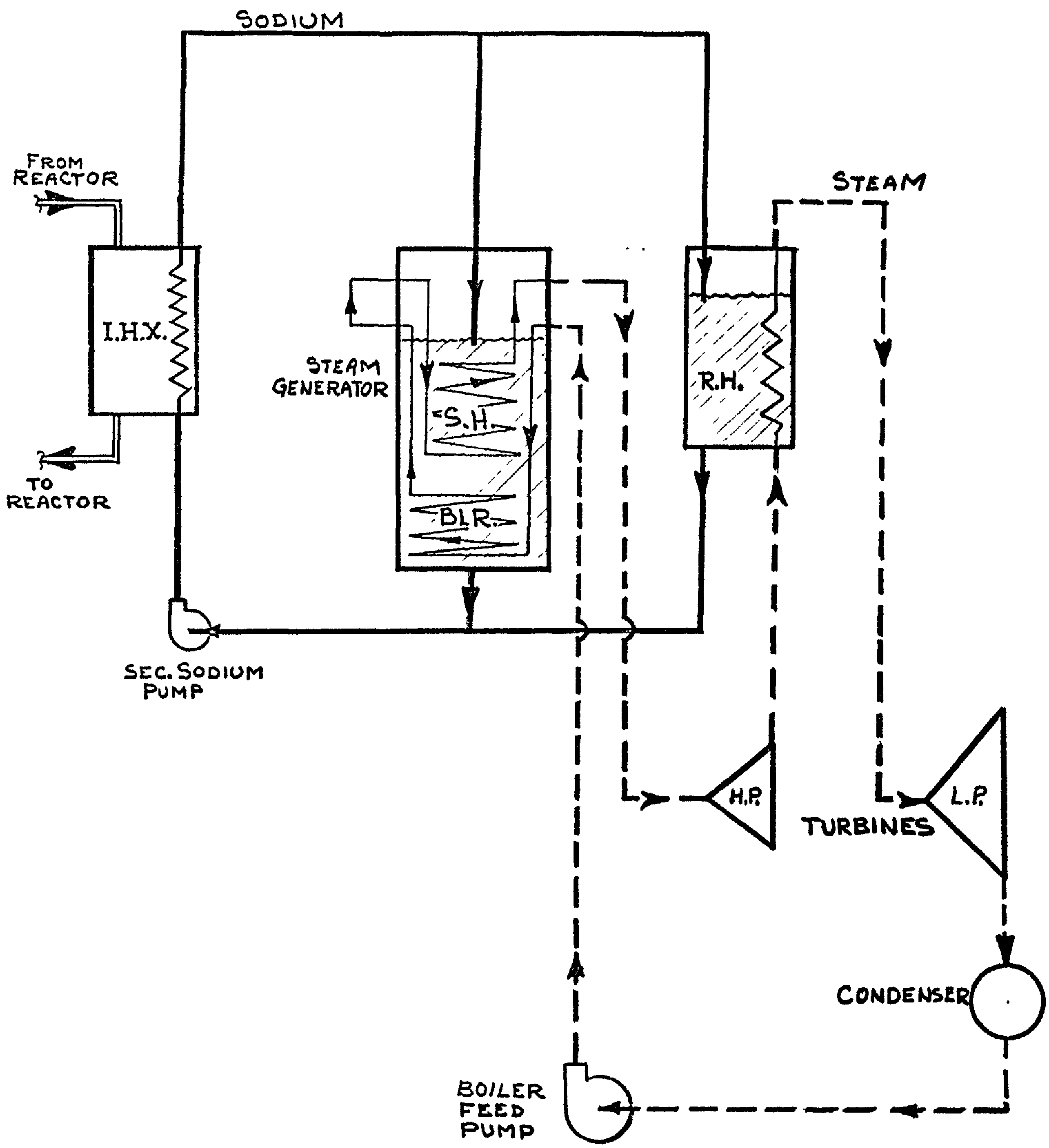
Additional studies are under way to design a unit which will have the desirable temperature characteristics shown on SK-1000-1. A type of design that would meet this requirement is the "Integral Reheat Steam Generator."



Schematic Arrangement of Superheater,

Boiler, and Reheater in Separate Pressure Vessels.

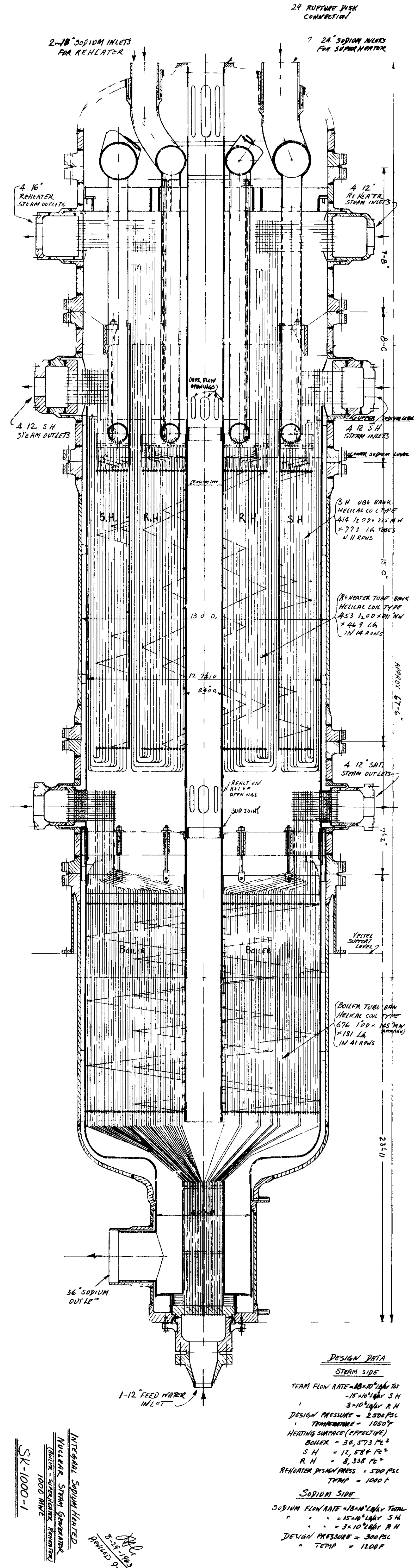
Figure 7



Schematic Arrangement of Steam Generator and Reheater

(Boiler and Superheater in one pressure shell)

Figure 8



24 RUPTURE DISK CONNECTION
2-18" SODIUM INLETS FOR REHEATER
2 24" SODIUM INLETS FOR SUPERHEATER
4 16" REHEATER STEAM OUTLETS
4 12" REHEATER STEAM INLETS
7-8"
8-0
OVER FLOW OPENINGS
4 12 S H STEAM OUTLETS
UPPER SODIUM LEVEL
4 12 S H STEAM INLETS
LOWER SODIUM LEVEL
SODIUM LEV
S.H.
R.H.
R.H.
S H
S H TUBE BANK HELICAL COIL TYPE 414 1.0 OD x .225 MW x 77.2 LG TUBES IN 11 ROWS
15' 0"
REHEATER TUBE BANK HELICAL COIL TYPE 453 1.00 OD x .071 MW x 46.9 LG IN 14 ROWS
13' 0" O.
12' 7 1/2" I.D.
2' 6" O.D.
APPROX 67'-6"
4 12" SAT. STEAM OUTLETS
REACTION RELIEF OPENINGS
SLIP JOINT
7'-2"
VESSEL SUPPORT LEVEL
BOILER
BOILER
BOILER TUBE BANK HELICAL COIL TYPE 676 1" OD x .145" MW (AVERAGE) x 131 LG IN 41 ROWS
23'-11
36" SODIUM OUTLET
1-12" FEED WATER INLET
DESIGN DATA
STEAM SIDE
STEAM FLOW RATE = 18x10⁶ LB/HR TOT
" = 15x10⁶ LB/HR S H
" 3x10⁶ LB/HR R H
DESIGN PRESSURE = 2500 PSI
" TEMPERATURE = 1050°F
HEATING SURFACE (EFFECTIVE)
BOILER = 34,573 Ft²
S H = 12,584 Ft²
R H = 8,338 Ft²
REHEATER DESIGN PRESS = 500 PSI
TEMP = 1000 F
SODIUM SIDE
SODIUM FLOW RATE = 18x10⁶ LB/HR TOTAL
" " " = 15x10⁶ LB/HR S H
" " " = 3x10⁶ LB/HR R H
DESIGN PRESSURE = 300 PSI
" TEMP = 1200 F
INTEGRAL SODIUM HEATED NUCLEAR STEAM GENERATOR (BOILER - SUPERHEATER REHEATER) 1000 MWE
SK-1000-1
8-29-1963
REVISED 9-17 1963

3.0 DESIGN CRITERIA:

There are certain basic design criteria that are important in the design of steam generators. Some are important in the design of any steam generator, some are important in the design of a once-through steam generator, and some are of vital importance in the design of a sodium-heated once-through steam generator.

3.1 Once-Through Type Steam Generator:

In order to develop economical, practical, reliable central station steam generators, the work under this Contract has centered on the once-through type steam generator. Economic studies have shown that the once-through boiler costs considerably less than a recirculating boiler, especially in large sizes and high pressures. The once-through steam generator has the ability to respond to load changes easily and gives greater flexibility of operation.

3.2 Design Can Be Extrapolated to Larger Sizes or Supercritical Pressure:

By using a helical coil design of boiler, superheater and reheater, great flexibility is possible in arranging the heat transfer surface to meet the particular design requirements of different size reactor plants.

The design can also be extrapolated to pressures greater than the critical pressure. Many of the new central stations are being built for pressures above the critical pressure (3206 psi). In large size units the saving in fuel cost because of the higher efficiency of the super critical pressure units more than offsets the additional costs of these units. The design of this steam generator will be relatively easy to extrapolate to pressures above the critical pressure as required to take advantage of advancing technology in central station design.

3.3 Ease of Inspection and Maintenance:

Experience has shown that unforeseen accidents can do serious damage to a tube bundle. Outages for repair of large central stations are very expensive, not only for the man hours spent in making the repairs, but also for the lost revenue when the generating equipment is shut down. Any features in a steam generator design that make them easy and quick to repair are worthwhile.

1. For inspection and plugging of individual tubes, handholes have been provided in each inlet and outlet header. If a larger access opening is required the interconnecting pipes can be cut.
2. For a complete examination of the tube bundles, the boiler, superheater and reheater are individually removable. The bundles can then be repaired or replaced.

3.4 Single Tube Wall Separating the Fluids:

A single tube wall construction was used for this steam generator design to achieve maximum economy in construction, reliability of operation, and simplicity of maintenance. This design principle has been accepted over the course of ten years design experience and extensive sodium-water reaction tests. These tests indicate that, if shock waves are properly cushioned, and the hydrogen generated by the reaction is adequately diluted and vented, a complete rupture of a steam generator tube can be handled with undue hazard.

Further experience gathered over the years in steam generator model and prototype testing indicate that leaks have invariably occured as minute cracks and pin holes rather than complete ruptures. Thus, detection of small leaks provides the opportunity to take corrective action before major failures occur.

Using a single tube wall will result in considerable saving in tube cost. A multiple tube wall adds cost to the steam generator not only because of the additional thickness of tubing, but also the resistance to heat flow through the additional barrier requires that the steam generator have more heat transfer surface to produce the same amount of steam.

3.5 Tube Sheet Exposed to Inert Gas Only:

This sodium-heated steam generator will be subjected to some rapid sodium temperature changes caused by operational transients. Any temperature changes in the sodium are quickly reflected in any metal parts in contact with the sodium, due to the high heat transfer coefficients of the sodium. A thin tube wall will follow the temperature changes rapidly, so any thermal stresses will be somewhat minimized.

However, tube sheets and shell flanges are more severely affected since they cannot change temperature fast enough to prevent the build-up of large thermal gradients and the associated thermal stresses. For this reason the shell flanges, the boiler inlet and outlet tube sheets, and the superheater and reheater inlet and outlet tube sheets are attached to the shells in locations where they are exposed to inert gas only. The only temperature transients that exist on the tube sheets originate on the water-steam side.

3.6 Bi-Metallic Welds Out of Heat Transfer Zone:

The boiler bundle is fabricated of Croloy 2-1/4 material, and the superheater tube bundle is stainless steel TP-316. Butt welds of similar material are used in sodium, but bi-metallic welds are not used. The bi-metallic welds between the two tube bundles are located in the interconnecting pipes external to the steam generator shell. In this area the bi-metallic welds are readily accessible, can be easily inspected, and if they should leak it will not result in a sodium-water reaction.

3.7 Protection of Shell from Temperature Transients and Corrosion:

The tube bundles are enclosed in a shell liner which contains the sodium. This liner is separated from the shell by a two-inch annulus filled with inert gas, and protects the shell from sodium thermal transients, and pressure, or temperature excursions or corrosion due to a sodium-water reaction.

3.8 Helical Coil Concept:

The helical coiled tube bundles provide a method of arranging compact bare tube heat transfer surface in a cylindrical vessel. A given number of tubes can be arranged to have nearly equal lengths by varying the number of parallel circuits for each coil diameter proportional to coil diameter. This feature permits great latitude in arranging heat transfer surface for any required tube side or shell side mass flow. Other features of the helical coil concept are:

1. Each coiled tube is capable of expansion independent of another tube, in addition to providing for differential expansion between tube and shell.
2. Coil fabrication requires no hot bends.
3. Pitch of the coils provides continous positive up-flow in the heat transfer zone.
4. It is ideally suited for counterflow arrangement of heat transfer surface.
5. Tube sheet diameters and thicknesses are minimized by using a fewer number of longer tubes.

4.0 DESIGN PARAMETERS:

The Full Size Steam Generator Plant has a full power capacity of 1000 MWe, and is designed in accordance with the following conditions.

4.1 Heat Load:

1 - Design and operating load for the entire plant is approximately 7971 x 10^6 Btu/hr for 1000 MWe. There are three loops in the plant. Therefore each loop has a heat load of 2657 Btu/hr. This heat load is divided between the steam generator, 2330 x 10^6 Btu/hr and the reheater, 327 x 10^6 Btu/hr.

4.2 Steam Flow:

1 - High pressure steam flow is 7.21 x 10^6 lb/hr at full load for three loops each steam generator has a steam flow of 2.403 x 10^6 lb/hr.

2 - Total Reheat steam flow is 5.13 x 10^6 lb/hr at full load. Each reheater has a steam flow of 1.71 x 10^6 lb/hr.

3 - Variation of steam flow with load is shown on Figure 10.

4.3 Sodium Flow:

1 - Sodium flow for each loop is 18.0 x 10^6 lb/hr at full load. This flow splits at the exit of the intermediate heat exchanger; 15.59 x 10^6 lb/hr going to the steam generator and 2.41 x 10^6 lb/hr going to the reheater.

In order to maintain the sodium Δ T across the IHX at part load, some of the sodium must by-pass the steam generator and the reheater through a by-pass connection, located in the center of the steam generator.

2 - Sodium flows at part load as shown on Figure 5.

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

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FIGURE 9

Steam Generator Temperatures Vs. Load

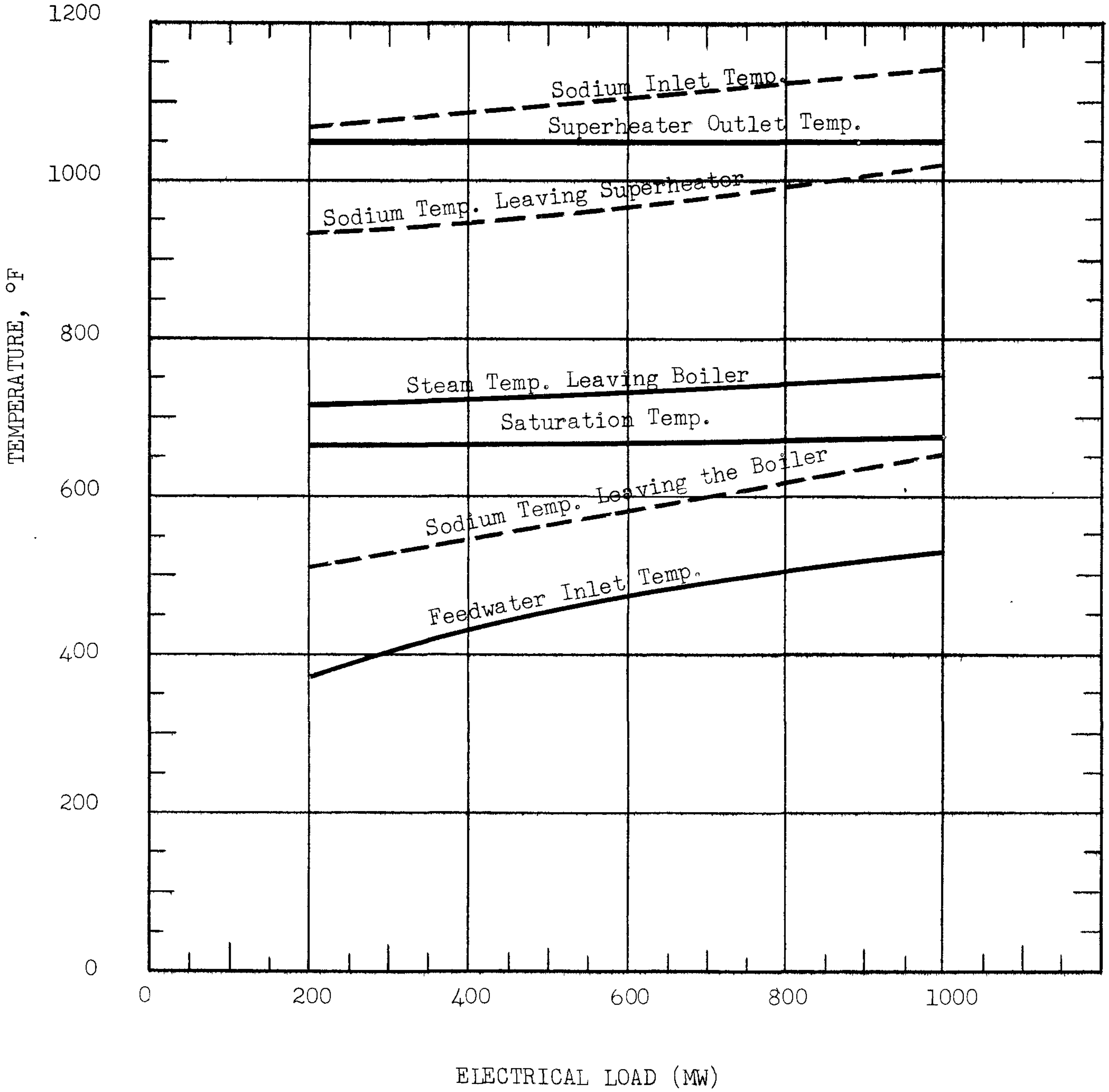
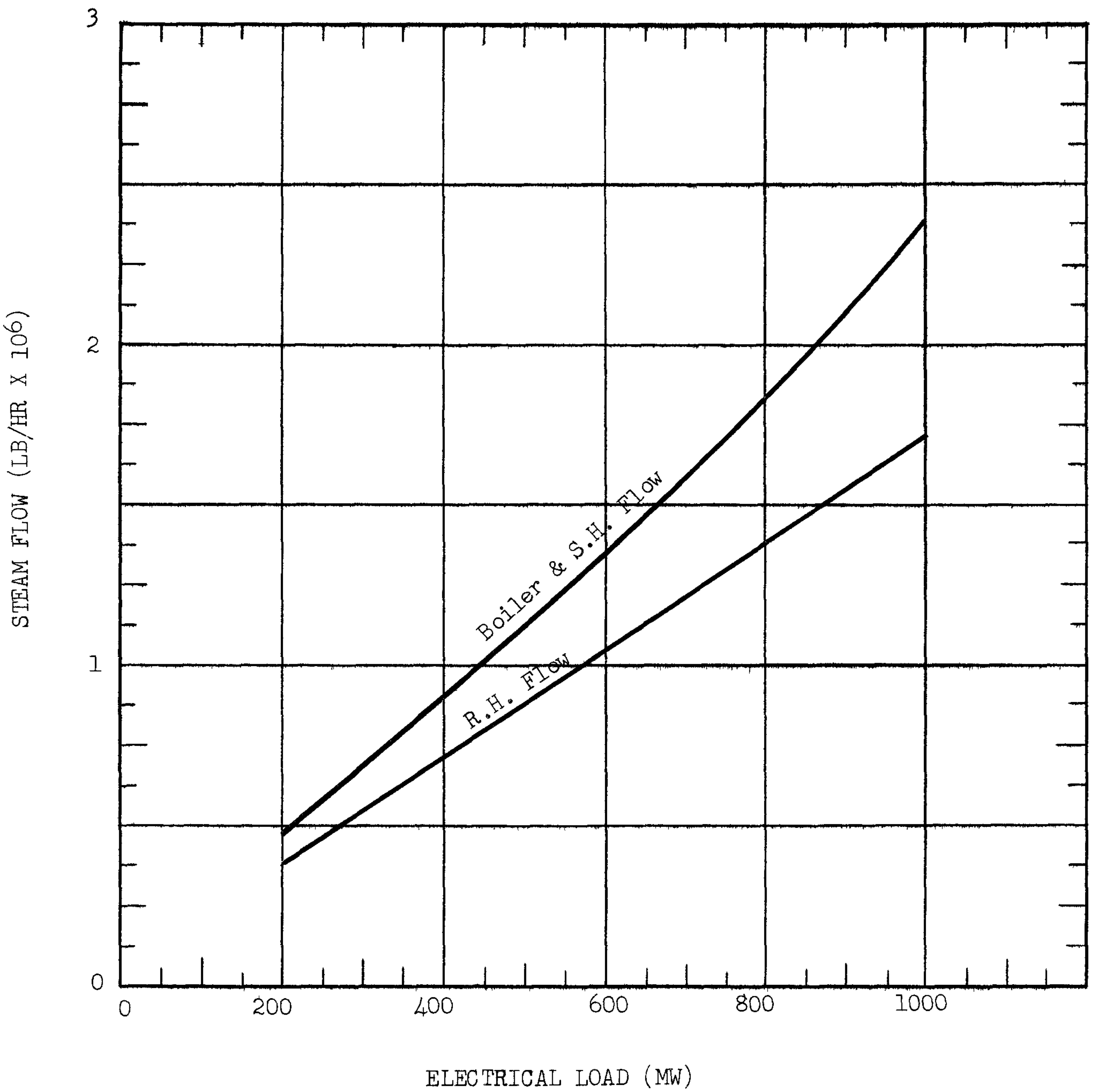


FIGURE 10

Steam Flow Vs. Load



4.4 Steam Conditions - Operating:

1 - Pressure - Operating steam pressure at the turbine throttle is 2400 psig. This pressure is constant with load. Operating pressure at the superheater outlet is 2425 psig. Reheat pressure at the turbine inlet is 475 psig at full load.

2 - Temperature - Steam temperature at the superheater outlet is 1050 F. This temperature is held constant from 20% to 100% load by regulating the sodium by-passed around the steam generator. Steam temperature at the reheater outlet is held constant with load at 1000F.

a - Feedwater temperature varies from 530F at 100% load to 370F at 20% load. (See Figure 11)

b - Steam entering the reheater is 655F at 100% load and decreases to 485F at 20% load.

4.5 Sodium Conditions - Operating:

1 - Sodium inlet temperature to the steam generator and reheater is 1140F maximum, and varies from 1140F (100% load) to 1050F (zero load).

2 - Sodium outlet temperature leaving the steam generator and reheater and entering the IHX varies between 650F at 100% load and 750F at zero load.

3 - Operating sodium pressure is 20 psig maximum.

4.6 Design Conditions - Pressure:

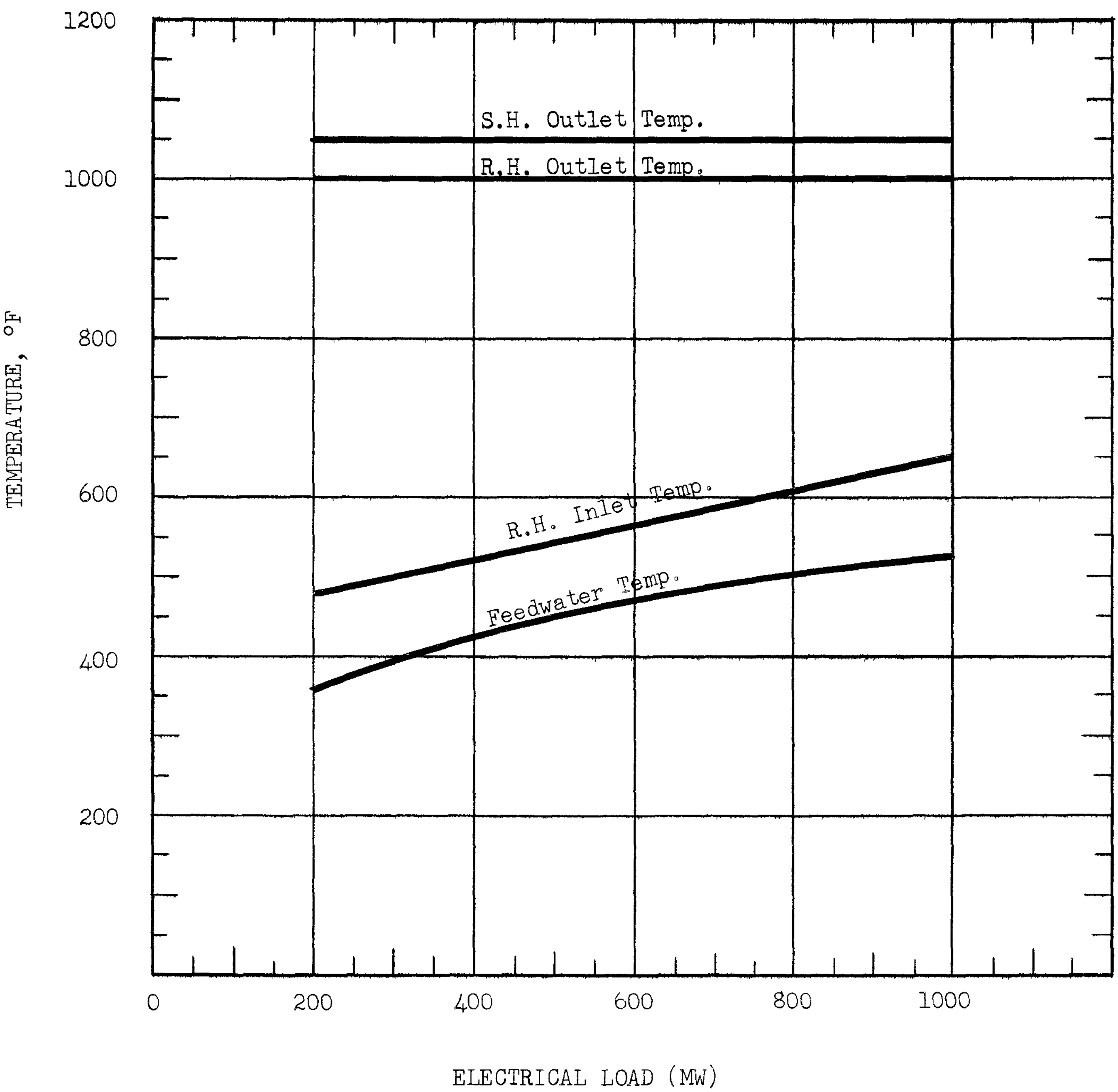
1 - Sodium Side - Steam Generator and Reheater

a. Pressure - 200 psig

2 - Steam Side

FIGURE 11

Steam Side Temperature Vs. Load



The design pressure of the water-steam side of the steam generator tubes is shown on Figure 12. This concept of stepped pressure design is used in central station practice for once-through boilers and has been given ASME Code approval.

The maximum operating pressure datum of a once-through boiler is established by the nominal operating supply pressure at the turbine throttle required to generate full load on the turbine. This is 2400 psig for this plant. The maximum operating pressure at any point in this once-through boiler is defined as the normal full load pressure at the turbine throttle increased by the accumulated pressure drop from the point of interest to the turbine throttle at normal full load steam flow. The total full load pressure drop from feedwater inlet to turbine throttle is 250 psi.

The required design pressure at any point in the boiler is defined as 105 per cent of the normal full load pressure at the turbine throttle, increased by the accumulated pressure drop from the point desired to the turbine throttle at 105 per cent of the normal full load steam flow.

This method of calculation allows for a minimum of 5% design margin in terms of both flow and pressure above the normal full load for all steam generator components. Based on this criteria the pressures can be calculated as follows:

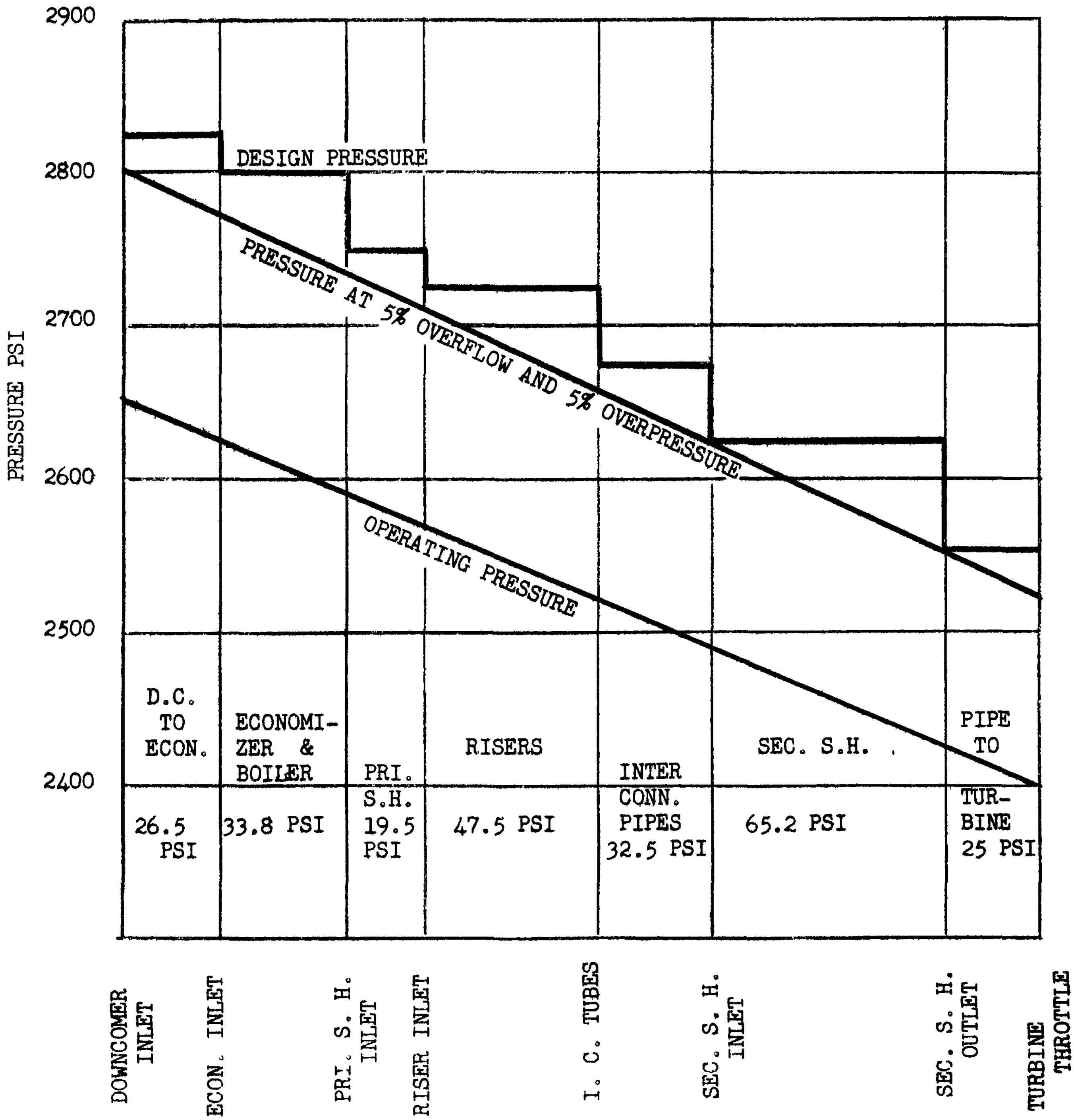
a - Maximum operating pressure is defined as the nominal

FIGURE 12

DESIGN PRESSURE - BOILER AND SUPERHEATER
STEPPED DESIGN PRESSURE FOR ONCE-THROUGH BOILERS
5% OVERFLOW, 5% OVERPRESSURE

DESIGN PRESSURES

D. C. TO ECON.	2825 PSI
ECON. & BOILER	2800 PSI
PRIMARY S.H.	2750 PSI
RISERS	2725 PSI
I.C. PIPE	2675 PSI
SEC. S.H.	2625 PSI
PIPE TO TURBINE	2550 PSI



operating pressure at the turbine throttle plus the accumulated pressure drop from the point of interest to the turbine throttle at full load steam flow.

b - Required design pressure is defined as: 1.05 (Nominal operating supply pressure at turbine throttle) plus the accumulated pressure drop from the point desired to the turbine throttle at 105% full load steam flow. Design Pressure at inlet = $1.05\ (2400) + (1.05)^2\ (250) = 2796$ psi.

c - Design pressure for boiler components is the required design pressure at the inlet of the component.

d - The popping pressure of the safety valves shall be set at 110% of the maximum operating pressure at the point where the valve is located in order to minimize simmering and leakage.

The design pressure of the reheater is 625 psi. No stepped pressure criteria was used in this component since the total pressure drop from turbine outlet to turbine inlet was only 50 psi. The steam inlet pressure at full load is 525 psi.

4.7 <u>Design Conditions - Temperature</u>:

1 - Sodium Side - Steam Generator and Reheater

a. Temperature - 1200 F

2 - Steam Side

In conjunction with the establishment of a design pressure for various components in the steam generator, design temperature for the tubes was established based on their location in the steam generator.

Design temperatures in the boiler bundle were based on a steam flow unbalance caused by the geometry of the worst tube. This one tube was considered to have:

a - Smallest ID based on manufacturing tolerances.

b - Longest length in the coiled bundle.

c - Smallest coil diameter.

d - Longest downcomer tube.

e - Longest riser tube.

f - Header unbalance of tube sheet.

Since all tubes have almost an equal number of bends, a flow unbalance due to increased bends was not considered. The sodium temperature entering the boiler bundle was assumed to be at uniform temperature.

The resultant steam flow unbalance gave a flow for the "worst" tube of 89.3% of average full load flow. The "worst" tube was 65 F superheated with steam leaving the boiler bundle at a temperature of 815 F instead of 750 F for the average tube. Using this decreased flow it was possible to calculate the tube wall design temperature at various locations in the bundle. The design temperature of a tube is the arithmetic average between the outside surface temperature and the inside surface temperature. The outside surface temperature was established using average sodium flow and average sodium film temperature drops. The inside tube temperature was based on steam film conductance and local heat flux at the unbalanced flow, and includes the film temperatures drop due to fouling. (Fouling Factor = .0003) Complete calculations to determine tube wall temperatures are included in the Appendix.

Based on these calculations the design temperature for the economizer and nucleate boiling section was (T = 738 F); for film boiling section, (T = 855 F); and the primary superheater section and the outlet riser tubes, (T = 956 F). Additional temperature steps were not used, since three different tube wall thicknesses were sufficient to minimize the tube bundle size without increasing the fabrication difficulties.

The design temperature for the stainless steel tubes in the superheater bundle was established using similar geometric assumptions as those in the boiler section. The resultant steam flow unbalance was 89.0% of average full load flow. The "worst" tube was 50 F superheated with steam leaving the superheater at 1100 F instead of 1050 F.

It is not necessary to use more than one design temperature in the superheater The calculated maximum tube wall temperature is 1133 F at the superheater outlet. Calculations to determine tube wall temperature for the superheater are included in the Appendix.

Reheater - The design temperature of the reheater was figured on a similar basis to that used in the boiler bundle. The reheater bundle was divided into three areas, each with its own design temperature. The design metal temperature for the tubes at the lower section is 850 F, the middle section design metal temperature is 1000 F, and the top section which sees incoming sodium at 1140 F and 1000 F steam is 1140 F.

4.8 Recommended Feedwater Chemistry Requirements:

The recommended limits on feedwater entering the steam generator are listed below. These limits are not established by the steam generator which can operate with 1 ppm total dissolved solids in the water as specified in this Contract. The recommended limits are set by considering all of the equipment in the steam cycle, especially the turbine. They are not unrealistic, but common in modern power plant practice.

The pH valve should be adjusted to obtain 0.01 ppm iron maximum. This will normally require a pH valve without the range of 8.5 to 9.2 at 77F.

Item	Limit
Total Dissolved Solids	0.05 ppm Max.
Suspended Solids	Minimum - Preferably Zero
Hardness	0.0 ppm
Organic	0.0 ppm
Free Caustic	0.0 ppm
Dissolved Oxygen	0.007 ppm Max. Preferably Zero
Carbon Dioxide	Minimum - Preferably Zero
Total Silica (as $S_i O_2$)	0.02 ppm Max.
Total Iron (as Fe)	0.01 ppm Max.
Total Copper (as C_u)	0.002 ppm Max.

In modern central stations this feedwater purity is maintained by elimination of condenser leakage, demineralization of make-up water, careful control of chemistry of condensate system, and full-flow condensate polishing demineralizers.

5.0 GENERAL DESCRIPTION OF STEAM GENERATOR:

Three (3) steam generators are required in the 1000 M.W.E. system. One steam generator is shown assembled on drawing 20950 F.

5.1 Pressure Shell:

The pressure shell is 13 ft. I.D. and approximately 69 ft. long, including the upper and lower hemispherical heads. The vessel stands vertically to an overall height of approximately 77 ft. including the cylindrical support skirt and the sodium by-pass valve operating mechanism on the upper head. Two sodium inlet nozzles are located in the upper head. One sodium outlet nozzle is located in the lower head. Four superheater inlet and four superheater outlet nozzles are alternately arranged at equal spaces around the shell just below the upper head. Nine feet lower, in the boiler shell spool piece, four feedwater inlet and four boiler outlet nozzles also are alternately arranged at equal spaces around the shell. The boiler outlet nozzles are connected to the four superheater inlet nozzles by external piping.

Drawings 20951 F, 20952 F, and 20953 F, show the three main sections from which the steam generator is assembled, the shell, boiler, and superheater respectively. These three sections would be fabricated separately in the shops and assembled into one complete unit in the field. The full flanged connections joining the three main sections allow the boiler and superheater tube bundles to be individually removed for repair or replacement. To provide a leak-proof seal at the flanges, a welded seal membrane is used.

The superheater section, (drawing 20953 F), consists of the upper hemispherical head, top shell, top shell flange, superheater nozzles and their tubesheets, the sodium inlet and distribution system, the upper section of the sodium by-pass valve, superheater tube bundle and its riser and downcomer tubes, the superheater shrouds and superheater tube supports, and the various safety devices in the upper head. By cutting the boiler to superheater external interconnecting pipes and the seal membrane, and unbolting the upper flanges, the superheater section and its tube bundle can be removed separately from the boiler section and shell. The superheater tube bundle and shrouds are supported from the upper hemispherical head.

The boiler section, (drawing 20952 F), consists of a flanged spool shaped shell section, the feedwater inlet and boiler outlet nozzles and their tube sheets, the boiler tube bundle with its riser and downcomer tubes, the boiler shroud and tube supports, and the lower section of the sodium by-pass valve. The boiler tubes, shroud and tube support beams are supported from its shell. Unbolting the lower flanges allows the boiler section and its tube bundle to be withdrawn from the shell leaving the shell and its liner in place.

The shell section (drawing 20951 F) consists of the shell flange, straight shell section, lower hemispherical head, sodium outlet nozzle, support skirt, and shell liner. This section is bolted to the foundation steel.

5.2 <u>Sodium Flow Path (Figures for 100% Load)</u>:

By referring to drawing 20950 F one can trace the flow path of sodium through the steam generator. Total sodium flow rate through the steam generator is 15.59 x 10^6 lb/hr. Incoming sodium at 1140° F enters through two - 24 inch sodium inlet nozzles at the top of the vessel and flows downward through the sodium distribution system, and is uniformly distributed over the tubes at the entrance of the superheater. It then flows downward in cross flow over the helical coil superheater tube bundle, and leaves the superheater at 1013°F. The sodium continues downward in cross flow over the helical coil boiler tube bundle (primary superheater section, film boiling section, nucleate boiling section, and economizer section) leaving the steam generator at 644°F through one - 32 inch sodium outlet nozzle at the bottom.

5.3 Steam and Water Flow Path (Figures for 100% load):

By referring to drawing 20950 F one can also trace the flow path through the water and steam side of the steam generator. Total steam flow rate through the steam generator is 2.403 x 10^6 lb/hr. Feedwater enters the steam generator at 530° F through the four boiler inlet nozzles arranged around the vessel and flows downward in downcomer tubes arranged in the annular space between the boiler tube bundle and the shell liner. Feedwater flows to the bottom of the boiler tube bundle in these downcomer tubes then turns and flows upward in the helical coil boiler tube bundle, (economizer section, nucleate boiling section, film boiling section, and primary superheater section), where it changes to steam and continues upward in the boiler riser tubes at

750° F to the four boiler outlet nozzles. Each of the four circuits from feedwater inlet to boiler outlet contains 169 tubes for a total of 676 tubes in the boiler section. Each tube is continuous from the inlet header to the outlet header.

The steam flows at 750° F from the four boiler outlet nozzles to the four superheater inlet nozzles through external interconnecting pipes then flows downward in the superheater downcomer tubes arranged in the annular space around the superheater tube bundle. The steam then turns and flows upward in the helical coil superheater tube bundle, continues upward in the superheater riser tubes and leaves the steam generator at 1050° F through the four superheater outlet nozzles. Each of the four superheater inlet-to-superheater outlet circuits contains 305 tubes for a total of 1220 tubes in the superheater section.

1. Steam Flow During Start-Up. The start-up system is described in section 8.0. The steam generator is connected to the start-up system through the boiler outlet-to-superheater interconnecting pipes. During start-up while the boiler section is not yet producing dry steam, the steam and water mixture coming from the boiler outlet nozzles is taken to a flash tank in the start-up system where the steam and water mixture is separated. The dry steam from the flash tank is then returned to the steam generator and introduced into the superheater inlet nozzles through the interconnecting pipes. After the boiler section is producing dry steam, the start-up system flash tank is by-passed and the steam

flows directly from the boiler outlet nozzles to the superheater inlet nozzles through the interconnecting pipes.

5.4 Sodium By-Pass Valve:

With the use of a sodium by-pass around the superheater and boiler it is possible to maintain steam temperature at 1050 F from full load to loads as low as 20%. The sodium by-pass valve hangs vertically in the center of the steam generator. This location (center of the tube bundles) lends itself for this purpose because it would be impractical to coil the tube bundles all the way in to the center of the vessel. This by-pass valve is a motor operated sleeve type valve with two sets of ports, one set at the bottom below the boiler tube bundle and the other set above the superheater tube bundle but below the sodium level. The two sets of ports are operated in tandem on a single sleeve, one set of ports opening as the other set is closing. For full load operation the valve sleeve is raised to close the upper ports and open the lower ports. All the sodium flows down through the tube bundles, through the lower ports, and leaves the steam generator through the sodium outlet nozzle. During part-load operation the sleeve is lowered, closing off a portion of the lower ports and opening a portion of the upper ports. This permits a portion of the sodium to by-pass the tube bundles and flow directly down through the valve sleeve to the sodium outlet nozzle.

5.5 Argon Gas Blanket:

The tube bundles are enclosed in a shell liner which contains the sodium. This liner is separated from the shell by a two-inch annular space filled with argon gas. The gas volume above the sodium level is approximately 2300 ft^3 and operates at a pressure of 20 psi. The argon gas serves to dampen pressure excursions that may result in the event of a sodium-water reaction.

Since the tube sheets, vessel flanges, and the support skirt-to-shell attachment are most sensitive to temperature changes these parts are arranged to be in contact with argon gas instead of sodium. Therefore, they are protected from the rapid sodium temperature changes that are typical of any sodium-heated steam generator. Thermal stresses in the tube sheets are limited to very small values.

5.6 Access to Tube Ends:

Access to the steam and water side of the tube sheets is provided through six 4" diameter removable handhole caps in the spherical portion of each inlet and outlet header. These removable handhole caps are of the conventional type used in normal power plant design, and provide access to the tube ends for inspection and plugging. For performing major work within the headers, the connecting piping or the whole hemispherical cover may be removed to provide a larger access opening.

5.7 Shrouds:

Sodium flow is directed in cross flow over the tube bundles, and prevented from by-passing down through the annular spaces containing the riser and downcomer tubes, by the use of long cylindrical shrouds extending up above the sodium level and down to the lower ends of their respective tube bundles. The superheater shrouds are suspended from the upper hemispherical head. The boiler shroud is suspended from beams attached to the shell of the boiler section.

At the center of the tube bundles, the 30" O.D. pipe serves as a shroud and also contains the sodium by-pass valve. The upper section of this pipe is suspended from the upper hemispherical head. The lower section is supported through the boiler section.

The superheater inner shroud separates the superheater downcomer tubes from the superheater tube bundle and its riser tubes. This shroud is 94" I.D. x 3/8" thick above the sodium level. Below the sodium level it changes to a double shroud whose inner wall is 93-1/2" I.D. x 3/8" thick and whose outer wall is 95-1/8" I.D. x 3/8" thick. A double shroud is used below the sodium level to reduce heat transfer to the downcomer tubes, and also to reduce the thermal stresses in the shroud itself due to high temperature gradients expected across the shroud in this area.

The superheater outer shroud separates the superheater downcomer tubes from the boiler riser tubes. This is a single thickness shroud 117-3/4" I.D. x 3/8" thick.

The boiler shroud separates the boiler downcomer tubes from the boiler tube bundle and its riser tubes. This shroud is 133-1/2" I.D. x 3/8" thick above the sodium level. Below the sodium level it changes to a double shroud whose inner wall is 133" I.D. x 3/8" thick and whose outer wall is 136-7/8" I.D. x 3/8" thick. A double shroud is used in this area to reduce heat transfer to the downcomer tubes, and also to reduce the thermal stresses in the shroud itself due to high temperature gradients expected across the shroud.

5.8 Sodium Distribution System:

Sodium entering the steam generator through the two sodium inlet nozzles flows into a 19-1/4" I.D. round ring type header then flows downward in eight - 12" I.D. sodium downcomer pipes whose lower ends are capped. The sodium flow from each of the eight sodium downcomers is distributed through an array of 1/2" diameter holes into the area above the superheater tube bundle, but below the normal sodium level. Baffles are arranged at the outlet ends of the sodium downcomers to assure that local high velocity streams leaving the downcomers of 11.4 ft/sec. will not cause superheater tube vibration. From this area the sodium flows downward in cross flow over the superheater helical coil tube bundle. The sodium velocity in the superheater tube bundle is 6.7 ft/sec.

5.9 Interconnecting Piping:

In order to conduct steam from the boiler section to the superheater section, four interconnecting pipes are installed, each carrying steam from one boiler outlet nozzle to one superheater inlet nozzle in four parallel circuits. Each interconnecting pipe is located outside the steam generator and may be seen on the plant arrangement drawing, Figure 1. Steam flows from the boiler outlet nozzle into the lower horizontal leg of the pipe, turns and flows upward in the vertical leg, then turns and flows in the upper horizontal leg into the superheater inlet nozzle. The piping is 8" double extra heavy pipe size with a concentric reducer at each end adapting to the 12" Sch. 160 pipe size boiler outlet and superheater inlet nozzles.

This interconnecting piping serves as a convenient location for the bi-metallic weld joining the Croloy 2-1/4 boiler material to the TP-316 stainless steel superheater material, having the bi-metallic joint outside the heat transfer zone, and exposed to room atmosphere. With this arrangement if a leak should occur in the dissimilar weld, it would leak to atmosphere rather than a leak to sodium.

This interconnecting pipe also serves as a convenient location for superheater by-pass control during start-up. Each interconnecting pipe has in its vertical leg a superheater isolation valve and two connections leading to the start-up system. The start-up system is described in section 8.0.

The steam pressure drop at 100% load through this interconnecting piping from the boiler outlet headers to the superheater inlet headers is approximately 31 psi.

An alternate piping design was considered wherein the four boiler outlet nozzles were connected to a circular header around the steam generator and the four superheater inlet nozzles were also connected to a circular header around the steam generator. The two circular headers were interconnected with vertical piping. This design was not practical for thermal stress reasons.

Another alternate piping design was also considered, wherein two boiler outlet nozzles were connected together with a horizontal pipe and two superheater inlet nozzles were also connected together with a horizontal pipe. These two horizontal pipes were then connected with one vertical leg. In this manner two parallel circuits joined the boiler outlet nozzles to the superheater inlet nozzles. This design concept appears feasible and may be adopted pending economic considerations.

5.10 Design of Tube Bundle:

The boiler and superheater sections are made up of helical coiled tubes. There tubes are formed into a circular bundle around a 30 inch diameter center pipe.

The boiler tubes are 1" O.D. Croloy 2-1/4" on 1-1/2" transverse spacing and 1-3/8" parallel spacing. The pitch angle on each tube is approximately six degrees. The tubes are arranged in 34 rows with the number of tubes per row set to give nearly equal tube lengths of 131 ft. With 676 tubes in the bundle the inner coil diameter is 32 inches and the outer coil diameter is 131 inches. The number of tubes per row varies from 8 on the inner row to 32 on the outer row.

The superheater tubes are 7/8" O.D., SA-213, TP-316 stainless steel, on 1-1/4" transverse spacing and 1-1/4" parallel spacing. The pitch angle on each tube is approximately 17 degrees. The tubes are arranged in 25 rows with the number of tubes set to give nearly equal tube lengths of 40 ft. The number of tubes per row varies from 24 on the inner row to 72 on the outer row. (total 1220 tubes)

The tube ends at the lower end of each bundle are connected to downcomers. In the lower boiler bundle these downcomers descend from the feedwater tubesheets located in the spool section of the shell. The downcomers are 5/8" O.D. x .076" MW and are fitted to the coiled section by means of a swaged tube section. The smaller downcomer tubes provide an added pressure drop at the boiler entrance to improve boiler flow stability. The superheater downcomers are the same size as the superheater bundle tubes.

5.11 Description of Mechanical Parts of Steam Generator

1. Boiler Tube Supports

A system of Boiler Beam Supports attached to the boiler shroud serves as the main support for attachment of the helical coil tube bundle supports (See drawings 20950F, 20954F, and 20952F). Eight coil supports are equally spaced around the coil. Each coil support (SK-1012-4) consists of a hanger bar attached to the beam supports through two adjustable hanger rods, and individual coil support bars suspended from the eight hanger bars. Each individual coil support bar is scalloped to hold a vertical row of tubes. The tubes are held into the individual coil support bars by two scalloped side bars which also serve to hold the individual coil support bars in radial rows. This coil support arrangement allows individual expansion of each vertical row of tubes in the coiled bundle.

The boiler riser and downcomer tubes pass through plate type and also strap type vibration supports.

2. Superheater Tube Supports

The superheater tube supports are similar to the boiler tube supports. See drawings 20950F, 20954F, 20953F, and SK-1015-4.

3. By-Pass Valve Control Rod Seal

The by-pass valve is actuated by a control rod through the top cover plate. Two seals are provided between this actuating rod and the cover plate (See drawing SK-1030-2). The upper seal is of the conventional packing gland type. The lower seal is a bellows-type with its upper end attached to the cover plate and its lower end attached to the control rod.

4. Sodium Inlet Nozzle

The sodium inlet nozzle (drawing SK-511-4) contains a thermal sleeve to protect the nozzle-to-vessel joint from the thermal transients associated with sodium systems.

5. Steam Generator Cross Section Dimensions

The pertinent radial dimensions throughout the steam generator are shown on drawing SK-1026-2.

TABLE 1

HEAT TRANSFER AND PRESSURE DROP RESULTS

BOILER BUNDLE

Parameters for One Unit	Three Units Required for 1000 MWe
Operating Conditions (Full Load)	
Heat Load	1734×10^6 Btu/hr
Sodium Flow	15.59×10^6 lb/hr
Sodium Inlet Temperature	1013 F
Sodium Outlet Temperature	644 F
Sodium Pressure Drop	1.8 psi
Steam Flow	2.403×10^6 lb/hr
Feedwater Temperature	530 F
Outlet Temperature	750 F
Outlet Pressure	2565 psia
Material	
Tubes	Croloy 2-1/4 T-22
Shells, Heads	Croloy 2-1/4
Tube Sheets, Nozzles	Croloy 2-1/4

Heat Transfer Results

	Number	Size	Effective Length
Tubes - Econ. & Nucleate Boiling Sec.	676	1" O.D. x .120" MW	60.0 ft.
Film Boiling Section	676	1" O.D. x .145" MW	53.0 ft.
Superheat Section	676	1" O.D. x .165" MW	18.4 ft.
			131.4 ft.

Over-all Heat Transfer Coefficient	
Economizer	589 B/hr ft^2 F
Boiler — Nucleate Boiling	709 B/hr ft^2 F
Boiler — Film Boiling	464 B/hr ft^2 F
Superheater	473 B/hr ft^2 F
Fouling Factor	3333 B/hr ft^2 F
Corrosion Allowance	0.009 inches

TABLE 1

(CONTINUED)

<u>Heat Transfer Surface</u>

Total		23,255 ft^2
Economizer		9,380 ft^2
Boiler	Nucleate Boiling	1,240 ft^2
	Film Boiling	9,380 ft^2
Superheater		3,255 ft^2

<u>Boiler Inlet Tubes</u>

Size	5/8" O.D. x 0.076" MW
Length	53 ft.

<u>Boiler Outlet Legs</u>

Size	1" O.D. x 0.165" MW
Length	32 ft.

<u>Pressure Drop</u> (Steam Side)

Boiler Inlet Legs		25.20 psi
Economizer		6.52 psi
Boiler	Nuclear Boiling Section	1.00 psi
	Film Boiling Section	26.30 psi
Superheater		19.54 psi
Outlet Legs		47.54 psi
Total		126.10 psi

Transverse Tube Spacing S_T	1.50"
Parallel Tube Spacing S_{11}	1.375"

TABLE 2

HEAT TRANSFER AND PRESSURE DROP RESULTS

SUPERHEATER BUNDLE

Parameters for One Unit	Three Units Required for 1000 MWe
Operating Conditions (Full Load)	
Heat Load	596×10^6 Btu/hr
Sodium Flow	15.59×10^6 lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	1013 F
Sodium Pressure Drop	6.7 psi
Steam Flow	2.403×10^6 lb/hr
Steam Inlet Temperature	750 F
Steam Outlet Temperature	1050 F
Outlet Pressure	2465 psia
Material	
Tube	SA-213 TP-316 S.S.
Shell	Croloy 2-1/4
Tube Sheets, Heads	TP-316 S.S.
Heat Transfer Results	
Tubes - Number	1220
Size	7/8" O.D. x .120" MW
Effective Length	40.6 ft.
Over-all H.T. Coefficient	361.5 B/hr/ft^2 F
LMTD	161.3 F
Surface	11,330 ft^2
Superheater Inlet Tubes	
Size	7/8" O.D. x .120" MW
Material	TP-316 S.S.
Length	28 ft.

TABLE 2

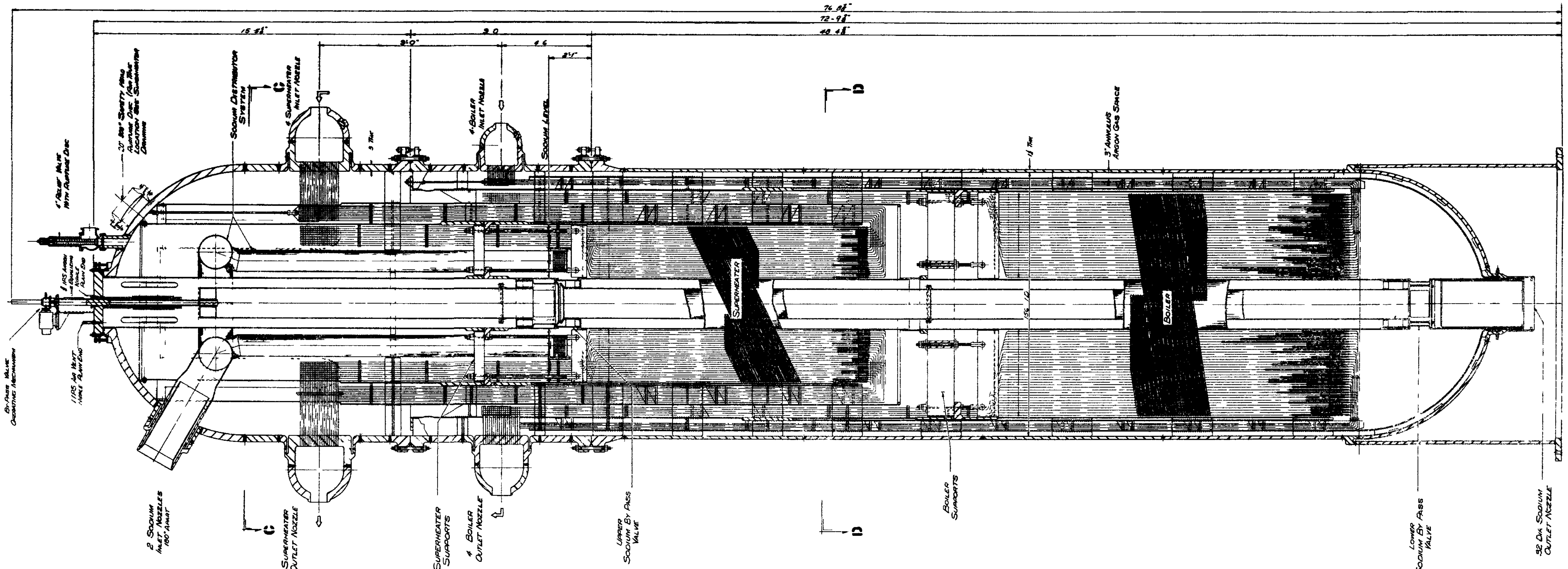
(CONTINUED)

Outlet Tubes

Size	7/8" O.D. x .120" MW
Material	TP-316 S.S.
Length	20 ft.

Pressure Drop (Steam Side)

Downcomer Tubes	15.64 psi
Tube Bundle	28.30 psi
Outlet Tubes	21.26 psi
Total	65.20 psi
Transverse Tube Spacing S_T	1.25"
Parallel Tube Spacing S_{11}	1.25"



General Notes

1. Vessel Designed In Accordance With The 1962 Edition Of ASME Pressure Vessel Code Section VIII And Code Case 1273N-7
2. Operating Conditions —
   - A. Steam Flow ---------- 2403 x 10³ Lb/Hr
   - B. Steam Pressure At Superheater Outlet 2450 PSIG
   - C. Steam Temperature At Superheater Outlet 1050° F
   - D. Sodium Flow ---------- 15.59 x 10⁶ Lb/Hr
   - E. Sodium Inlet Temperature - 1140° F
   - F. Sodium Outlet Temperature - 648° F
3. Superheater —
   - A. Number Of Tubes --- 1220
   - B. Outside Diameter ----- ⅝"
   - C. Effective Length ------- 40.6
   - D. Material ---------- SA-213 TP 316 SST
4. Boiler —
   - A. Number Of Tubes ------ 676
   - B. Outside Diameter ----- ⅝ 41
   - C. Effective Length ------ 131
   - D. Material ---- Croloy 2¼ SA-213 T-22
5. Shell —
   - A. Design Pressure --- 200 PSIG
   - B. Material ---------- Croloy 2¼ SA-387 Gr D

References		
No	Title	Dwg No
1	Cross Section Of Full Size Stm Gen	[illegible]
2	Shell Section Of Full Size Stm Gen	[illegible]
3	Boiler Section Of Full Size Stm Gen	[illegible]
4	Superheater Section Of Full Size Stm Gen	[illegible]

AEC Contract AT (11 1) 1280
B&W Contract 610 0067-55
Sodium Heated Steam
Generator Development

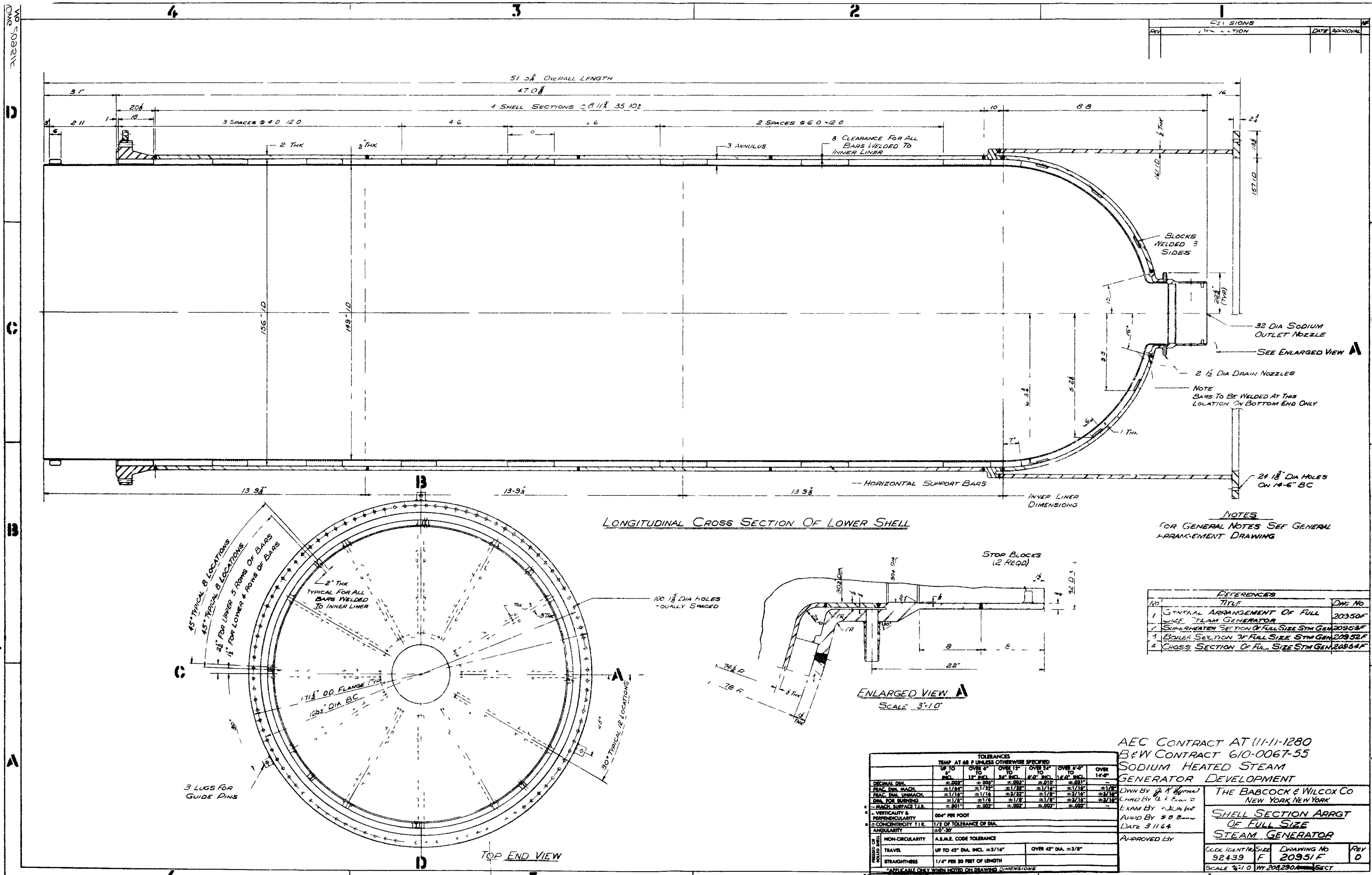
Dwn By [signature]
Chkd By [signature]
Exam By [signature]
Appd By [signature]
Date 3 12-65
Approved By

The Babcock & Wilcox Co
New York, New York

General Arrangement Of Full Size Steam Generator

Code Ident No	Size	Drawing No	Rev
92439	F	20930F	Q

The Babcock & Wilcox Co — 20930F — Rev 0



Notes

For General Notes See General Arrangement Drawing

References		
No	Title	Dwg No
1	General Arrangement Of Full Size Steam Generator	20950F
2	Superheater Section Of Full Size Stm Gen	20953F
3	Boiler Section Of Full Size Stm Gen	20952F
4	Cross Section Of Full Size Stm Gen	20954F

TOLERANCES
TEMP AT 68 F UNLESS OTHERWISE SPECIFIED

	Up to 6" Incl.	Over 6" to 12" Incl.	Over 12" to 24" Incl.	Over 24" to 6'-0" Incl.	Over 6'-0" to 14'-0" Incl.	Over 14'-0"
Decimal Dim.	±.003"	±.005"	±.005"	±.010"	±.031"	–
Frac. Dim. Mach.	±1/64"	±1/32"	±1/32"	±1/16"	±1/16"	±1/8"
Frac. Dim. Unmach.	±1/16"	±1/16	±3/32"	±1/8"	±3/16"	±3/16"
Dim. for Burning	±1/8"	±1/8	±1/8"	±1/8"	±3/16"	±3/16"
* ~ Mach. Surface T.I.R.	±.001"	±.002"	±.002"	±.003"	±.003"	–
* ⊥ Verticality & Perpendicularity	.004" per foot					
* ⊙ Concentricity T.I.R.	1/2 of tolerance of dia.					
Angularity	±0°-30'					
Pressed or Rolled Shell: Non-Circularity	A.S.M.E. Code Tolerance					
Pressed or Rolled Shell: Travel	Up to 42" dia. incl. ±3/16"			Over 42" dia. ±3/8"		
Pressed or Rolled Shell: Straightness	1/4" per 20 feet of length					

*Applicable only when noted on drawing dimensions

AEC Contract AT (11-1)-1280
B&W Contract 610-0067-55
Sodium Heated Steam Generator Development

Dwn By J K [signature]
Chkd By A K [signature]
Exam By [signature]
Appd By [signature]
Date 3 11 64
Approved By

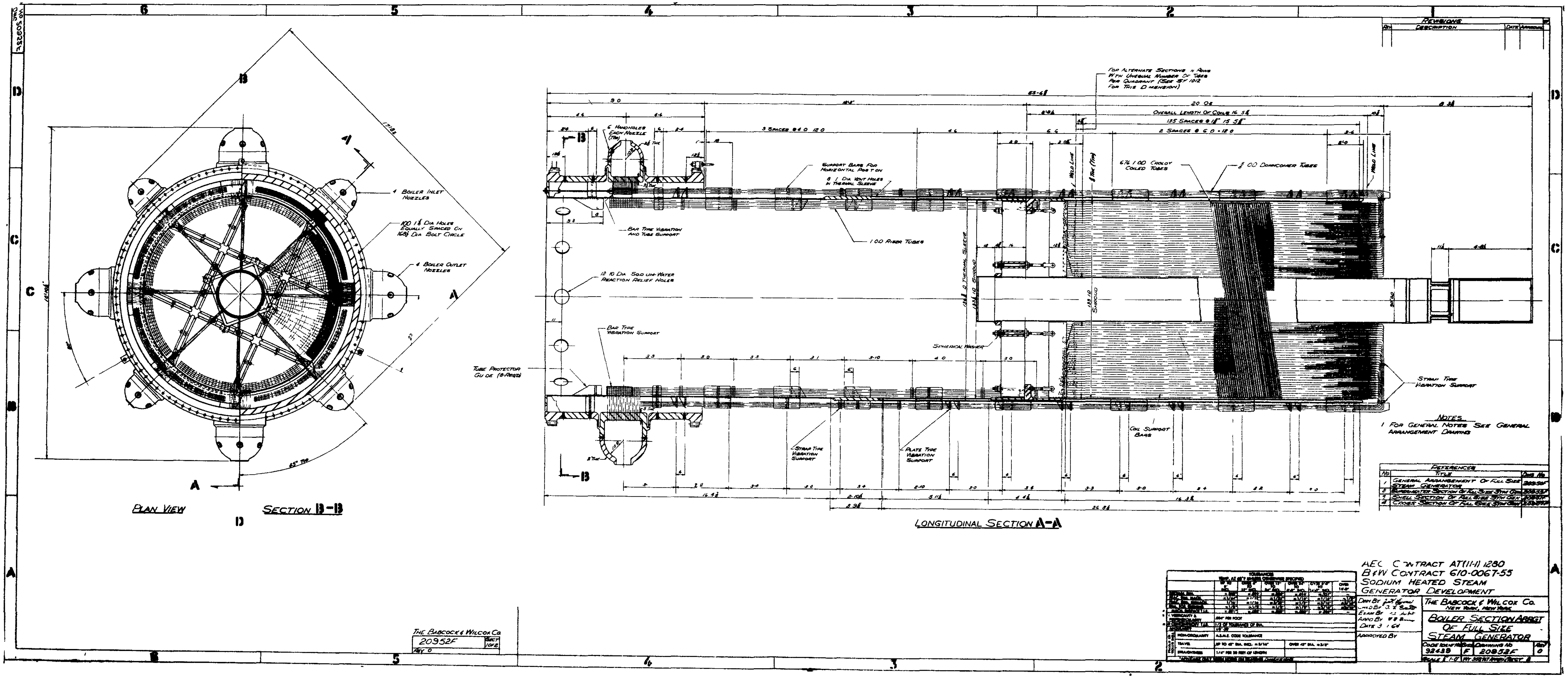
The Babcock & Wilcox Co
New York New York

Shell Section Arrgt Of Full Size Steam Generator

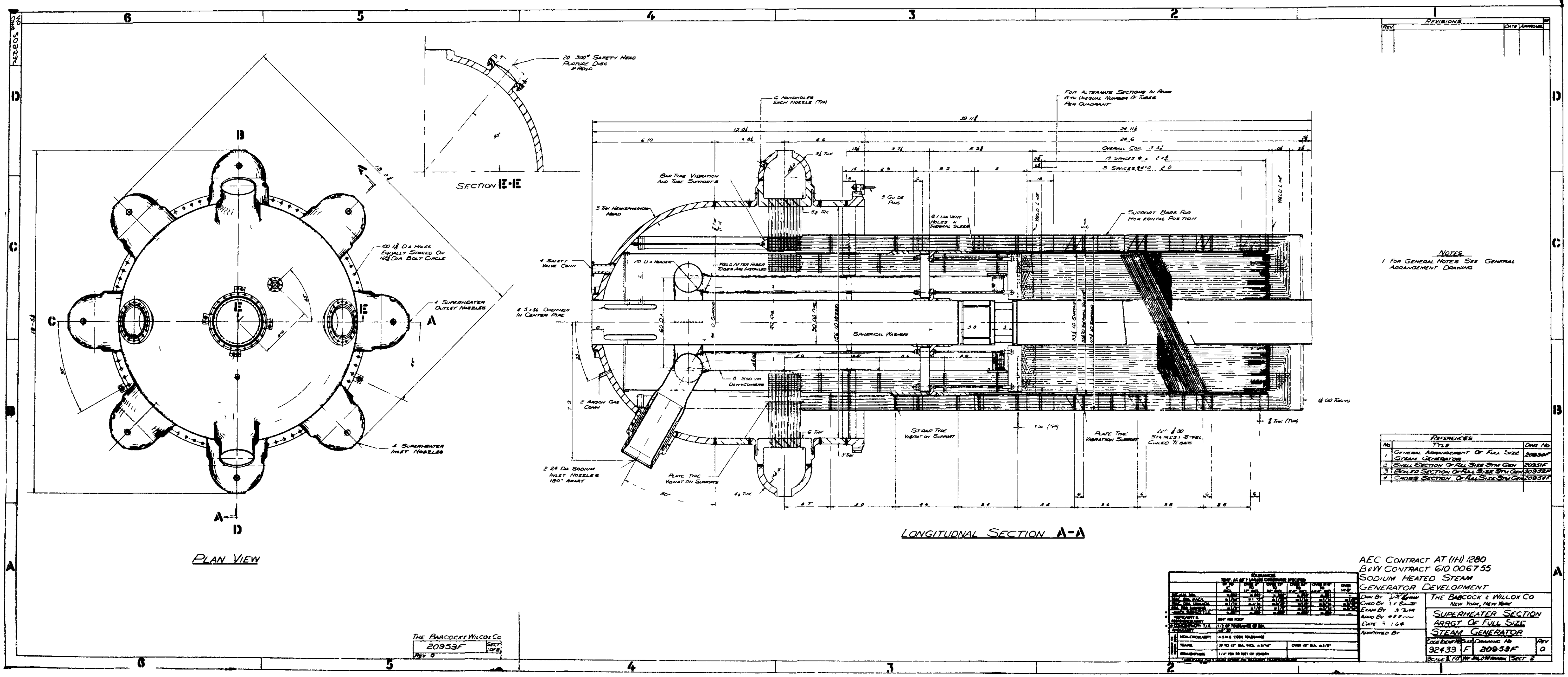
Code Ident No	Size	Drawing No	Rev
92439	F	20951F	0

Scale 1/4"=1 0 | Wt 208,290 | Sect

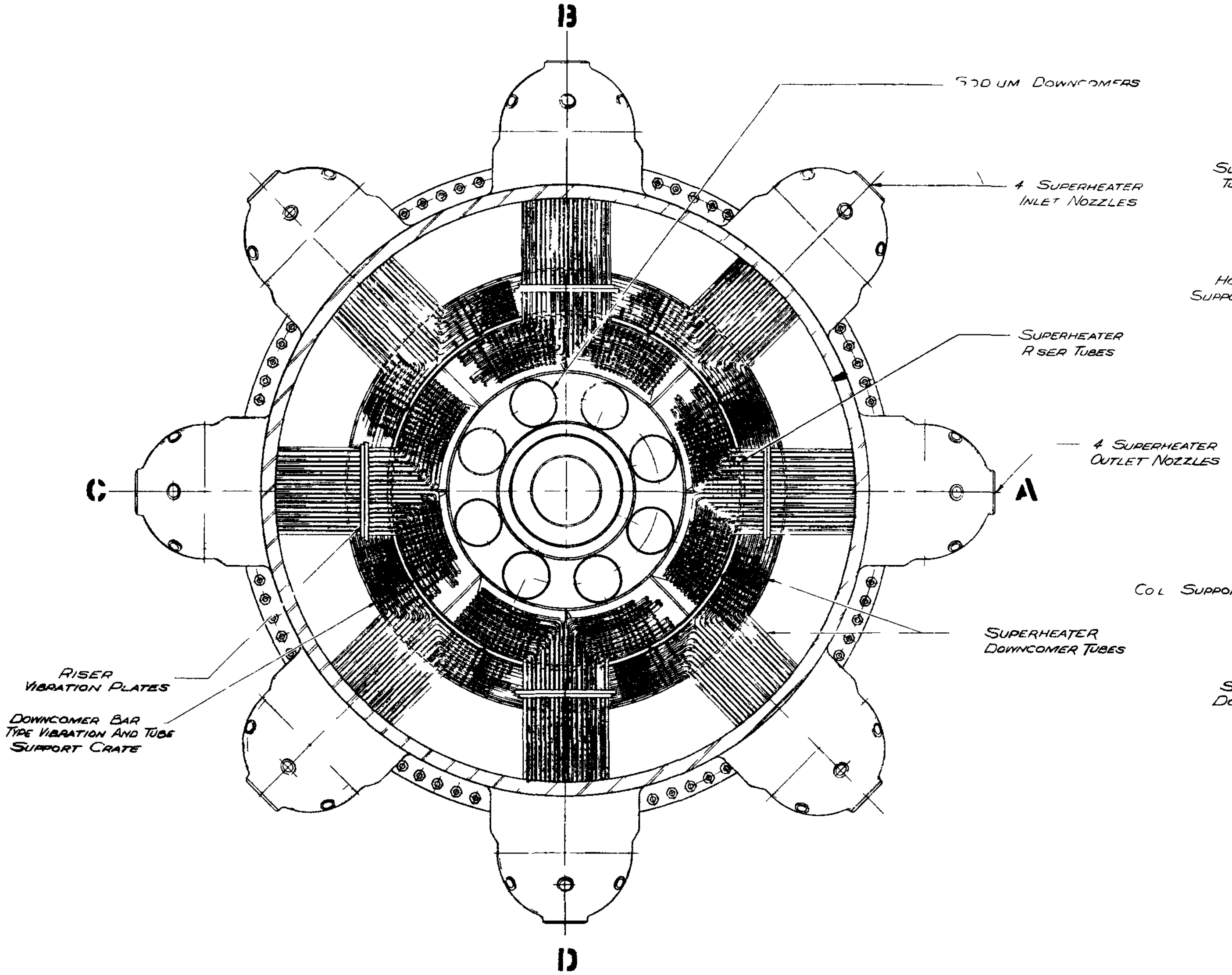
Dwg 20951F



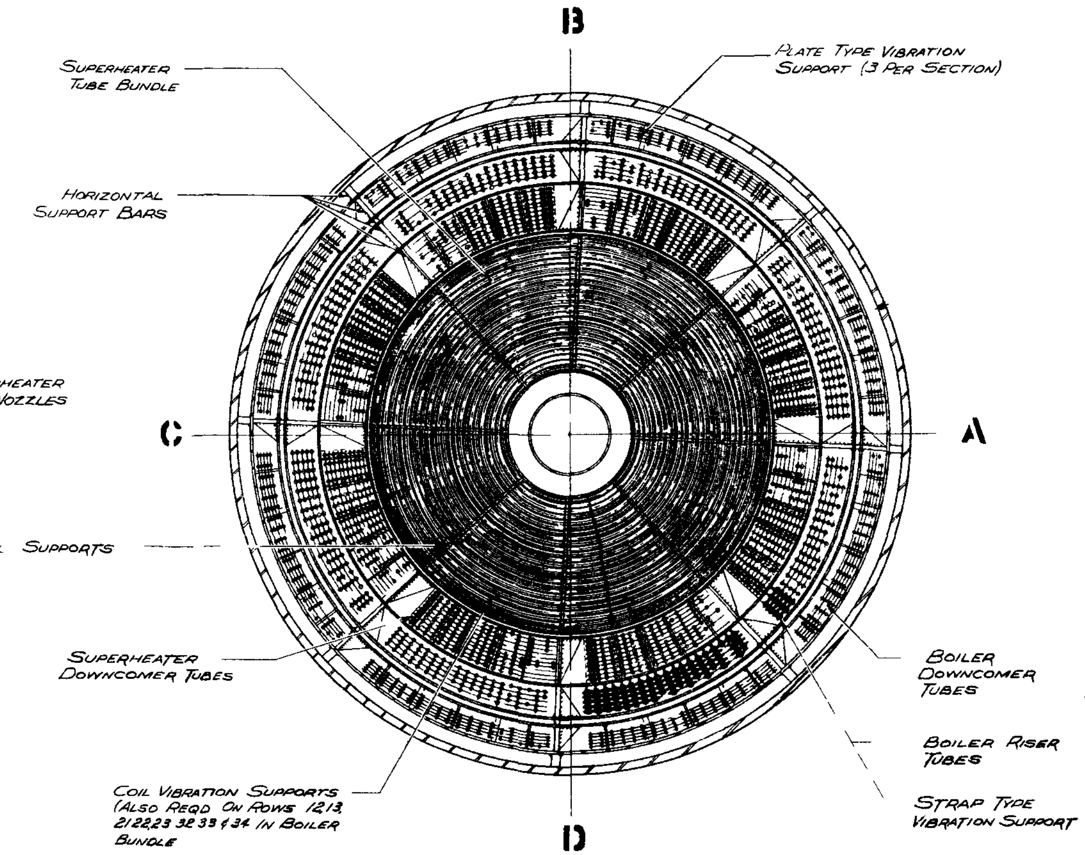
Plan View
Section B-B
Longitudinal Section A-A
4 Boiler Inlet Nozzles
100 1⅛ Dia Holes Equally Spaced On 60⅞ Dia Bolt Circle
4 Boiler Outlet Nozzles
6 Handholes Each Nozzle (Typ)
Bar Type Vibration And Tube Support
12 10 Dia Sodium-Water Reaction Relief Holes
Bar Type Vibration Support
Tube Protector Guide (8-Reqd)
Support Bars For Horizontal Position
1.00 Riser Tubes
Spherical Washer
Strap Type Vibration Support
Plate Type Vibration Support
Coil Support Bars
⅝ OD Downcomer Tubes
Overall Length Of Coils
Weld Line
Notes
1 For General Notes See General Arrangement Drawing
References
No | Title | Dwg No
1 | General Arrangement Of Full Size Steam Generator |
2 | Superheater Section Of Full Size Stm Gen |
3 | Shell Section Of Full Size Stm Gen |
4 | Cross Section Of Full Size Stm Gen |
AEC Contract AT(11-1) 1280
B&W Contract 610-0067-55
Sodium Heated Steam Generator Development
Tolerances
Non-Circularity
A.S.M.E. Code Tolerance
Straightness
1/4" Per 20 Feet Of Length
Drwn By
Chkd By
Exam By
Appd By
Date 3 1 64
Approved By
The Babcock & Wilcox Co.
New York, New York
Boiler Section Arrgt Of Full Size Steam Generator
Code Ident No 92439
Size F
Drawing No 20952F
Rev 0
The Babcock & Wilcox Co.
20952F
Rev 0



Section E-E
20 300° Safety Head Rupture Disc 2 Reqd
Plan View
Longitudnal Section A-A
Spherical Washers
Support Bars For Horizontal Position
Strap Type Vibration Support
Plate Type Vibration Supports
Plate Type Vibration Supports
2 24 Dia Sodium Inlet Nozzles 180° Apart
2 Argon Gas Conn
4 Safety Valve Conn
4 Superheater Outlet Nozzles
4 Superheater Inlet Nozzles
Bar Type Vibration And Tube Supports
6 Handholes Each Nozzle (Typ)
For Alternate Sections In Rows With Unequal Number Of Tubes Per Quadrant
Overall Coil
Notes
1 For General Notes See General Arrangement Drawing
References
No | Title | Dwg No
1 General Arrangement Of Full Size Steam Generator | 20850F
2 Shell Section Of Full Size Stm Gen | 20951F
3 Boiler Section Of Full Size Stm Gen | 20952F
4 Cross Section Of Full Size Stm Gen | 20954F
Revisions
Rev | Date | Approval
AEC Contract AT (11-1) 1280
B&W Contract 610 0067 55
Sodium Heated Steam
Generator Development
The Babcock & Wilcox Co
New York, New York
Superheater Section
Arrgt Of Full Size
Steam Generator
Drwn By
Chkd By
Exam By
Appd By
Date
Approved By
Code Ident No | Size | Drawing No | Rev
92439 | F | 20953F | 0
Sect 2
The Babcock & Wilcox Co
20953F
Rev 0



SECTION C-C



SECTION D-D

NOTES

1 FOR GENERAL NOTES SEE GENERAL ARRANGEMENT DRAWING

REFERENCES

NO	TITLE	DWG NO
1	GENERAL ARRANGEMENT OF FULL SIZE STEAM GENERATOR	20950F
2	SHELL SECTION OF FULL SIZE STM GEN	20951F
3	BOILER SECTION OF FULL SIZE STM GEN	20952F
4	SUPERHEATER SECTION OF FULL SIZE STM GEN	20953F

TOLERANCES
TEMP AT 68 F UNLESS OTHERWISE SPECIFIED

	UP TO 6" INCL	OVER 6" TO 12" INCL	OVER 12" TO 24" INCL	OVER 24" TO 6'-0" INCL	OVER 6'-0" TO 14'-0" INCL	OVER 14'-0"
DECIMAL DIM.	±.003"	±.005	±.005	±.010	±.031"	–
FRAC. DIM. MACH.	±1/64"	±1/32"	±1/32"	±1/16	±1/16	±1/8"
FRAC. DIM. UNMACH.	±1/16	±1/16	±3/32'	±1/8"	±3/16'	±3/16"
DIM. FOR BURNING	±1/8	±1/8'	±1/8"	±1/8	±3/16	±3/16"
* ~ MACH. SURFACE T.I.R.	±.001	±.002	±.002	±.003'	±.003"	–
* ⊥ VERTICALITY & PERPENDICULARITY	004" PER FOOT					
* ⊙ CONCENTRICITY T I R	1/2 OF TOLERANCE OF DIA.					
ANGULARITY	±0 30'					
PRESSED OR ROLLED SHELL: NON-CIRCULARITY	A.S.M.E. CODE TOLERANCE					
PRESSED OR ROLLED SHELL: TRAVEL	UP TO 42" DIA. INCL. ±3/16"			OVER 42" DIA ±3/8"		
PRESSED OR ROLLED SHELL: STRAIGHTNESS	1/4" PER 20 FEET OF LENGTH					

*APPLICABLE ONLY WHEN NOTED ON DRAWING DIMENSIONS

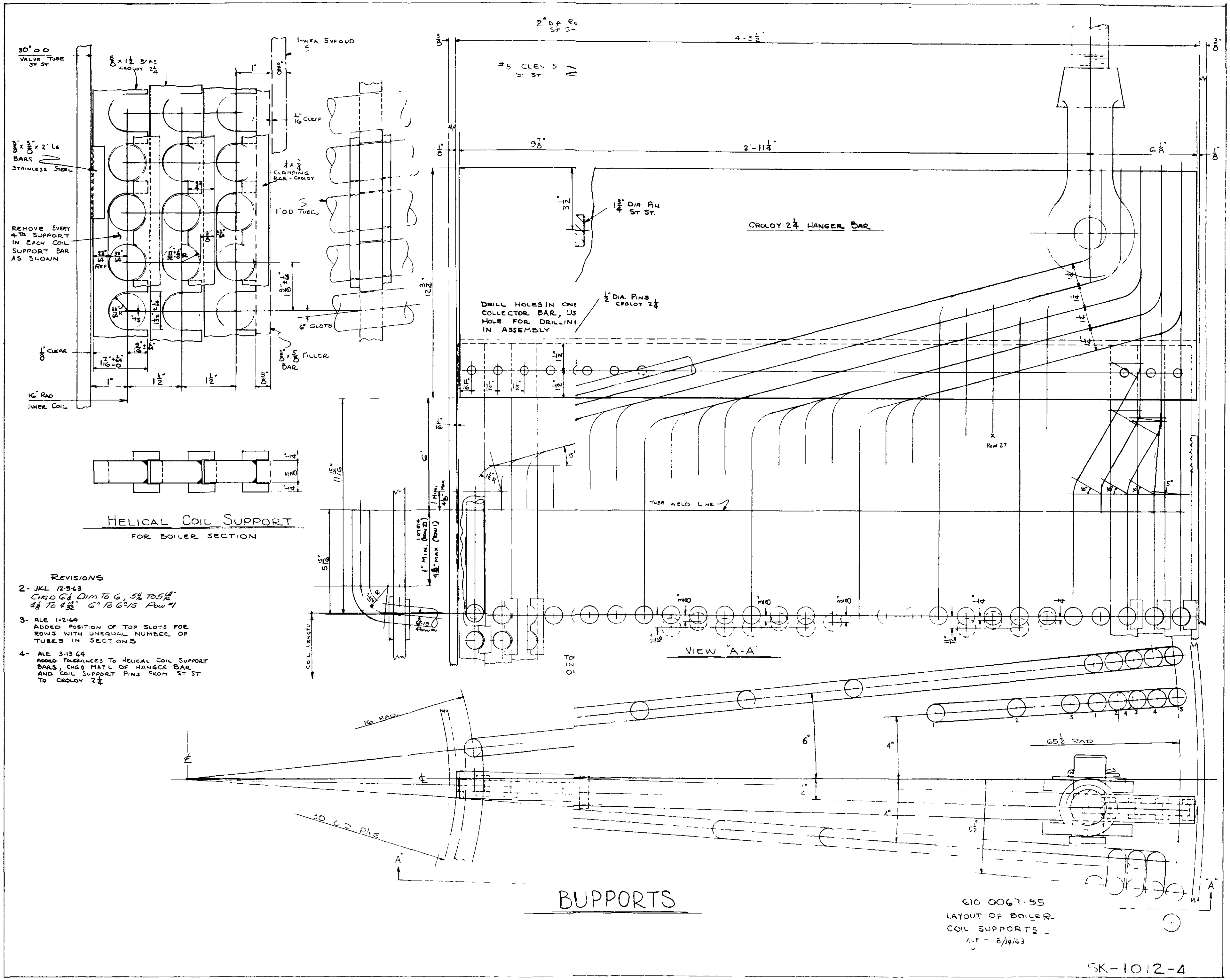
AEC CONTRACT AT (11-1) 1280
B&W CONTRACT 610 0067-55
SODIUM HEATED STEAM
GENERATOR DEVELOPMENT

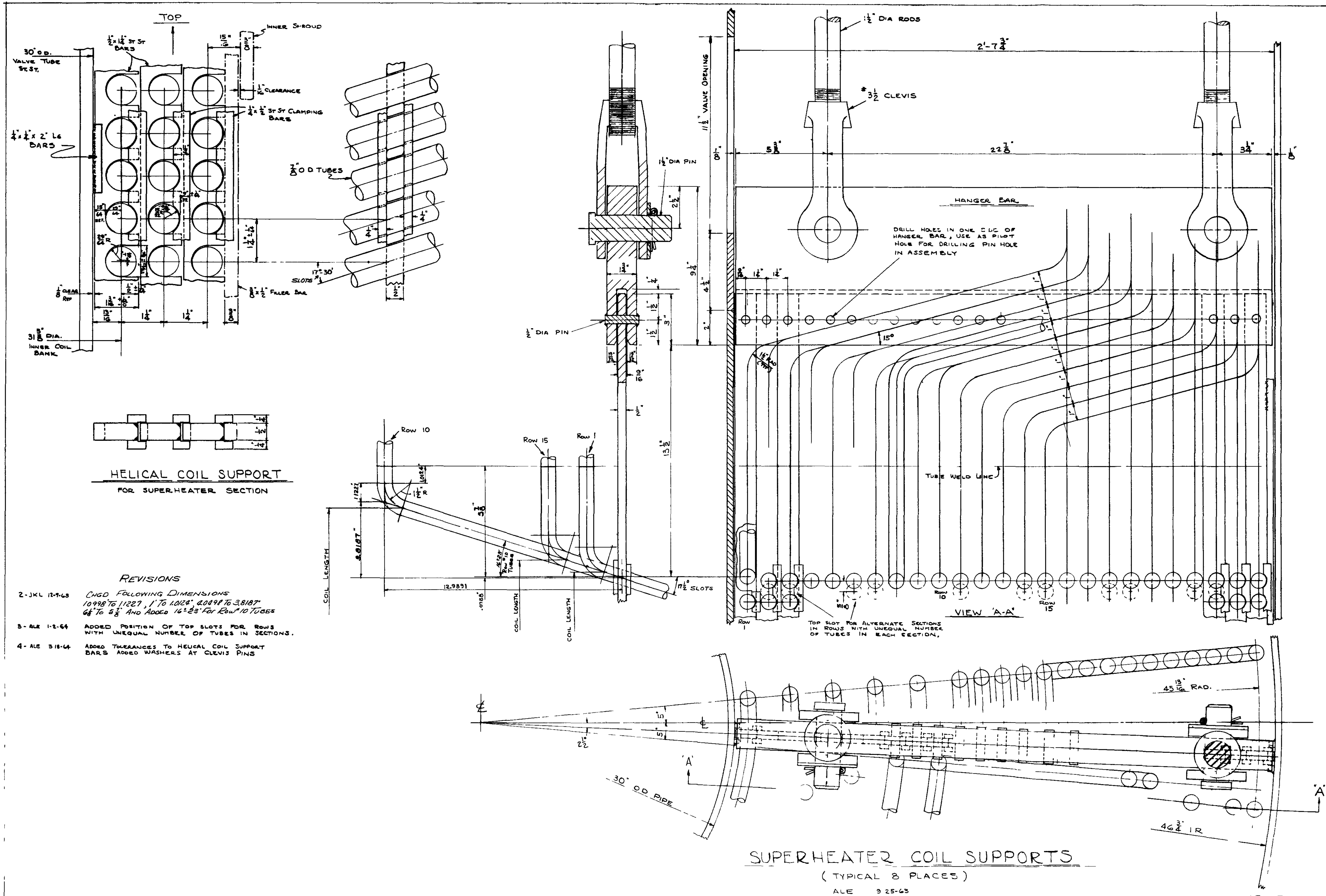
DWN BY J. K. Lyons
CHKD BY A. L. Evans
EXAM BY [illegible]
APPD BY [illegible]
DATE 3 11 64
APPROVED

THE BABCOCK & WILCOX CO
NEW YORK, NEW YORK

CROSS SECTIONS
OF FULL SIZE
STEAM GENERATOR

CODE IDENT NO	SIZE	DRAWING NO	REV
92439	F	20954F	0
SCALE 3/4"=1-0	WT		SECT


30" OD VALVE TUBE ST ST
5/8 x 1 1/2 BARS CROLOY 2 1/4
INNER SHROUD
1/16" CLEAR
3/8" x 3/8" x 2" LG BARS STAINLESS STEEL
1/2 x 3/4 CLAMPING BAR - CROLOY
1" OD TUBE
REMOVE EVERY 4TH SUPPORT IN EACH COIL SUPPORT BAR AS SHOWN
6" SLOTS
1/8" CLEAR
3/8" x 5/8 FILLER BAR
16" RAD INNER COIL
HELICAL COIL SUPPORT
FOR BOILER SECTION
REVISIONS
2- JKL 12-9-63 CHGD 6 1/4 DIM TO 6, 5 1/16 TO 5 15/16, 4 5/8 TO 4 13/32, 6° TO 6°15 ROW #1
3- ALE 1-2-64 ADDED POSITION OF TOP SLOTS FOR ROWS WITH UNEQUAL NUMBER OF TUBES IN SECTIONS
4- ALE 3-13-64 ADDED TOLERANCES TO HELICAL COIL SUPPORT BARS, CHGD MATL OF HANGER BAR AND COIL SUPPORT PINS FROM ST ST TO CROLOY 2 1/4
2" DP RG ST ST
#5 CLEVIS ST ST
4-3 1/2"
2'-11 1/4"
1 3/4" DIA PIN ST ST
CROLOY 2 1/4 HANGER BAR
1/2" DIA. PINS CROLOY 2 1/4
DRILL HOLES IN ONE COLLECTOR BAR, USE HOLE FOR DRILLING IN ASSEMBLY
ROW 27
TUBE WELD LINE
COIL LENGTH
VIEW "A-A"
16" RAD
30" OD PIPE
65 1/2 RAD
A
BUPPORTS
610 0067-55
LAYOUT OF BOILER COIL SUPPORTS
ALF - 8/14/63
SK-1012-4



REVISIONS

2-JKL 12-9-63 CHGD FOLLOWING DIMENSIONS 1.0998 TO 1.1227, 1" TO 1.0124", 4.0498 TO 3.8187" 6 1/8" TO 5 7/8" AND ADDED 16°-23' FOR ROW #10 TUBES

3-ALE 1-2-64 ADDED POSITION OF TOP SLOTS FOR ROWS WITH UNEQUAL NUMBER OF TUBES IN SECTIONS.

4-ALE 3-18-64 ADDED TOLERANCES TO HELICAL COIL SUPPORT BARS ADDED WASHERS AT CLEVIS PINS

SUPERHEATER COIL SUPPORTS

(TYPICAL 8 PLACES)

ALE 9-25-63
CHKD - JKL 3-18-64

MATERIAL - STAINLESS STEEL

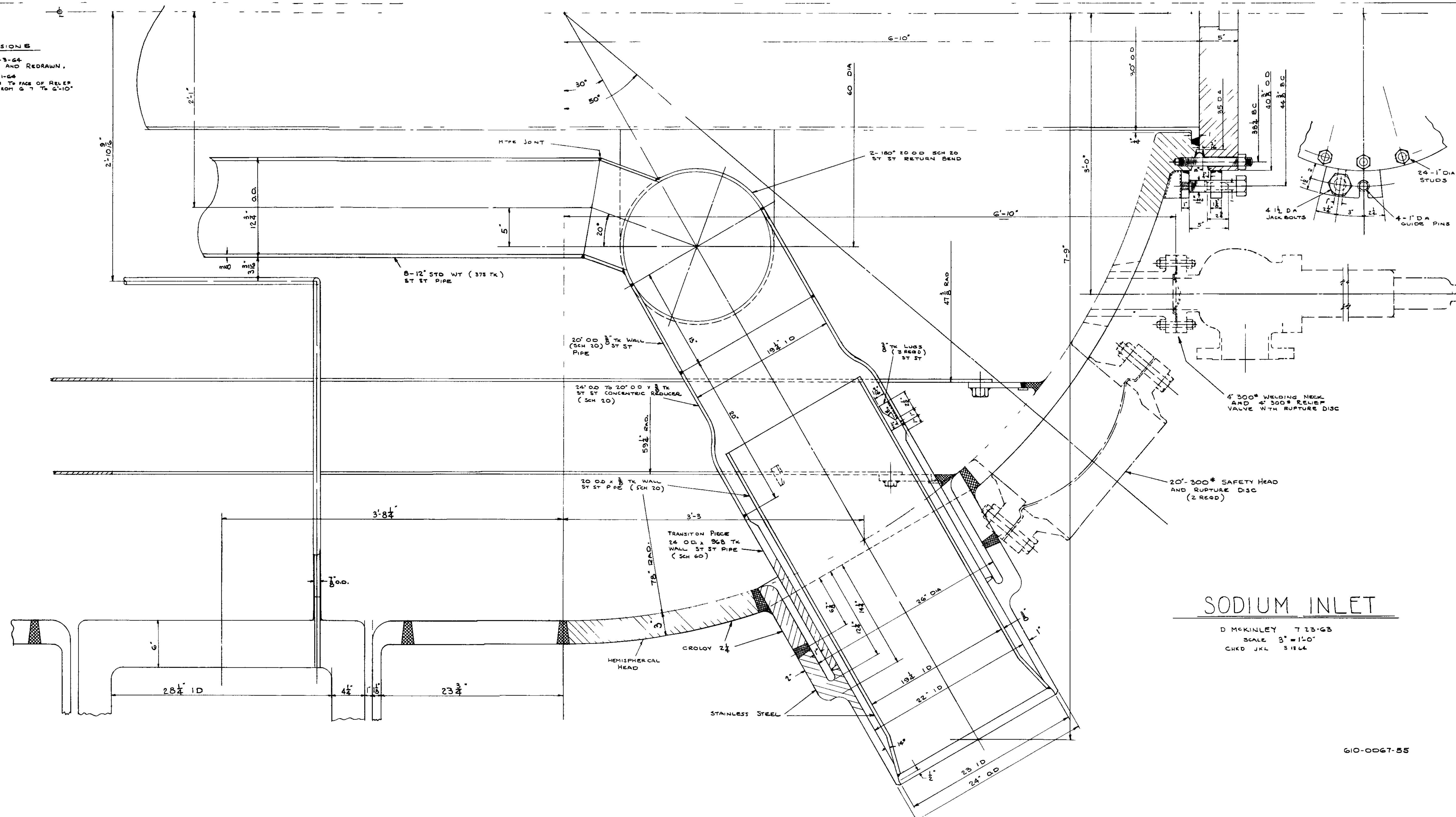
G10-0067-55

SK-1015-4

REVISIONS

3 ALE 2-3-64
REVISED AND REDRAWN.

4 ALE 3-11-64
CHGD DIM TO FACE OF RELIEF VALVE FROM 6' 7" TO 6'-10"



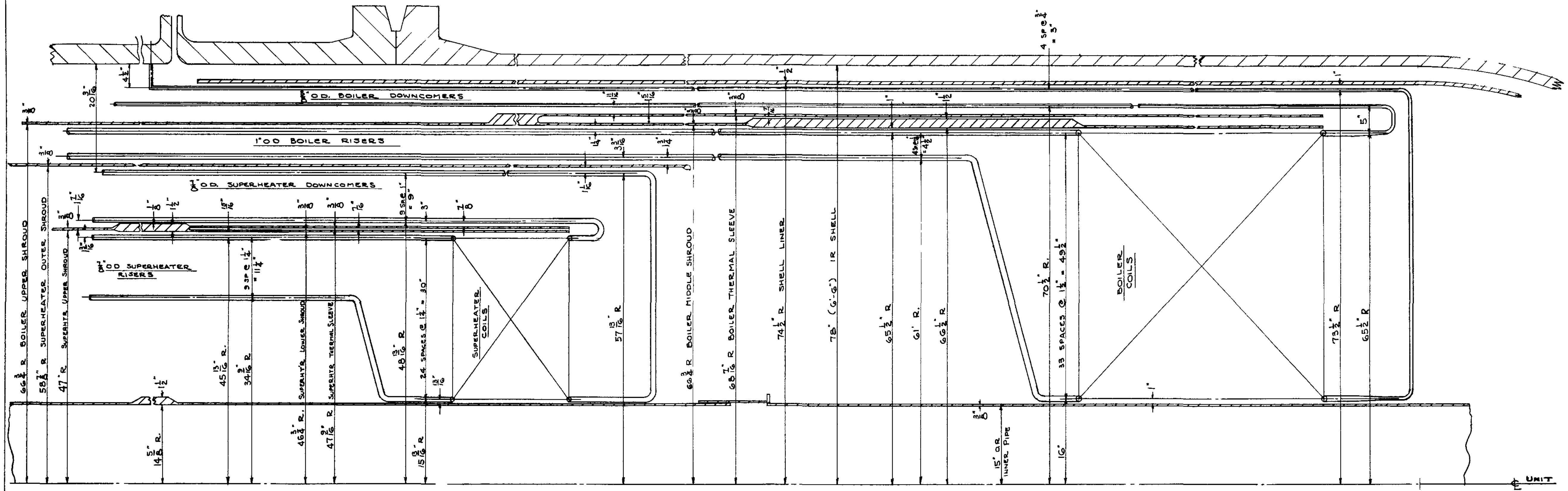
SODIUM INLET

D McKINLEY 7 23-63
SCALE 3" = 1'-0"
CHKD JKL 3 18 64

610-0067-55

SK-511-4

REVISIONS
1 CHGD ⅞ SPACE BETWEEN SUPERHEATER OUTER MOST RISER AND SHROUD TO 15/16"
2. CHGD 1⅛" SPACE BETWEEN SUPERHEATER OUTER MOST RISER AND UPPER SHROUD TO 1 3/16"



STEAM GENERATOR CROSS-SECTION DIMENSIONAL DRAWING

A L EVANS 10-31-63
CHKD JKL 3 17 64

610-C067-55

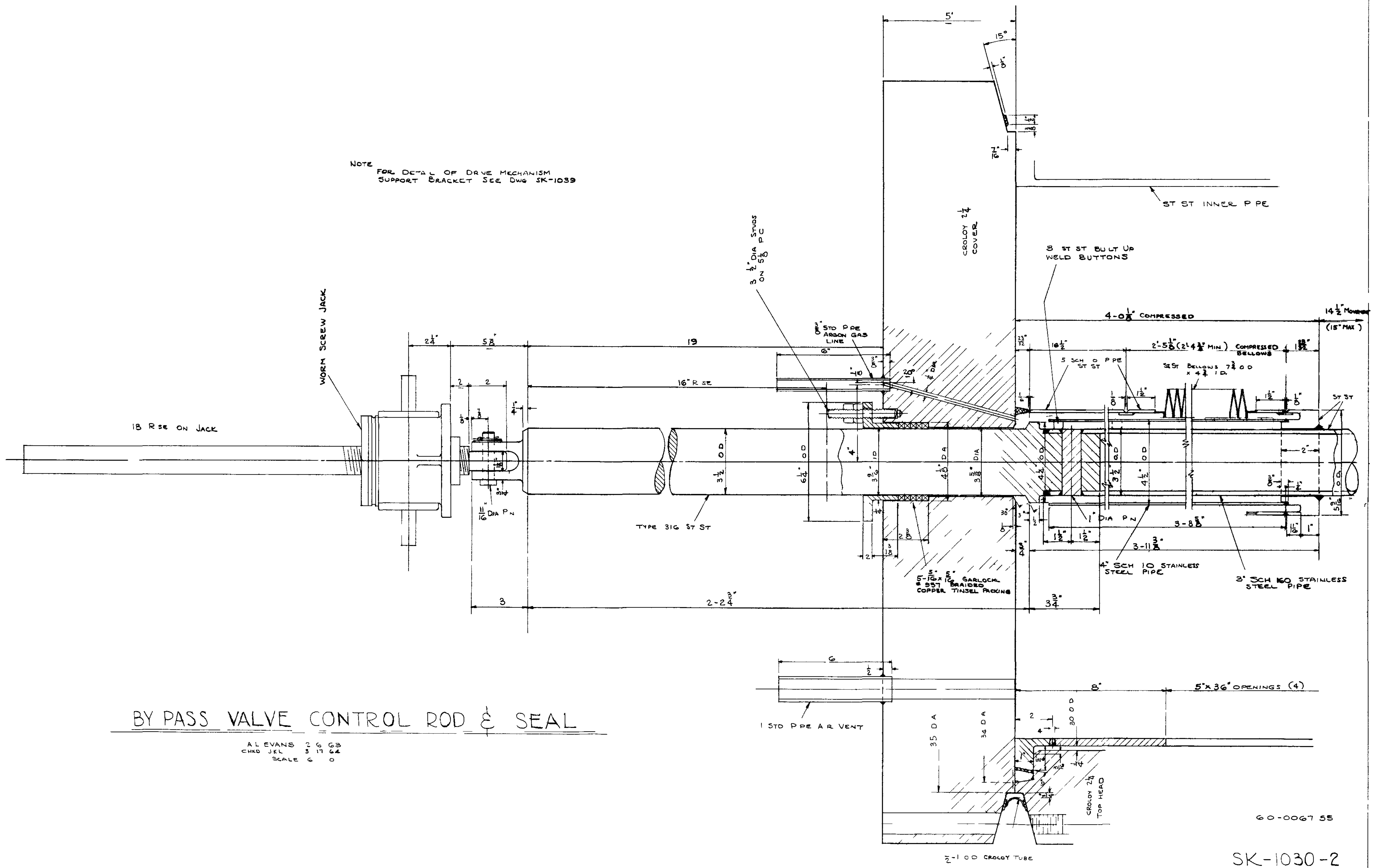
SK-1026-2

REVISIONS

1 ALE -6 64
ADDED SLEEVE INSIDE OF BELLOWS, CHGD THICKNESS OF COVER FROM 7" TO 8

2 AE 3 6 64
ADDED AR VENT PIPE CHGD MAT'L OF FLANGE SEAL FROM ST ST TO CROLOY CHGD 3½ PIPE FROM SCH 80 TO SCH

NOTE
FOR DETAIL OF DRIVE MECHANISM SUPPORT BRACKET SEE DWG SK-1039



BY PASS VALVE CONTROL ROD & SEAL

A L EVANS 2 6 63
CHKD JKL 3 17 64
SCALE 6 0

60-0067 55

SK-1030-2

6.0 GENERAL DESCRIPTION OF REHEATER:

Three (3) sodium heated reheaters are required in the 1000 MWe system. One reheater is shown on drawing no. 20955 F. Sectional views are shown on drawing no. 20956 F.

6.1 Pressure Shell:

The reheater shell stands vertically on a support skirt and consists of two major sections, namely the upper section and the lower section. Steam entrance and exit headers, and also the sodium entrance pipe, are located in the upper section. The tube bundle is attached to the upper section. Sodium exits from the lower section. The support skirt is attached to the lower section. The two major sections are joined by a bolted-flanged connection.

6.2 Sodium Flow Path:

Referring to drawning no. 20955 F, sodium enters near the top of the vessel through two sodium inlet nozzles, flows downward through a sodium distribution system and is dispersed uniformly across the top of the tube bundle to prevent local high velocity streams from causing tube vibration problems. Sodium then flows downward across the helical coil tube bundle, leaving the vessel at the bottom through the sodium outlet nozzle. Sodium flow is directed over the helical coil tube bundle with the use of an inner and outer shroud, each extending above the sodium level.

The space above the sodium level is filled with argon gas, Argon gas is also used in an annular space between the sodium and the vessel shell to protect the vessel from rapid sodium temperature changes.

6.3 Steam Flow Path:

Steam enters the torroidal rectangular box inlet header through ten 6" steam inlet nozzles and flows downward to the bottom of the helical coil tube bundle in vertical inlet tubes arranged in the annular space between the helical coil tube bundle and the shell liner. The steam turns and flows upward in the helical coil tube bundle where it is heated and passes upward in the vertical outlet tubes to the torroidal rectangular box outlet header and exits through ten 8" steam outlet nozzles. The torroidal rectangular box headers serve as annular tube sheets and are located above the sodium level to protect them from rapid sodium temperature changes. Removable handhole covers around the top of each torroidal box header provide ready access to the ends for inspection and repair.

6.4 Helical Coil Tube Bundle:

The helical coil tube bundle has a "stepped" tube wall thickness to take advantage of thinner tube wall at lower design temperatures, thereby increasing the overall heat transfer rate and reducing the tube bundle size. The three tube wall thicknesses are designated as Section A, Section B, and Section C progressively, starting at the steam inlet (or lower) end of the helical coil tube bundle. The vertical inlet tubes, Section A, and Section B, are of Croloy 2 1/4.

Section C is Croloy 5, since the tube will operate under conditions which can cause steam side corrosion, commonly called exfoliation, of Croloy 2 1/4. Some trouble has been experienced in Croloy 2 1/4 reheaters of fossil fuel fired steam generators from "exfoliation" when the inner surface temperature of the reheater tubes was higher than 1025F. Oxide scale built up on the inside of the tube, then flaked off and was carried into the steam turbine. Some jobs had trouble at 1025F, many did not, but until more service experience is available it was decided to change to Croloy 5, which is more resistant to exfoliation, when the inner surface temperature exceeds 1025F. The vertical outlet tubes from the bundle to the torroidal rectangular box outlet header are also Croloy 5.

The reheater tubes are on 2" transverse and 2" parallel spacing throughout the bundle. The average pitch angle for each tube is approximately 18-1/2 degrees. The tubes are arranged in 20 rows with the number of tubes per row set to give nearly equal tube lengths of 100 ft. With 752 tubes in the bundle, the inner coil diameter is 32-1/2" and the outer coil diameter is 108-1/2 inches. The number of tubes per row varies from 16 on the inner row to 56 on the outer row.

6.5 Reheater Tube Supports

The reheater tube supports are similar to those in the steam generator. (See Par. 5.11-1 for boiler tube support description) (See reheater drawings 20955F, 20956F, and SK-1203).

TABLE 3

HEAT TRANSFER AND PRESSURE DROP RESULTS

REHEATER

Parameters for One Unit	Three Units Required for 1000 MWe
Operating Conditions (Full Load)	
Heat Load	326.7×10^6 Btu/hr
Sodium Flow	2.41×10^6 lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	690 F
Sodium Pressure Drop (approximately)	4 psi
Steam Flow	1.71×10^6 lb/hr
Steam Inlet Temperature	655 F
Steam Outlet Temperature	1000 F
Outlet Pressure	490 psia
Material	
Tubes (Downcomers, Section A, Section B)	Croloy 2-1/4 T-22
Tubes (Section C, Outlet Tubes)	Croloy 5 T-5
Shell	Croloy 2-1/4
Tube Sheets, Heads	Croloy 2-1/4

Heat Transfer Results

	Number	Size	Effective Length
Tubes - Section A	752	1-1/2" O.D. x .052" M.W.	53.20 ft.
- Section B	752	1-1/2" O.D. x .095" M.W.	28.06 ft.
- Section C	752	1-1/2" O.D. x .225" M.W.	18.90 ft.
			100.16 ft.

	Heat Transferred (BTU/hr)	L.M.T.D.	Over-all Heat Transfer Coef. (Btu/hr. ft^2 F)
Tube Bundle Section A	117.6×10^6	52.1 F	160.9
Section B	108.6×10^6	89.3 F	165.5
Section C	101.2×10^6	122.8 F	166.5
Total	326.7×10^6		

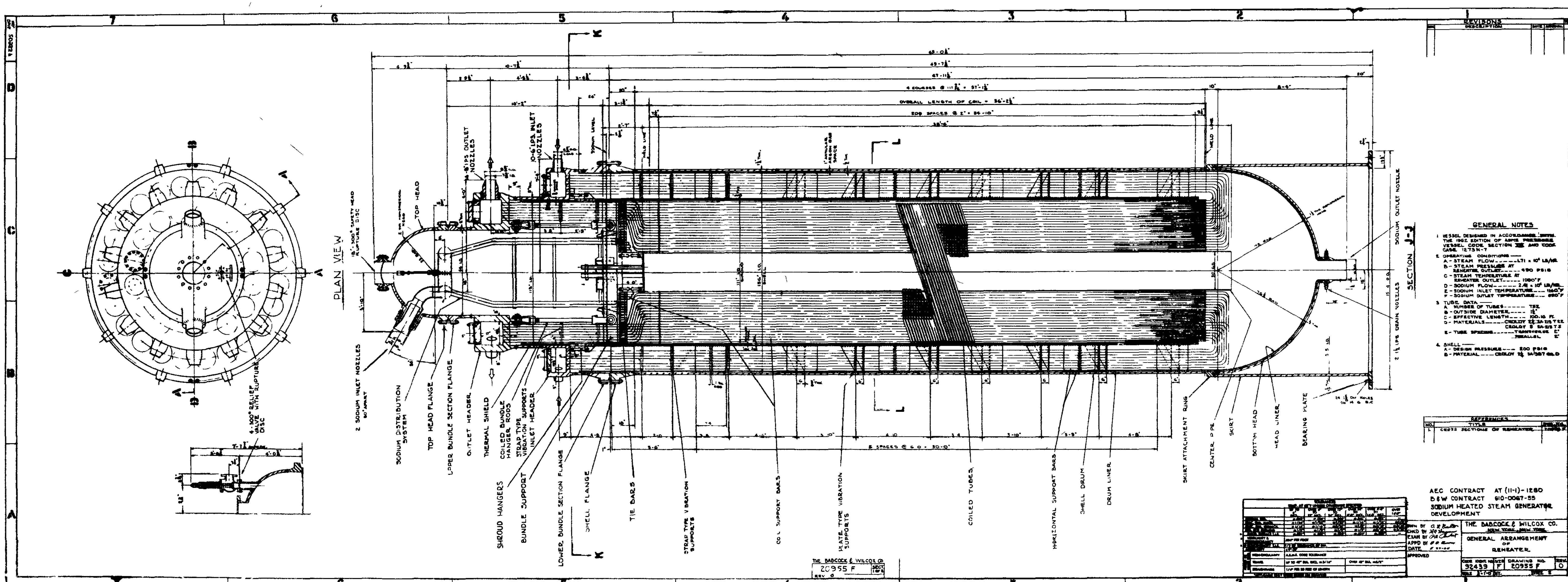
Fouling Factor 3333 Btu/hr ft^2 F.

Corrosion Allowance 0.009 inches.

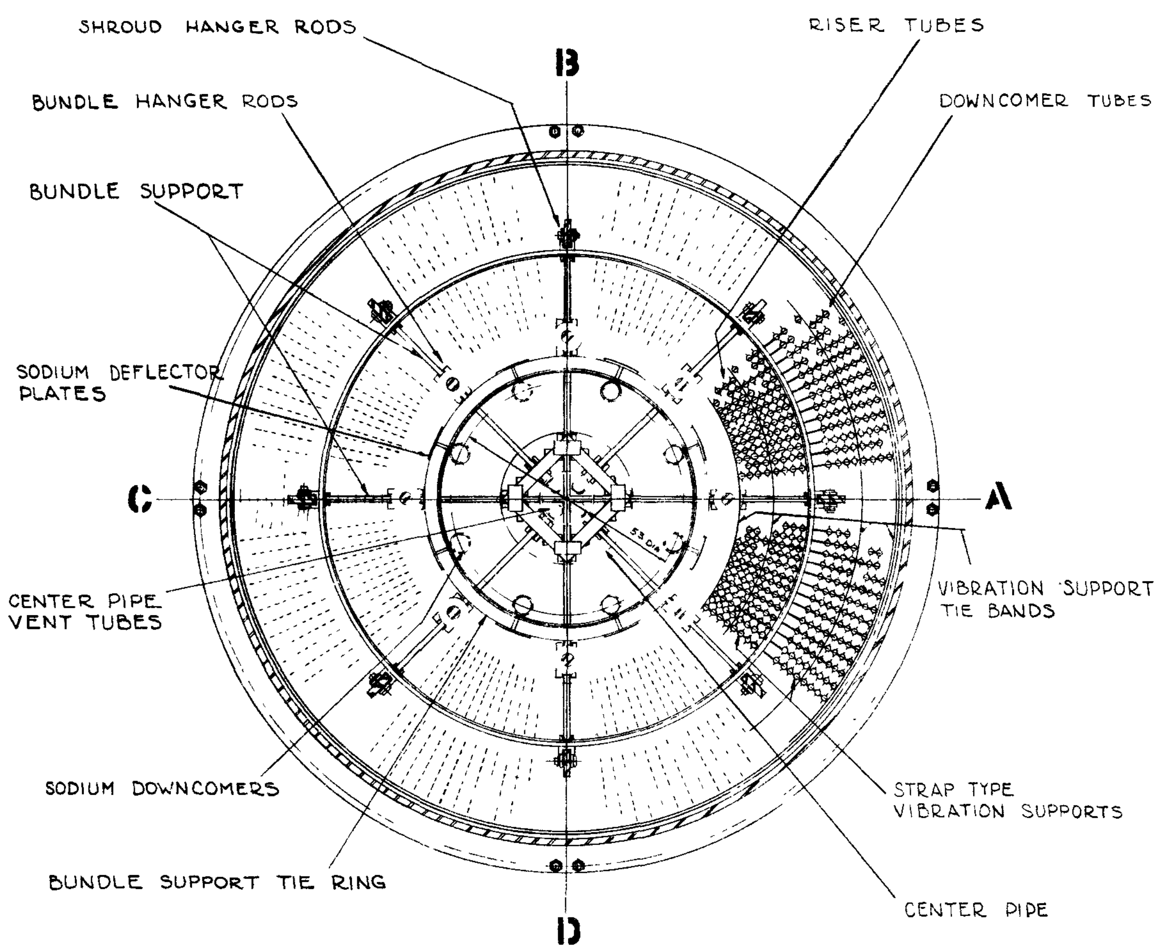
TABLE 3

(CONTINUED)

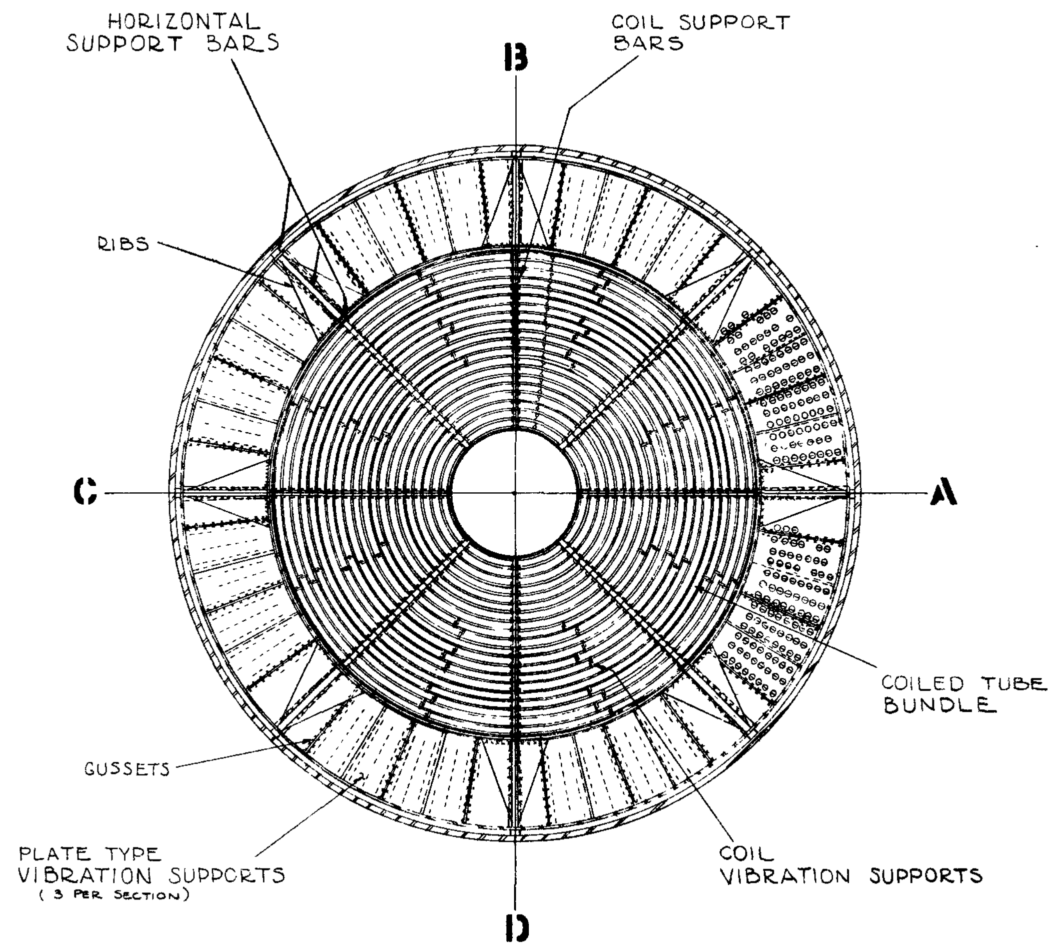
Heat Transfer Surface	
Section A	15,780 ft^2
Section B	8,280 ft^2
Section C	5,580 ft^2
Total	29,640 ft^2
Reheater Downcomer Tubes	
Size	1-1/2" O.D. x .052" M.W.
Number	752
Length	50 ft.
Reheater Outlet Tubes	
Size	1-1/2" O.D. x .225" M.W.
Number	752
Length	10 ft.
Pressure Drop (Steam Side)	
Downcomer tubes	2.22 psi
Section A	3.61 psi
Section B	3.48 psi
Section C	8.54 psi
Outlet Tubes	7.83 psi
Total	25.68 psi
Transverse Tube Spacing S_T	2"
Parallel Tube Spacing S_{11}	2"



PLAN VIEW
SECTION J-J
GENERAL NOTES
1 VESSEL DESIGNED IN ACCORDANCE WITH THE 1962 EDITION OF ASME PRESSURE VESSEL CODE SECTION III AND CODE CASE 1273N-7
2 OPERATING CONDITIONS
A - STEAM FLOW ---- 1.71 x 10⁶ LB/HR
B - STEAM PRESSURE AT REHEATER OUTLET ---- 450 PSIG
C - STEAM TEMPERATURE AT REHEATER OUTLET ---- 1050°F
D - SODIUM FLOW ---- 2.41 x 10⁶ LB/HR
E - SODIUM INLET TEMPERATURE ---- 1160°F
F - SODIUM OUTLET TEMPERATURE ---- 880°F
3 TUBE DATA
A NUMBER OF TUBES ---- 752
B - OUTSIDE DIAMETER ---- 1½"
C - EFFECTIVE LENGTH ---- 100.16 FT
D - MATERIALS ---- CROLOY 2¼ SA-213 T22
CROLOY 5 SA-213 T5
E - TUBE SPACING ---- TRANSVERSE 2"
PARALLEL 2"
4. SHELL
A - DESIGN PRESSURE ---- 200 PSIG
B - MATERIAL ---- CROLOY 2¼ SA-387 GR D
SODIUM OUTLET NOZZLE
2 1½ IPS DRAIN NOZZLES
2 SODIUM INLET NOZZLES 180° APART
SODIUM DISTRIBUTION SYSTEM
TOP HEAD FLANGE
UPPER BUNDLE SECTION FLANGE
OUTLET HEADER
THERMAL SHIELD
COILED BUNDLE HANGER RODS
STRAP TYPE VIBRATION SUPPORTS
INLET HEADER
SHROUD HANGERS
BUNDLE SUPPORT
LOWER BUNDLE SECTION FLANGE
SHELL FLANGE
TIE BARS
STRAP TYPE VIBRATION SUPPORTS
COIL SUPPORT BARS
PLATE TYPE VIBRATION SUPPORTS
COILED TUBES
HORIZONTAL SUPPORT BARS
SHELL DRUM
DRUM LINER
SKIRT ATTACHMENT RING
CENTER PIPE
SKIRT
BOTTOM HEAD
HEAD LINER
BEARING PLATE
TOP HEAD
4-300° RELIEF VALVE WITH RUPTURE DISC
OVERALL LENGTH OF COIL = 36'-2¼"
8 SPACES @ 6'-0 = 30'-0"
REFERENCES
NO. | TITLE
1 | CROSS SECTIONS OF REHEATER
AEC CONTRACT AT (11-1)-1280
B&W CONTRACT 610-0067-55
SODIUM HEATED STEAM GENERATOR DEVELOPMENT
THE BABCOCK & WILCOX CO.
GENERAL ARRANGEMENT OF REHEATER
DRAWING NO. 20955 F
92439
REV. 0



SECTION **K-K**



SECTION **L-L**

REVISIONS				
REV.	DESCRIPTION	DATE	APPROVAL	

NOTES

1. FOR GENERAL NOTES SEE GENERAL ARRANGEMENT DRAWING.

REFERENCES		
NO.	TITLE	DWG NO.
1	GENERAL ARRANGEMENT OF REHEATER	20955 F

AEC CONTRACT AT (11-1)-1280
B&W CONTRACT 610-0067-55
SODIUM HEATED STEAM GENERATOR DEVELOPMENT

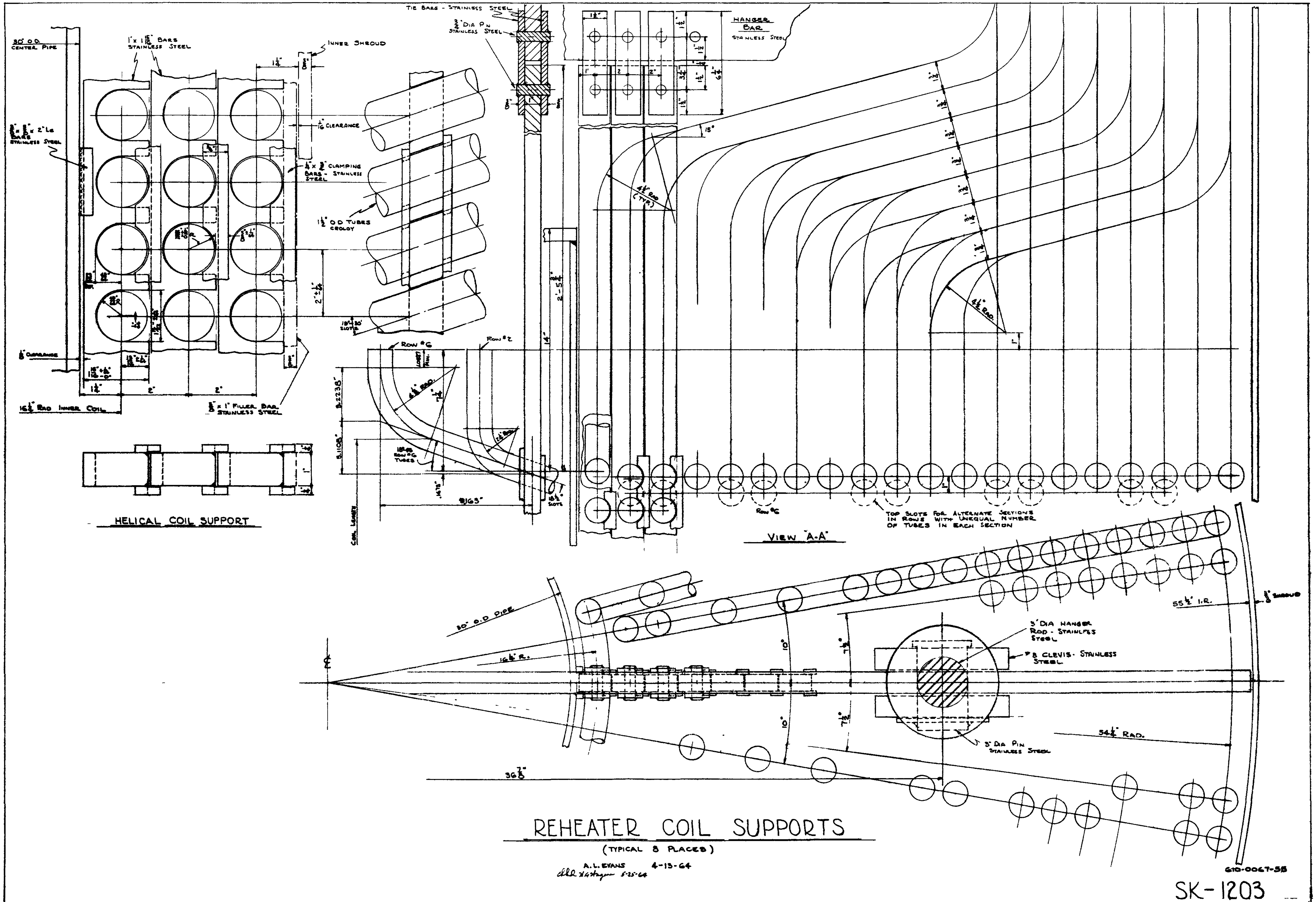
TOLERANCES TEMP. AT 68°F UNLESS OTHERWISE SPECIFIED						
	UP TO 6" INCL.	OVER 6" TO 12" INCL.	OVER 12" TO 24" INCL.	OVER 24" TO 6'-0" INCL.	OVER 6'-0" TO 14'-0" INCL.	OVER 14'-0"
DECIMAL DIM.	±.003"	±.005"	±.005"	±.010"	±.031"	–
FRAC. DIM. MACH.	±1/64"	±1/32"	±1/32"	±1/16"	±1/16"	±1/8"
FRAC. DIM. UNMACH.	±1/16"	±1/16"	±3/32"	±1/8"	±3/16"	±3/16"
DIM. FOR BURNING	±1/8"	±1/8"	±1/8"	±1/8"	±3/16"	±3/16"
MACH. SURFACE T.I.R.	±.001"	±.002"	±.002"	±.003"	±.003"	–
VERTICALITY & PERPENDICULARITY	.004" PER FOOT					
CONCENTRICITY T.I.R.	1/2 OF TOLERANCE OF DIA					
ANGULARITY	-0°-30'					
*PRESSED OR ROLLED SHELL: NON-CIRCULARITY	A.S.M.E. CODE TOLERANCE					
TRAVEL	UP TO 42" DIA. INCL. ±3/16"			OVER 42" DIA. ±3/8"		
STRAIGHTNESS	1/4" PER 20 FEET OF LENGTH					
*APPLICABLE ONLY WHEN NOTED ON DRAWING						

DWN BY A. L. Evans
CHKD BY H. A. Wagner
EXAM BY J. B. Partat
APPD BY F. E. Ivins
DATE 5-27-64
APPROVED

THE BABCOCK & WILCOX CO.
NEW YORK, NEW YORK

CROSS SECTIONS OF REHEATER

CODE IDENT. NO.	SIZE	DRAWING NO.	REV.
92439	F	20956 F	0
SCALE 3/4"=1'-0"	WT.		SECT.


REHEATER COIL SUPPORTS
(TYPICAL 8 PLACES)
A. L. EVANS 4-13-64
HELICAL COIL SUPPORT
VIEW "A-A"
30" O.D. CENTER PIPE
1" x 1 15/16" BARS STAINLESS STEEL
INNER SHROUD
1/16" CLEARANCE
1/4" x 3/8" CLAMPING BARS - STAINLESS STEEL
1 1/2" O.D. TUBES CROLOY
16 1/2" RAD INNER COIL
3/8" x 1" FILLER BAR STAINLESS STEEL
TIE BARS - STAINLESS STEEL
3/4" DIA PIN STAINLESS STEEL
HANGER BAR STAINLESS STEEL
4 1/2" RAD. (TYP.)
ROW #6
ROW #2
TOP SLOTS FOR ALTERNATE SECTIONS IN ROWS WITH UNEQUAL NUMBER OF TUBES IN EACH SECTION
30" O.D. PIPE
16 1/2" R.
3" DIA HANGER ROD - STAINLESS STEEL
3/8" CLEVIS - STAINLESS STEEL
3" DIA PIN STAINLESS STEEL
55 1/2" I.R.
3/8" SHROUD
54 1/4" RAD.
36 7/8"
GTO-0067-58
SK-1203

7.0 SUMMARY OF PERFORMANCE:

The steam generator and reheater were sized on the basis of full load conditions shown in Figure A. The starting point for thermal design was the calculation of a heat balance based on the specified sodium temperatures to and from the intermediate heat exchanger shown on Figure 5, and the heat requirements of the steam cycle.

The main variable in the secondary loop was the sodium flow to each component to satisfy heat balance requirements. Once this was established, it was possible to set surface requirements in the steam generator and reheater for full load conditions.

In addition to the heat balance requirements, the steam generator and reheater were designed to fixed pressure drops, 250 psi in the steam generator and 50 psi in the reheater and piping. The pressure drop of the major components in the steam generator are shown on Figure 12. The 250 psi pressure drop was selected as an economic balance between pumping cost and heat transfer surface.

7.1 Heat Transfer:

1. Sodium Side:

The sodium side heat transfer calculation is based on the correlation developed for heat transfer to cross-flowing mercury in a staggered tube bank. The correlation is as follows:

$$Nu = 4.03 + 0.228 (Pe)^{.67}$$

For definition of terms see Section 7.3

This correlation does not fit our tube geometry exactly, since the helical coiled bundle has flow across an in line tube bank. However, the inaccuracy due to using this correlation is estimated to be less than ± 10%. Since the sodium film resistance has little effect on the total heat transfer resistance of the steam generator, any small error in using this cross flow correlation does not materially affect the over-all heat transfer surface requirements.

2. Fouling Factor:

A fouling resistance of 0.0003 $\frac{hr\ ft^2\ F}{Btu}$ was used on the inside (steam) side of the tubes. This factor is small but with the type of water chemistry required for once-through steam generators, very little fouling is expected.

3. Tube Wall:

The tube wall thickness was calculated based on Section VIII of the ASME Boiler and Pressure Vessel Code. The allowable stress for the Croloy 2-1/4 material and the TP-316 stainless steel material were reduced to allow for the 30 year design life and the affect of sodium on design stress. This is discussed in another section of this report.

For vessels used in steam serviced the ASME Code Section VIII, requires a corrosion allowance on the metal surface in contact with the steam. For the type of feedwater chemistry required in once-through steam generators outlined in Section 4.8, the rate of corrosion is .0001" per year or a total of .003" for a 30 year life of the unit. In addition, periodic acid cleaning of the unit will corrode the tubes to the extent of approximately .00011 inches per year or a total for 30 years of .0033".

The addition of these two values gives a corrosion rate .0063 inches in a 30 year life. The minimum allowance for corrosion used in most of the Croloy 2-1/4 section of this steam generator is .009 inches, which should be sufficient for this type of unit.

For heat transfer calculations an equivalent thickness was used. The expression for this is $te = \frac{OD}{2} \ln \frac{OD}{ID}$.

The tube wall heat transfer conductance is $h_m = K/te$ where K is the thermal conductivity (Btu/hr-ft^2-F/ft) tube wall temperature.

4. <u>Water-Steam Side</u>:

A - Economizer - The heat transfer conductance on the inside diameter of the tubes is based on the Colburn equation for single phase fluids as follows:

$$h = 0.023 \frac{K}{D} \left(\frac{DG}{\mu}\right)^{.8} \left(\frac{Cp\mu}{K}\right)^{.4}$$

$$h = 0.023\left(\frac{G^{.8}}{D^{.2}}\right)\left(\frac{Cp^{.4}\ k^{.6}}{\mu^{.4}}\right) \quad \text{(Modified Form)}$$

At some point in the tube near the region of saturated nucleate boiling, subcooled nucleate boiling will occur. This results in a higher heat transfer coefficient than that for a single phase water, but this increase was not considered in the design of this unit. The tube side mass flow is high enough to prevent subcooled film boiling which gives a very low film conductance.

B - Nucleate Boiling - The saturated nucleate boiling film conductance was based on the Rohsenow equation.

$$h_{NB} = C\ (\Delta T_f)^2$$

$$h_{NB} = \frac{q/A}{\Delta T_f}$$

$$C = \left[\frac{h_{fg}\,\mu}{\sqrt{\frac{\sigma}{\rho_L - \rho_v}}} \right] \left[\frac{C_p}{.013\, h_{fg} \left(\frac{C_p \mu}{k} \right)^{1.7}} \right]^3$$

C - Film Boiling - The heat transfer conductance for film boiling was calculated using 50% of the value given by the Colburn Equation based on average steam film properties.

$$h_{FB} = (0.5)(.023)\left(\frac{G^{.8}}{D^{.2}}\right)\left(\frac{C_p^{.4}\,k^{.6}}{\mu^{.4}}\right)$$

The values obtained using this correlation agree closely with published data on film boiling and also with calculation procedures used by the B&W Company in the design of central station boilers.

D - Superheat - The heat transfer conductance for the superheat region of the steam generator and the superheater bundle was based on average steam film properties in the superheated region.

$$h_{SH} = 0.023\left(\frac{G^{.8}}{D^{.2}}\right)\left(\frac{C_p^{.4}\,k^{.6}}{\mu^{.4}}\right)$$

7.2 Pressure Drop:

1 - Sodium Side - Cross-Flow of Sodium - The pressure drop correlation was for air and gas but the correlation is in a general form and applies equally well for pressure drop of water and liquid metals flowing across tube banks. The equation is:

$$\Delta P = 4 f N V_h$$

2 - Water - Steam Side - For the single phase regions of water and steam the pressure drop used was the Darcy-Weisbach equation listed below, using the Moody friction factor.[1] $\Delta P = \frac{f\ell}{D} \frac{V^2}{2g}$

This equation has been modified to a more convenient form.

$$\Delta P = \left(\frac{f\ell}{D} + \frac{V_h}{12}\right) w \left(\frac{G}{10^5}\right)^2$$

For the two phase region in nucleate and film boiling, the correlation used was that developed by Martinelli and Nelson.[2]

[1] Moody, L.F., Friction Factors for Pipe Flow ASME Trans. Vol. 66 (1944) p. 671

[2] Martinelli, R.C., Nelson, D.B. - Prediction of Pressure Drop During Forced Circulation Boiling of Water" - ASME Paper No. 47-A-113, ASME Transaction, Vol. 70 (1948) P 695-702.

This correlation modifies the single phase pressure drop by the addition of two phase flow factors.

$$\Delta P_{TP} = \Delta P_o \left(\frac{\Delta P_{TPF}}{\Delta P_o} \right) + \Delta P_a$$

Coiled tubes increase the straight tube pressure drop due to the curvature of the tube. Therefore, the pressure drop was increased by the factor.

$$\Delta P = e^{\pi d/R} \times \Delta P'$$

7.3 Definition of Terms

1 - $Nu = 4.03 + 0.228 (Pe)^{.67}$ (1)

$$Nu = \frac{\bar{h} D}{K} \qquad Pe = \left(\frac{DG}{\mu}\right)\left(\frac{Cp\,\mu}{k}\right)$$

$\bar{h}$ = Average heat transfer coefficient, BTU/hr ft^2 F

D = Outside diameter of tube, ft.

K = Thermal conductivity of sodium evaluated at average bulk temperature, Btu/hr-ft/F

G = Mass flow of sodium - $\frac{W}{A}$, lb/hr ft^2

W = Flow rate of sodium - lb/hr

A = Cross sectional flow area of tube bundle exposed to sodium flow ft^2

1 Heat Transfer Rates to Cross-Flowing Mercury in a Staggered Tube Bank II - By C.L Rickard, O.E. Dwyer and D. Dropkin. ASME Transactions 57 - HT - 11

μ = Absolute viscosity of sodium evaluated at average bulk fluid temperature, lb/hr-ft

Cp = Specific heat of sodium evaluated at average bulk fluid temperature, Btu/lb-F

2 - $h = 0.023 \frac{k}{D} \left(\frac{DG}{\mu}\right)^{.8} \left(\frac{Cp\mu}{k}\right)^{.4}$ (1)

$$h = 0.023 \left(\frac{G^{.8}}{D^{.2}}\right)\left(\frac{Cp^{.4}k^{.6}}{\mu^{.4}}\right)$$

G = Mass flow of water or steam = $\frac{W}{A}$, lb/hr-ft^2

W = Flow rate of water or steam, lb/hr

A = Flow area of inside of tubes, ft^2

D = Inside diameter of tube, ft.

Cp = Specific heat of water or steam, B/lb-F

k = Thermal conductivity of water or steam, B/hr-ft^{2}F

μ = Absolute viscosity of water or steam, lb/hr-ft.

This general equation is used for the subcooled water region, film boiling and superheat regions. Properties are evaluated at conditions existing in each region.

3 - $h_{nb} = C\,(\Delta T_f)^2$ (2)

$$C = \left[\frac{h_{fg}\,\mu}{\sqrt{\frac{\sigma}{\rho_L - \rho_v}}}\right]\left[\frac{C_p}{0.013\,h_{fg}\left(\frac{C_p\mu}{k}\right)^{1.7}}\right]^3$$

[1]McAdams, W.H. Heat Transmission 3rd. Edition, 1954, p. 219.

[2] Heat Transfer Notes, 1958, Summer Session M.I.T., W. H. Rohsenow.

h_{nb} = Heat transfer coefficient for nucleate boiling

T = Temperature drop across nucleate boiling film, F

hfg = Latent heat of saturated liquid Btu/lb.

μ = Absolute viscosity of saturated liquid, lb/ft-ft.

σ = Surface Tension of saturated liquid, lb/ft.

ρ_L = Density of saturated water, lb/ft^3

ρ_V = Density of saturated vapor, lb/ft^3

Cp = Specific heat of saturated liquid, Btu/lb-F

k = Thermal conductivity of saturated liquid, B/hr-ft.F

C = Property Constant

4 - $\Delta P = 4 f N V_h$

ΔP = Cross flow pressure drop, psi

N = Number of major restrictions to flow through tube bank.

f = Friction Factor[1]

[1] Friction factors are based on the following papers:

Gram, A.J., Mackey, C.O., Monroe, E.S.
"Convection Heat Transfer and Pressure Drop of Air Flowing Across In-Line Tube Banks - ASME Paper 56-A-127

Grimison, E.D.
"Correlation and Utilization of New Data on Flow Resistance and Heat Transfer for Cross Flow of Gases over Tube Banks" ASME Transaction, 1937, p. 583-594.

Jones, C.E., Monroe, E.S.
Convection Heat Transfer and Pressure Drop of Air Flowing Across In-Line Tube Banks - ASME Paper 56-A-126

5 - $$\Delta P = \left(\frac{f\ell}{D} + \frac{V_h}{12}\right) v \left(\frac{G}{10^5}\right)^2$$

ΔP = Pressure Drop - psi

f = Moody friction factor for cold drawn tubes.

ℓ = Tube length, ft.

D = Inside diameter of tube, in.

V_h = Number of velocity heads lost in entrance, exit and bends.

v = Specific volume of fluid, ft^3/lb

G = Mass flow of fluid, $lb/hr\text{-}ft^2$

6 - $$\Delta P_{TP} = \Delta P_o \left(\frac{\Delta P_{TPF}}{\Delta P_o}\right) + \Delta P_a$$

ΔP_{TP} = Two phase flow pressure drop, psi

ΔP_o = Pressure drop for saturated water flow, psi

$\left(\frac{\Delta P_{TPF}}{\Delta P_o}\right)$ = Local two phase flow pressure drop factor

ΔP_a = Pressure drop resulting from acceleration loss, psi

7 - $$\Delta P = e^{\pi d/R} \times \Delta P'$$

d = Inside diameter of tube, in.

R = Centerline radius of coil, in.

ΔP = Pressure drop in coiled tubes, psi

$\Delta P'$ = Pressure drop in straight tubes, psi

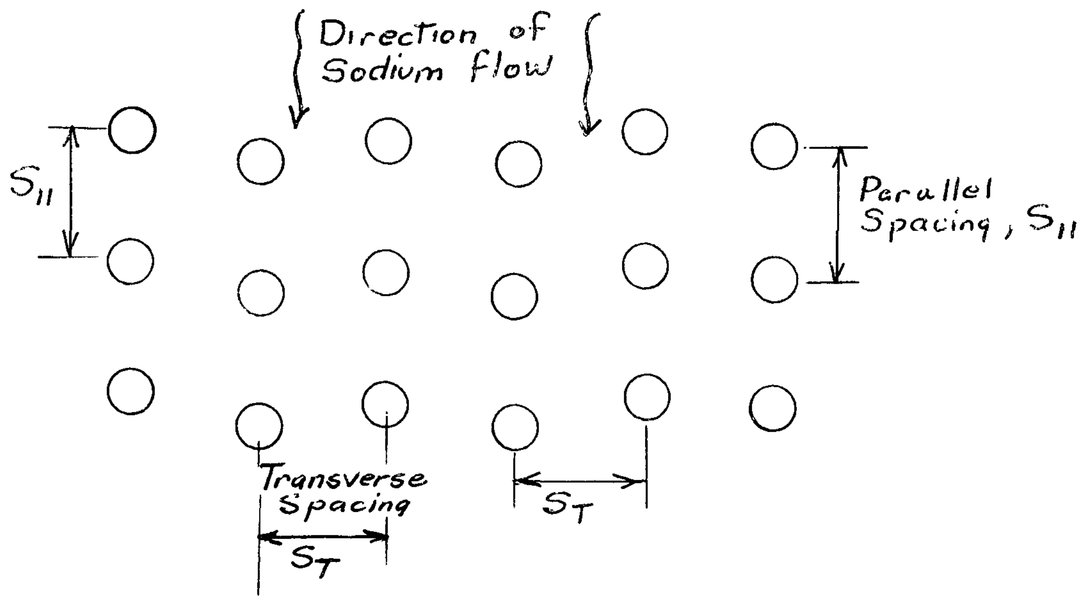
7.4 Effect of Design Parameters on Heat Transfer:

1 - Location of Departure from Nucleate Boiling (DNB) -

The location of the point where nucleate boiling ceases and film boiling starts is important for the calculation of heat transfer surfaces. In nucleate boiling steam film conductance is high, resulting in good heat transfer coefficients and low tube metal temperatures. In film boiling the steam conductance is lower and tube metal temperatures increase.

If the location of the DNB is known accurately then the heat transfer surface required for the boiler can be carefully determined with a saving of heat transfer surface. For the initial design the DNB was set at 10% steam quality, based on DNB data in straight horizontal tubes. No data existed for the type of configuration used in coiled tubes. Test work done under the Research and Development part of this Contract indicates that the DNB occurs at a much higher quality than what was assumed. This means that there will be some excess surface in the boiler tube bundle, which will be adjusted when the test data is complete.

2 - <u>Tube Arrangement and Sodium Flow</u> - The tube geometry used in the helical coiled boiler bundle consists of vertical in line rows. The rows are slightly offset on the parallel plane due to requirements of tube bundle construction.



The transverse and parallel spacing were established based on manufacturing and tube support requirements. The bundle is kept as compact as possible within these requirements. The boiler tube spacing was 1-1/2" in the transverse direction and 1-3/8 inches in the parallel direction. The superheater is of similar construction except the tube spacing is 1-1/4 inches in the transverse direction and 1-1/4 inches in the parallel direction.

The sodium heat transfer coefficients is very high, 11,260 B/hr ft^2 F in the superheater bundle and 7,130 B/hr ft^2 F in the boiler bundle. Since flow and temperature are set as a function of load, the only variable is the flow area. The sodium heat transfer coefficient is proportional to $(\text{Flow/area})^{.67}$ Changes in flow area affect the sodium side heat transfer coefficient, but have little effect on the overall heat transfer coefficient. Therefore heat transfer surface requirements are only slightly affected by changes in sodium mass flow and tube spacing.

The main concern in tube spacing is to prevent the sodium from channeling through the tube bundle with little temperature change. This would possibly occur if the transverse spacing was greatly increased making wide lanes between the tube rows, and the parallel spacing was decreased. The helical coiled design does not approach this condition.

3 - <u>Effect of Steam Flow on Heat Transfer</u> - The two main resistances to heat flow are the tube wall and the inside steam film. Little can be done to change the tube wall thickness since it is designed to a specified temperature

and pressure. The steam film is a function of steam mass flow (W steam/Flow Area)$^{.8}$ The steam mass flow in this design has been set as high as possible compatible with the pressure drop requirements.

4 - Effect of Tube Size on Heat Transfer Requirements -

Early in the design stage, a study was made to determine optimum tube size. The tube wall is one of the major resistances to heat transfer, so the smaller the diameter the thinner tube wall, and the less heat transfer surface required.

The tube diameters considered for the boiler bundle were ½" to 1¼" by 1/8" increments. For Croloy 2-1/4 tubes the 3/4, 7/8 and 1" OD tubes were almost equal in cost. However, the number of required tube connections due to the increased number of smaller tubes exceeded most of the savings. The tube connections included the down-comer and riser lengths and the attachment to the tube-sheets.

The superheater tubes are Type 316 stainless steel, .875" OD. The minimum tube cost ranged between 5/8" OD and 7/8" OD. Again the larger tube was selected to minimize the cost of the end connections.

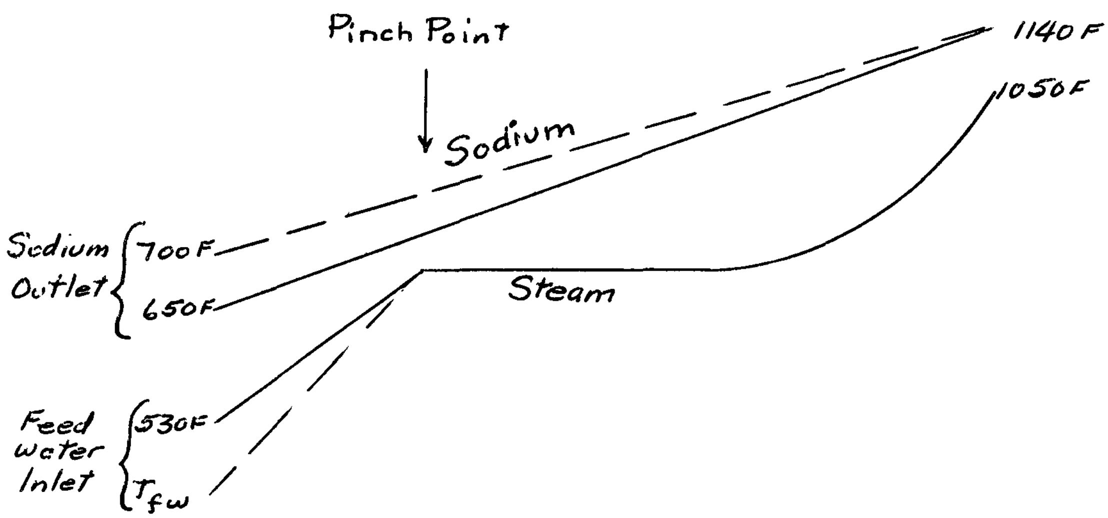
Since the allowable steam side pressure drop in the reheater is very low, only larger OD tubes were studied in the range of 1" OD to 2-1/2" OD. Tube costs were nearly equal, so 2" OD tubes were selected. They resulted in the best tube bundle configuration when length, tube spacing and number of tubes were considered.

5 - Effect of Temperature on Heat Transfer Requirements -

Since the tube wall and steam flow are somewhat fixed within narrow limits and tube spacing has only a small affect on sodium heat transfer, the over-all heat transfer coefficient is not easily changed to any degree.

The steam generator then becomes sensitive to the temperature differences between the sodium and the steam. Outlet steam temperature and sodium inlet and outlet temperature are fixed by the specified design conditions. With saturation temperature constant at 676F, the temperature difference from the superheater outlet to the economizer outlet are firmly established. Therefore the only temperature difference that can be varied is the one where cool sodium meets incoming feedwater. A colder feedwater temperature will increase the temperature difference and reduce required heat transfer surface as long as the gain in temperature difference is greater than the required heat input.

If the sodium outlet temperature is increased above 650F significant reductions in required heat transfer surface in the economizer and boiler can be made. A higher sodium outlet temperature will have a significant effect on temperatures at the "pinch point", which is the area where boiling starts. For example, if the sodium outlet temperature were increased to 700°F, the saving in steam generator heat transfer surface would be approximately 30%.



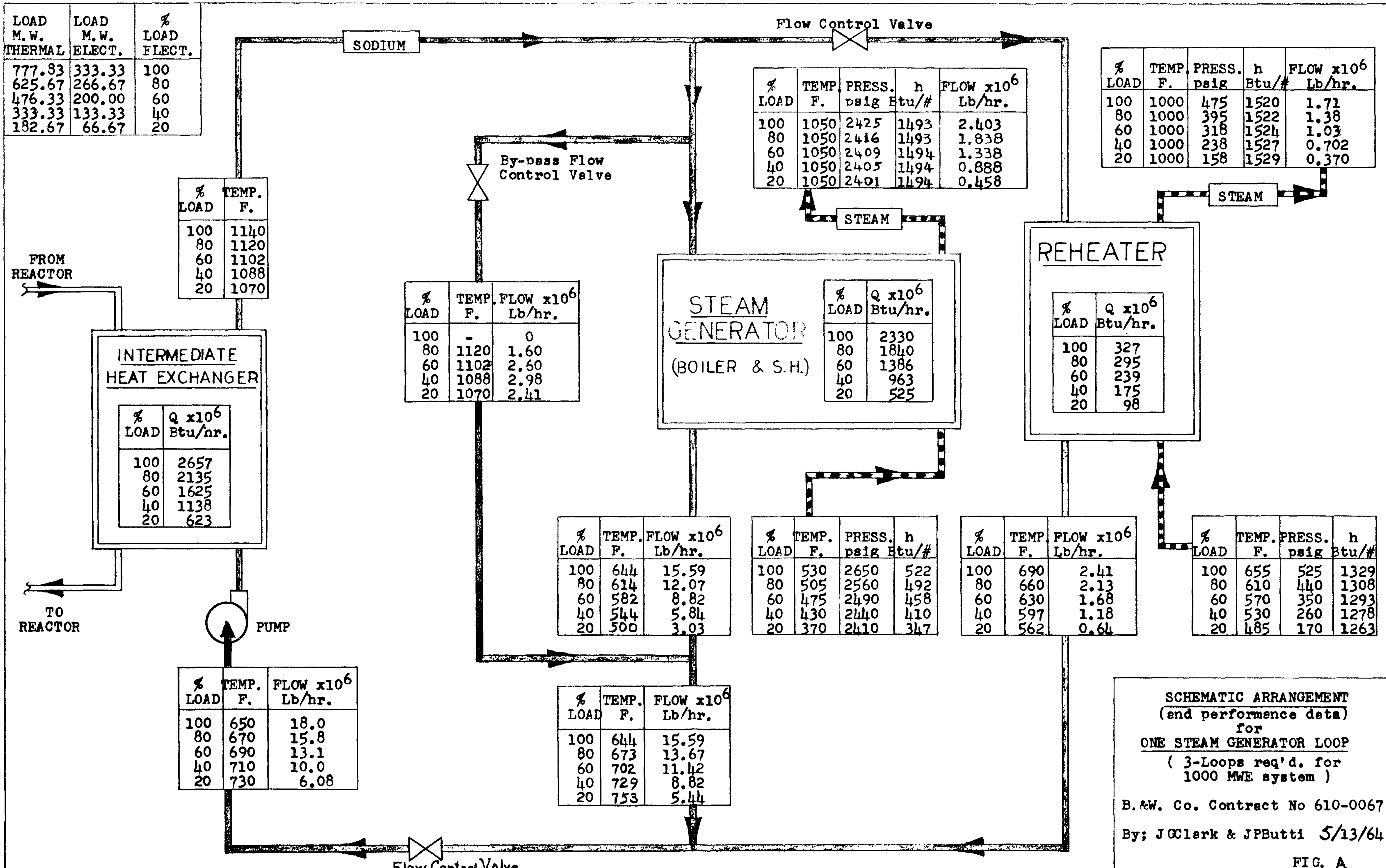
7.5 Summary of Part Load Operation:

The part load performance is summarized on figure A. The tabulation shows required steam and sodium flows, and associated temperatures from 100% load to 20% load. Since the steam generator and reheater were sized at 100% load, all the sodium flow goes to these components and the by-pass is closed.

At part load the by-pass valve is held in the proper position to receive all sodium flow not used in the steam generator and reheater. By-pass flow increases as load is reduced from 100% to 40%. Between 40% and 20% the by-pass flow decreases due to the heat requirements of the steam cycle.

Calculations show that the performance of the stainless steel superheater bundle is relatively stable. With outlet steam temperature constant at 1050 and a controlled sodium inlet temperature, the outlet sodium temperature varied from 1013 to 929 F as load was reduced from 100% to 20% and steam outlet temperatures vary from 750 F to 715 F for the same load range. This is shown on Figure 9.

The boiler bundle performance is sensitive to sodium flow particularly at lower loads. This is due to a reduction in sodium flow causing a low ΔT at the pinch point where nucleate



LOAD M.W. THERMAL	LOAD M.W. ELECT.	% LOAD ELECT.
777.83	333.33	100
625.67	266.67	80
476.33	200.00	60
333.33	133.33	40
182.67	66.67	20

% LOAD	TEMP. F.
100	1140
80	1120
60	1102
40	1088
20	1070

INTERMEDIATE HEAT EXCHANGER

% LOAD	Q x10^6 Btu/hr.
100	2657
80	2135
60	1625
40	1138
20	623

PUMP

% LOAD	TEMP. F.	FLOW x10^6 Lb/hr.
100	650	18.0
80	670	15.8
60	690	13.1
40	710	10.0
20	730	6.08

By-pass Flow Control Valve

% LOAD	TEMP. F.	FLOW x10^6 Lb/hr.
100	-	0
80	1120	1.60
60	1102	2.60
40	1088	2.98
20	1070	2.41

% LOAD	TEMP. F.	FLOW x10^6 Lb/hr.
100	644	15.59
80	614	12.07
60	582	8.82
40	544	5.84
20	500	3.03

% LOAD	TEMP. F.	FLOW x10^6 Lb/hr.
100	644	15.59
80	673	13.67
60	702	11.42
40	729	8.82
20	753	5.44

STEAM GENERATOR (BOILER & S.H.)

% LOAD	Q x10^6 Btu/hr.
100	2330
80	1840
60	1386
40	963
20	525

STEAM

% LOAD	TEMP. F.	PRESS. psig	h Btu/#	FLOW x10^6 Lb/hr.
100	1050	2425	1493	2.403
80	1050	2416	1493	1.838
60	1050	2409	1494	1.338
40	1050	2405	1494	0.888
20	1050	2401	1494	0.458

% LOAD	TEMP. F.	PRESS. psig	h Btu/#
100	530	2650	522
80	505	2560	492
60	475	2490	458
40	430	2440	410
20	370	2410	347

REHEATER

% LOAD	Q x10^6 Btu/hr.
100	327
80	295
60	239
40	175
20	98

STEAM

% LOAD	TEMP. F.	PRESS. psig	h Btu/#	FLOW x10^6 Lb/hr.
100	1000	475	1520	1.71
80	1000	395	1522	1.38
60	1000	318	1524	1.03
40	1000	238	1527	0.702
20	1000	158	1529	0.370

% LOAD	TEMP. F.	FLOW x10^6 Lb/hr.
100	690	2.41
80	660	2.13
60	630	1.68
40	597	1.18
20	562	0.64

% LOAD	TEMP. F.	PRESS. psig	h Btu/#
100	655	525	1329
80	610	440	1308
60	570	350	1293
40	530	260	1278
20	485	170	1263

SCHEMATIC ARRANGEMENT
(and performance data)
for
ONE STEAM GENERATOR LOOP
(3-Loops req'd. for 1000 MWE system)

B.&W. Co. Contract No 610-0067

By; J.C.Clark & J.P.Butti 5/13/64

FIG. A

boiling starts.

7.6 Flow Stability:

The flow in a parallel tube system of a once-through steam generator is stable only when an increase in flow always causes an increase in pressure drop. Unstable flow is defined as that condition where more than one flow can occur for the same pressure drop.

While a complete analysis has not been completed on this design, it is expected that instabilities will not exist above 20% load. Orifices at the boiler inlet in the form of smaller tubes have already been installed in the unit. The largest components of pressure drop occur in these inlet tubes and in the boiler outlet tubes. At steady state both of these areas have single phase flow.

Some instability may occur during start-up when a steam water mixture will be leaving the boiler. Because the unit will be operated on the start-up loop and the steam water mixture leaving the boiler will be taken directly to the flash tank no trouble is expected. After superheated steam is generated at the boiler bundle outlet at 20% flow, the flow will be stable at that and all higher steam flows.

Sodium flow and temperature are an important influence on the amount of superheat leaving the boiler bundle at any load. This superheat has a great deal to do with determining whether or not there is flow stability at that load. Consequently, flow stability must be a consideration when the part load control scheme is finally selected. However, even with this flow sensitivity a good control system will be able to keep this temperature near the design values.

7.7 Pump Location and Sodium Flow Control:

The sodium pump in the secondary sodium loop is a vertically mounted, centrifugal, free surface pump. It can be located in either the hot or cold leg of the loop. Since both the pump and steam generator have interconnected gas spaces, the gas pressure must be 47.7 psia in order for the pump to operate properly. For cold leg operation the pump will operate at atmospheric pressure. Calculations to determine the pump location are included in the Appendix.

Loop operation calls for variable sodium flow. This can accomplished by three methods. First, a variable speed motor could be coupled to the pump, but such a large motor would be very expensive and may not be feasible. A second solution could be a magnetic coupling between the motor and the pump. This method has been used in other sodium loops and has worked well. A third solution is to use a constant speed or two speed pump and a throttling valve in the sodium pipe. This will permit a flexible flow control with the least expense. The main disadvantage is the loss due to excess pump power at lower loads.

7.8 Effects of Possible Overdesign:

The heat transfer coefficients are based on correlations each of which are deemed to be accurate to no better than ± 10%. The tube wall thickness and thermal conductivity could also vary by at least ± 10%. Normal manufacturing tolerances can also add to inaccuracies to design calculations. The correlations are determined from data taken on carefully built and operated laboratory equipment. There is a good possibility that the performance of the three steam generators in this plant will vary 2% to 3% between units, and the performance will vary 2% to 3% during the life of the plant. Performance will also be affected if it is necessary to plug faulty tubes. Because of these inaccuracies the theoretical surface can also be in error by about ± 10%.

In order to be assured that the unit will meet performance requirements, the calculated heat transfer surface in the superheater bundle was increased by 10%. No excess surface was added to the calculated surface in the boiler bundle, due to the change in DNB from a quality of 10% as first assumed to a quality of 50% to 60% as determined by the R&D program undertaken simultaneously with this design. Also the effect of subcooled nucleate boiling has been ignored in the initial calculations. A combination of these two factors will give the boiler bundle about 7% excess surface.

If there is excess surface it will increase the performance capability of the unit. This means an increase in steam flow or steam temperature and will require some combination of increased sodium flow, higher sodium inlet temperature or lower sodium outlet temperature to balance the heat output. If the increase in capacity is not required, the surface can be made less effective by sodium by-passing through the pipe in the steam generator.

The use of spray attemperators may be required for fine control of steam temperature especially at part load. The superheater attemperator would be located in the pipe connecting the boiler outlet header to the superheater inlet header. The reheater attemperator would be located on the inlet side of the reheater.

7.9 <u>Part Load Analysis - Boiler and Superheater</u>:

The part load operating conditions of the steam generator are shown in figures 13, 14, 15, 16, and 17 for 100, 80, 60, 40, and 20 per cent of load. Part load is based on electrical generation capacity at the turbine bus bar. Steam flow is dependent to electrical load and cycle efficiency.

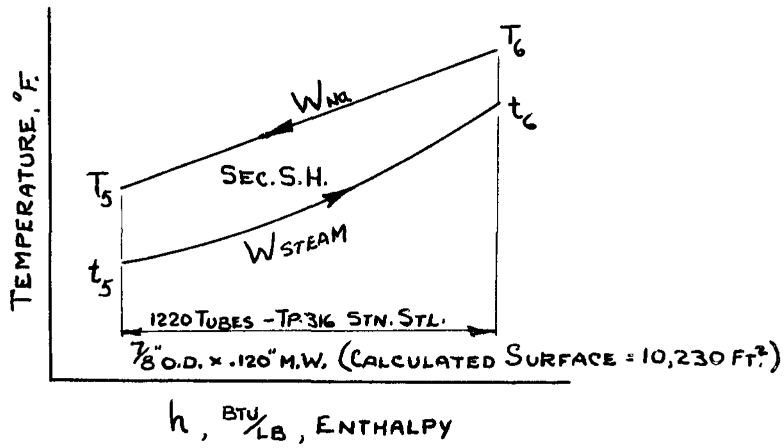
1. Determination of Total Sodium Flow

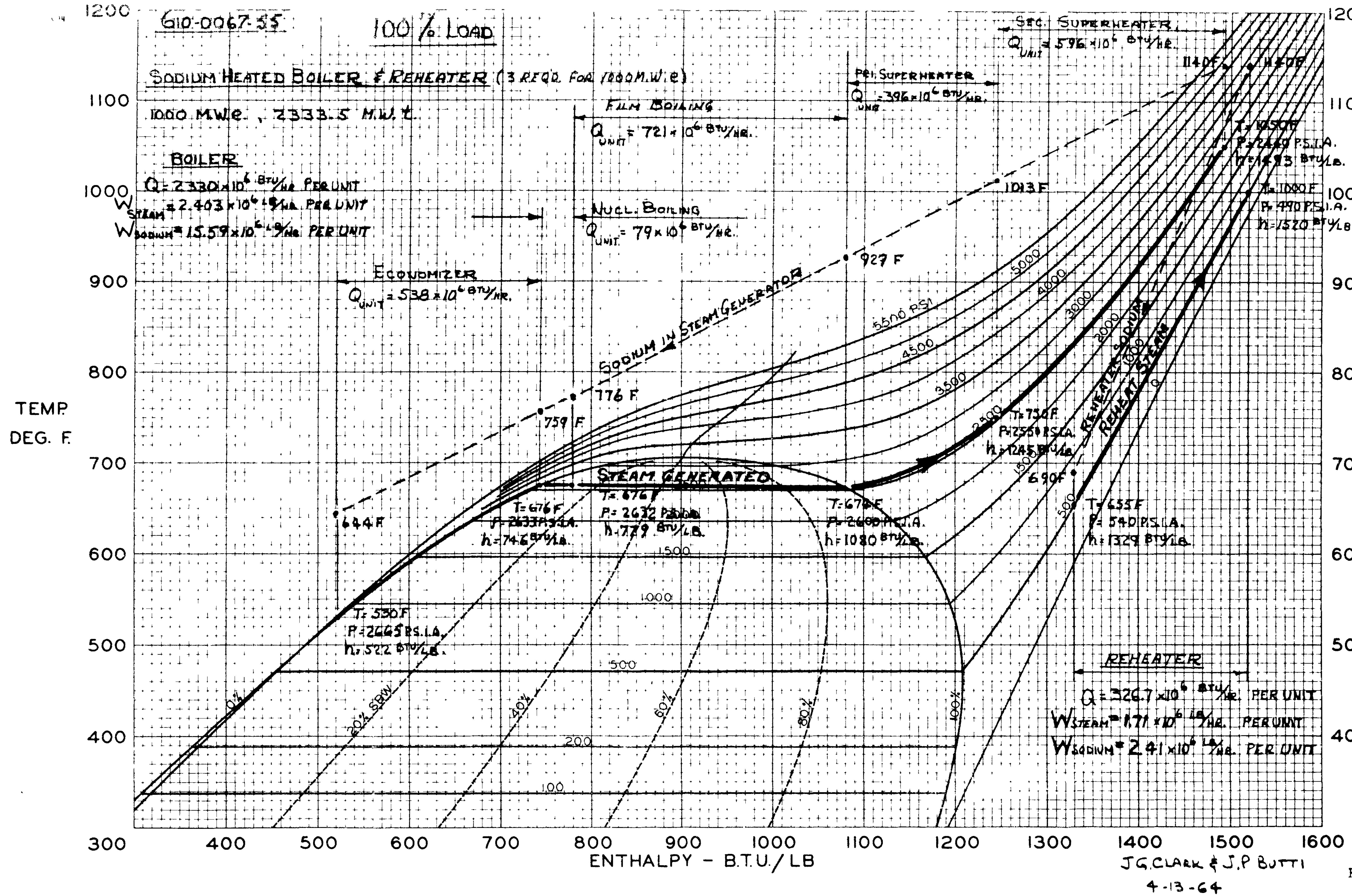
   The total sodium flow is determined by a heat balance on the loop. Steam inlet and outlet conditions and steam flow are known so that the total heat required can be established. The temperature conditions of the IHX are specified. Therefore:

$$W_{na} = \frac{Q}{Cp_{na}\,\Delta T_{na}}$$

2. Performance of Stainless Steel Superheater Bundle

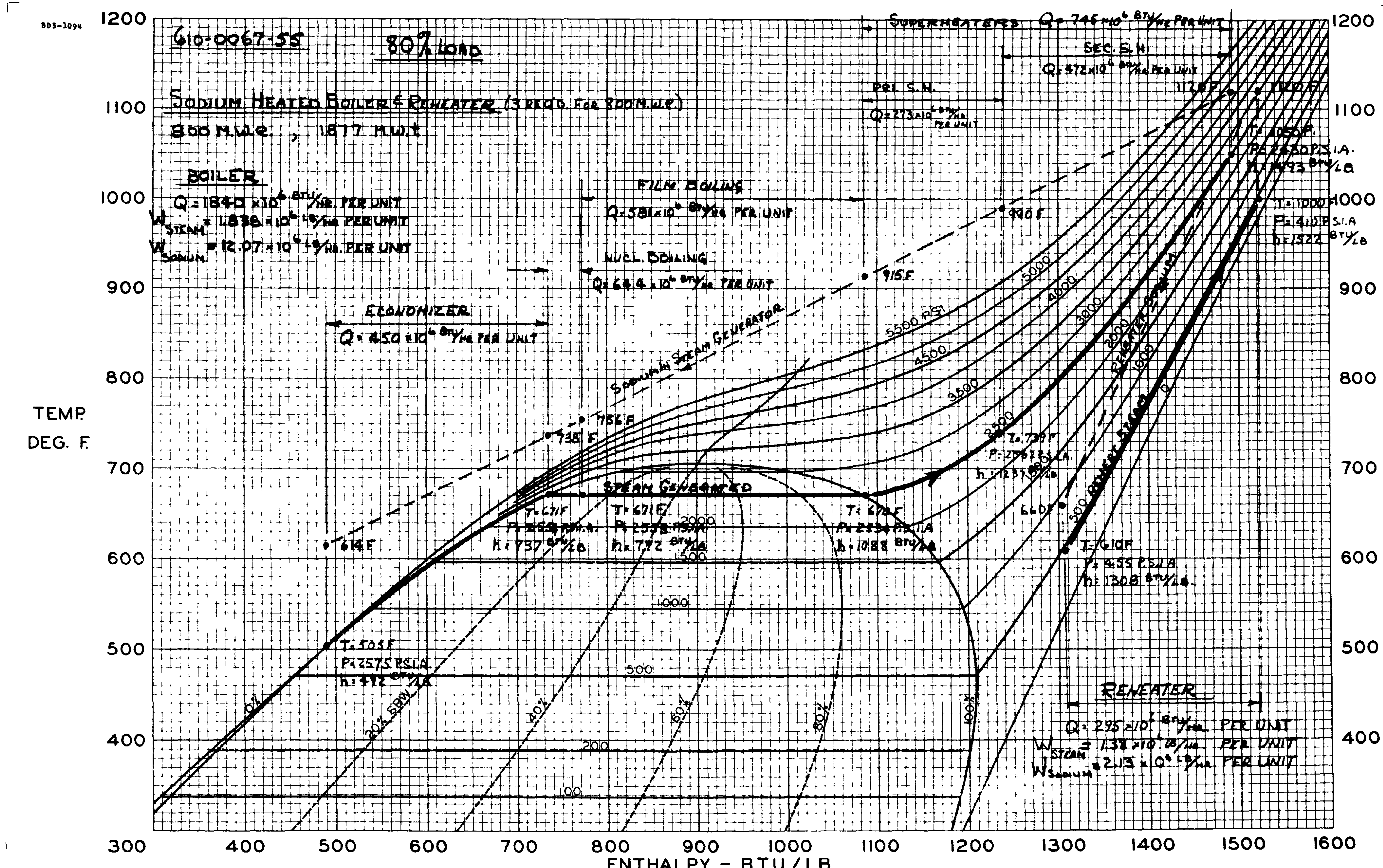
   The performance of the secondary (stainless steel) superheater is determined as a function of sodium flow based on the following data for part loads:





610-0067-55
100% LOAD
SODIUM HEATED BOILER & REHEATER (3 REQD. FOR 1000 M.W.e)
1000 MWe , 2333.5 MWt
BOILER
Q = 2330 x 10^6 BTU/HR. PER UNIT
W STEAM = 2.403 x 10^6 LB/HR. PER UNIT
W SODIUM = 15.59 x 10^6 LB/HR. PER UNIT
ECONOMIZER
Q UNIT = 538 x 10^6 BTU/HR.
NUCL. BOILING
Q UNIT = 79 x 10^6 BTU/HR.
FILM BOILING
Q UNIT = 721 x 10^6 BTU/HR.
PRI. SUPERHEATER
Q UNIT = 396 x 10^6 BTU/HR.
SEC. SUPERHEATER
Q UNIT = 596 x 10^6 BTU/HR.
SODIUM IN STEAM GENERATOR
STEAM GENERATED
REHEATER SODIUM
REHEAT STEAM
644 F
759 F
776 F
927 F
1013 F
1140 F
690 F
T = 530 F
P = 2665 P.S.I.A.
h = 522 BTU/LB.
T = 676 F
P = 2633 P.S.I.A.
h = 746 BTU/LB.
T = 676 F
P = 2632 P.S.I.A.
h = 779 BTU/LB.
T = 676 F
P = 2600 P.S.I.A.
h = 1080 BTU/LB.
T = 750 F
P = 2550 P.S.I.A.
h = 1245 BTU/LB.
T = 1050 F
P = 2460 P.S.I.A.
h = 1493 BTU/LB.
T = 1000 F
P = 490 P.S.I.A.
h = 1520 BTU/LB
T = 655 F
P = 540 P.S.I.A.
h = 1329 BTU/LB.
REHEATER
Q = 326.7 x 10^6 BTU/HR. PER UNIT
W STEAM = 1.71 x 10^6 LB/HR. PER UNIT
W SODIUM = 2.41 x 10^6 LB/HR. PER UNIT
5500 PSI
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
200
100
0%
20% SBW
40%
60%
80%
100%
TEMP. DEG. F
ENTHALPY - B.T.U./LB
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
J.G. CLARK & J.P. BUTTI
4-13-64

FIGURE 13



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4-13-64

FIGURE 14

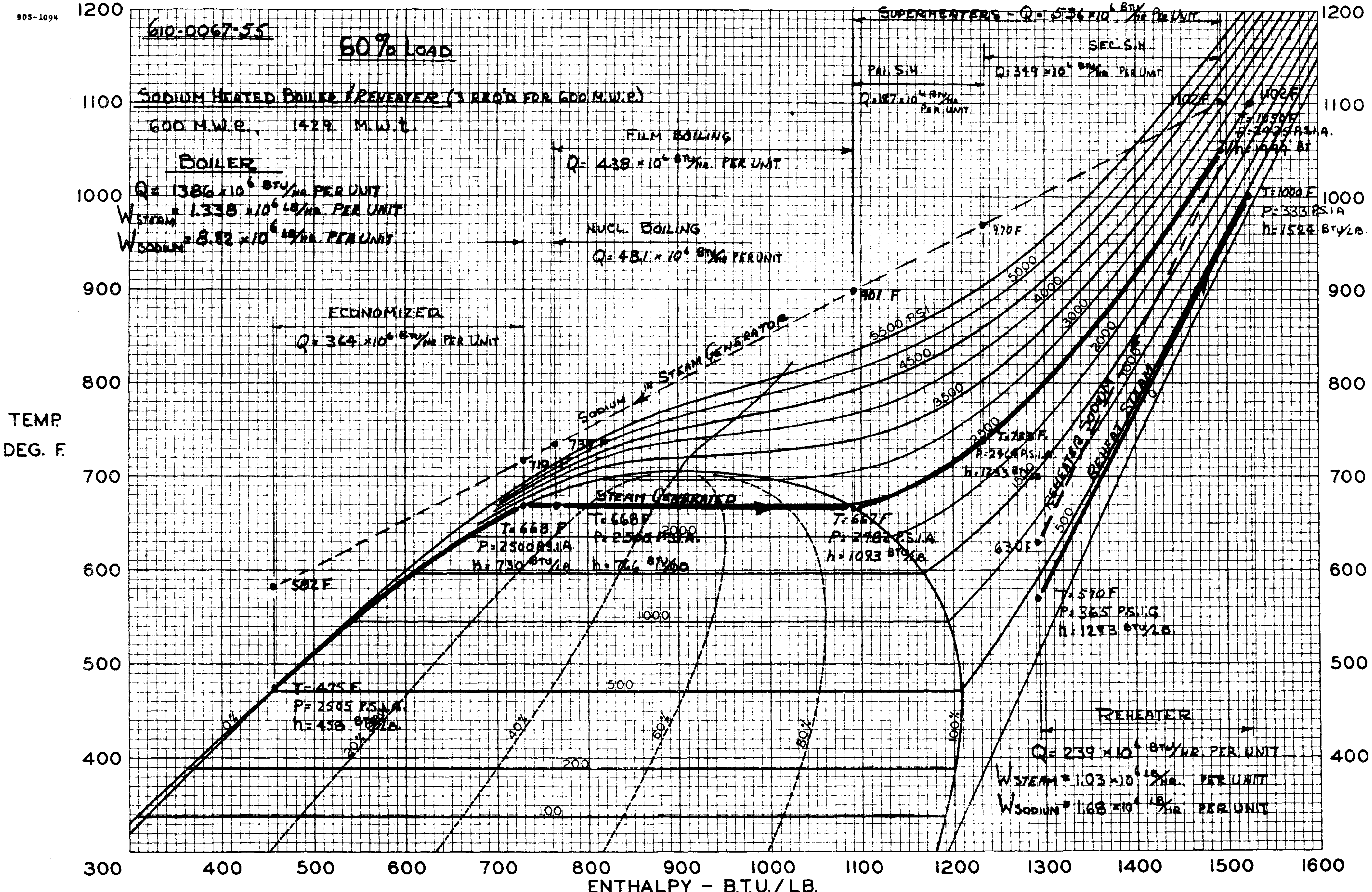

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FIGURE 15

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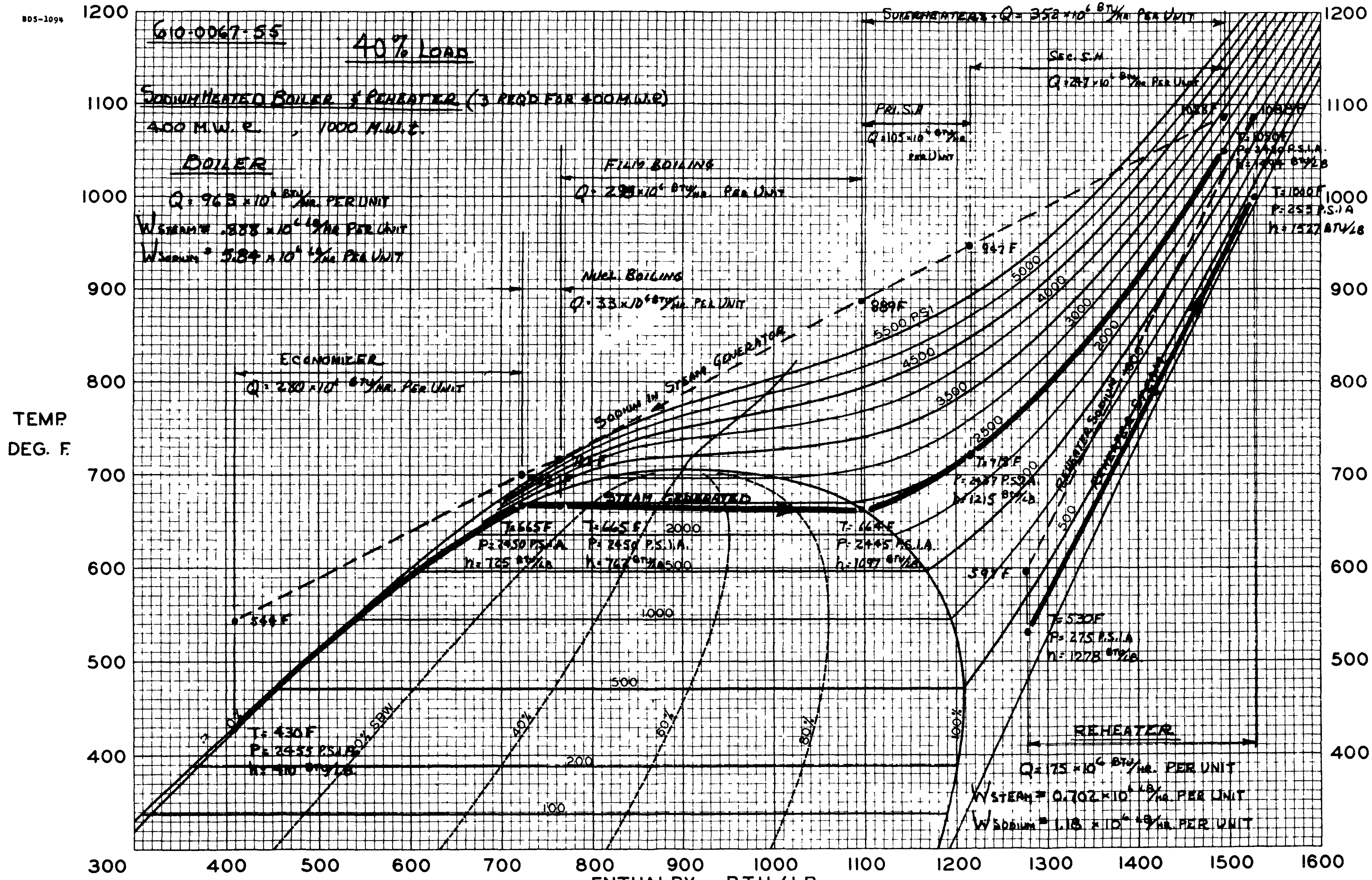

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FIGURE 16

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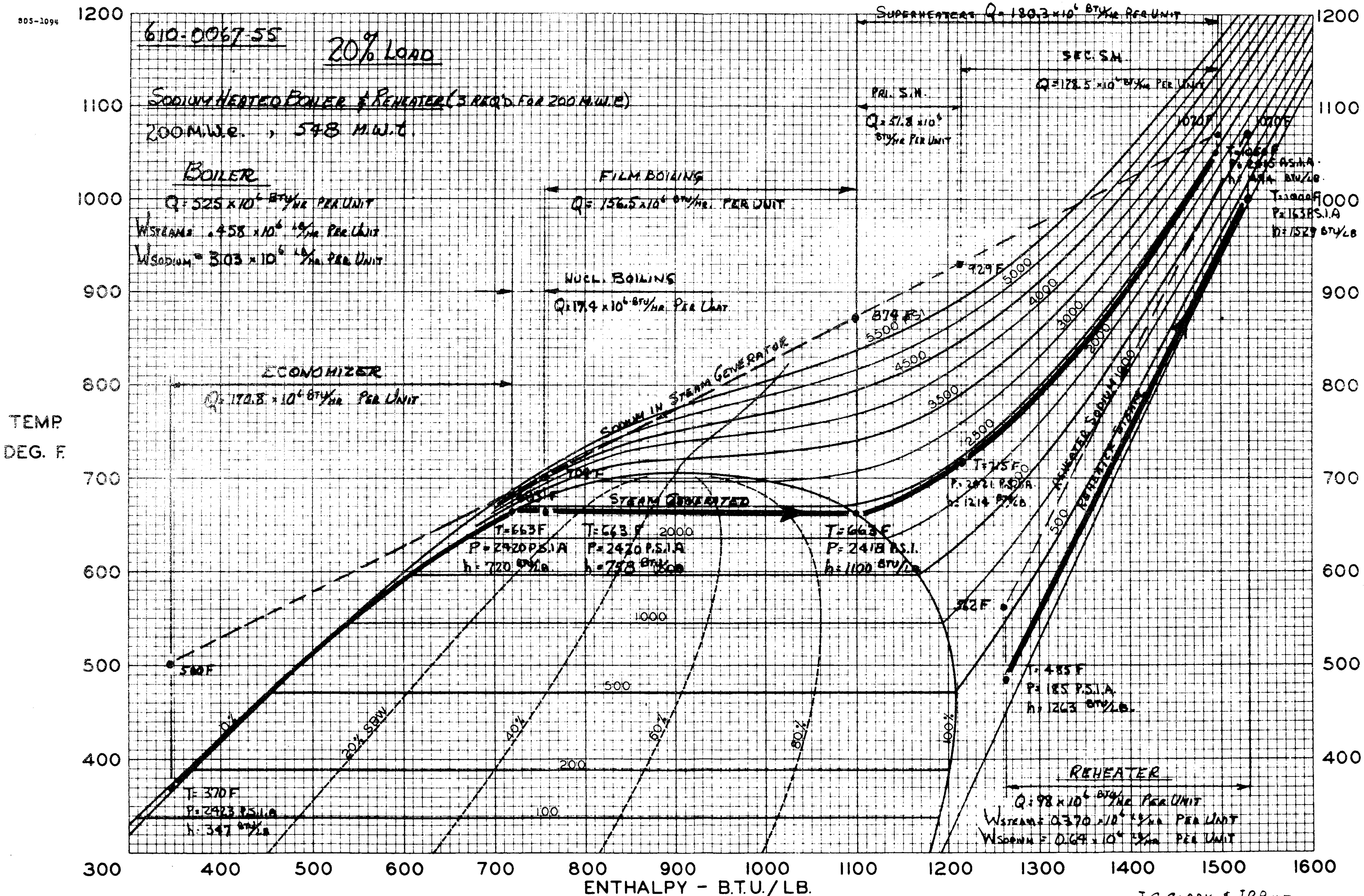

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FIGURE 17

Known Factors	Unknown Factors
T_6	T_5
t_6	t_5
W steam	W_{na}
$A = 10,230\ ft^2$ Sec. S.H. Surface	Q Sec. S.H.
h_6	h_5

The unknown factors are calculated as follows for the secondary Superheater for each load:

A. Assume a sodium flow (W_{na}) and several sodium outlet temperatures (T_5). Using this assumed sodium flow, (W_{na}), calculate heat transfer from sodium side (Q_{na}) for each sodium outlet temperature (T_5), based on Sodium heat balance.

$$Q_{na} = W_{na}\ Cp_{na}\ (T_6 - T_5)$$

$$Q_{na} = Q\ steam$$

B. Also for each sodium outlet temperature assumed (T_5), calculate steam side heat transfer based on surface area where steam enthalpy change is due to heat transferred from the sodium side.

a. $Q\ steam = W\ steam\ (\Delta h\ steam)$

b. $h_5 = h_6 - \dfrac{Q\ steam}{W\ steam}$

c. Determine t_5 from steam tables based on h_5.

d. Calculate over-all heat transfer coefficients based on known steam flow, assumed sodium flow, and resulting temperatures.

e. $\Delta Tm = \dfrac{(T_5 - t_5) - (T_6 - t_6)}{\ln \dfrac{(T_5 - t_5)}{(T_6 - t_6)}}$

f. Using over-all heat transfer coefficients (U_o) and ΔTm as determined in steps (d) and (e) above, and known superheater area (10,230 ft^2) calculate,

$$Q = U_o \, A \, \Delta Tm$$

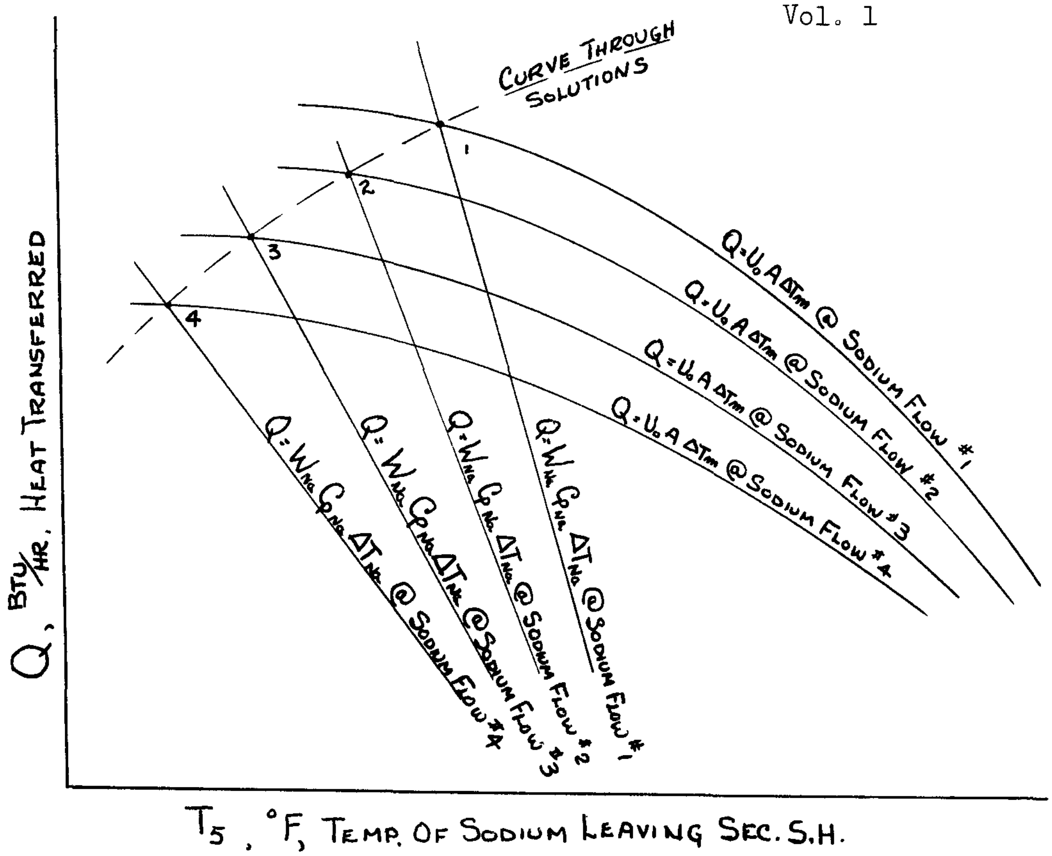
C. For the assumed sodium flow (W_{na}) and the assumed sodium outlet temperatures (T_5's) prepare a graph plotting heat transferred versus sodium outlet temperature. Two curves will be produced, one for:

$$Q_{na} = W_{na} \, Cp_{na} \, \Delta T_{na},$$

the other curve for:

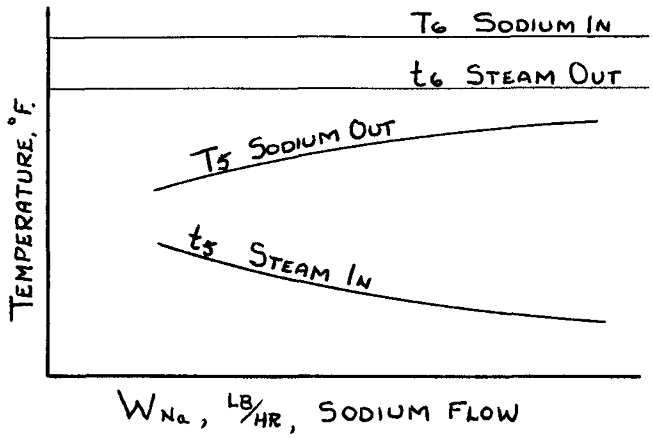
$$Q_{\,steam} = U_o \, A \, \Delta Tm$$

A graphical solution will be obtained at the intersection of these two curves. At this intersection heat transferred and sodium outlet temperature will be common to both sodium side and also steam side for the assumed sodium flow. Additional sodium outlet temperatures may be assumed if necessary to extend the curves for intersection. In most cases, the solution will lie between two assumed sodium outlet temperatures.



D. Assume additional sodium flows and repeat steps A, B, and C producing a solution for each sodium flow assumed. This family of curves should produce solutions generating a smooth curve.

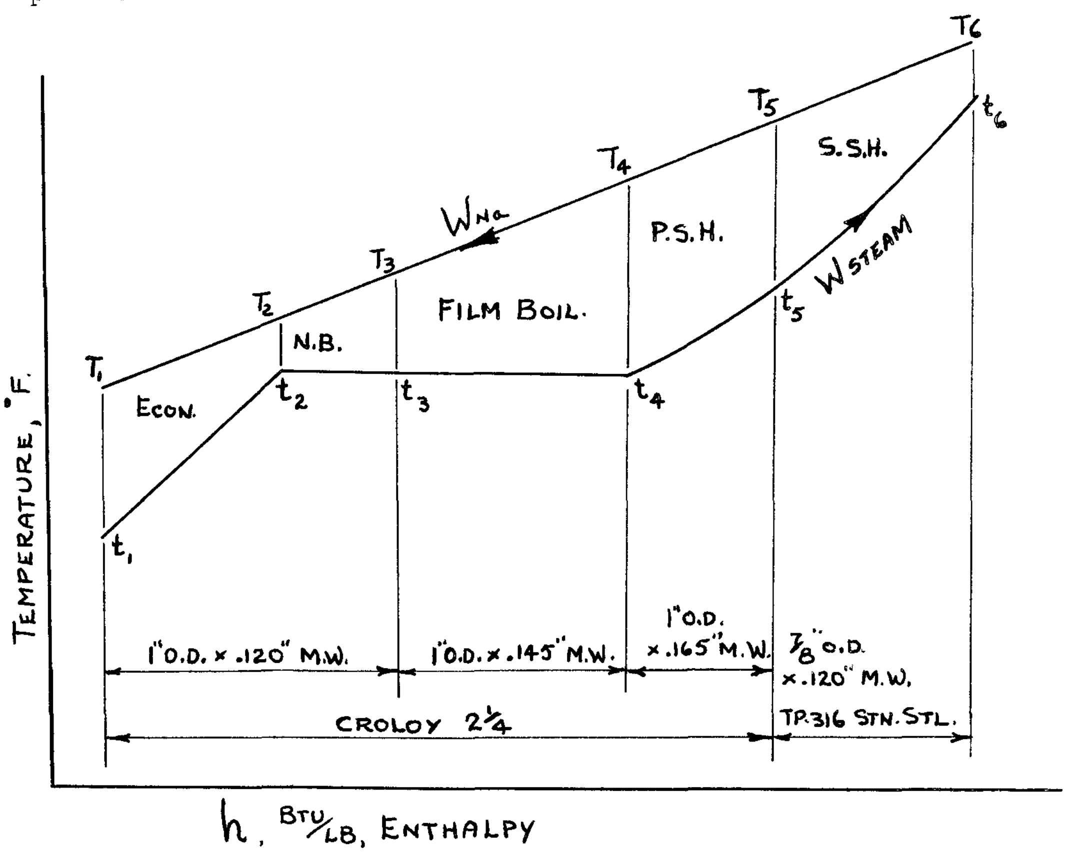
E. Having known solutions of heat transferred (Q) versus sodium temperature (T_5) leaving secondary superheater for each of the assumed sodium flow rates, determine the corresponding steam inlet temperature (t_5) by the methods in steps A and B above and prepare a graph plotting temperatures (T_5, T_6, t_5, and t_6) versus sodium flow. The steam outlet temperature (t_6) and also sodium inlet temperature (T_6) will be constant for all sodium flows. Sodium outlet temperature (T_5) and steam inlet temperature (t_5) will be as determined from the above procedure.



F. Repeat the above procedure (Steps A, B, C, D, and E) for each load.

3. Performance of Boiler Bundle

The performance of the boiler tube bundle is determined as a function of sodium flow based on the following data for part loads:



The Known Factors Are:			The Unknown Factors Are:
T_6	t_4	t_2	T_5
t_6	t_3	t_1	T_4
W steam			T_3
Q steam generator			T_2
Q econ			T_1
Q NB			W sodium
Q FB			t_5
Q S.H. (Total For P.S.H. & S.S.H.)			
Surface Areas of Each Material			

The procedure for calculation of the unknown quantities is as follows:

A - Assume a sodium flow and calculate T_1 based on heat balance.

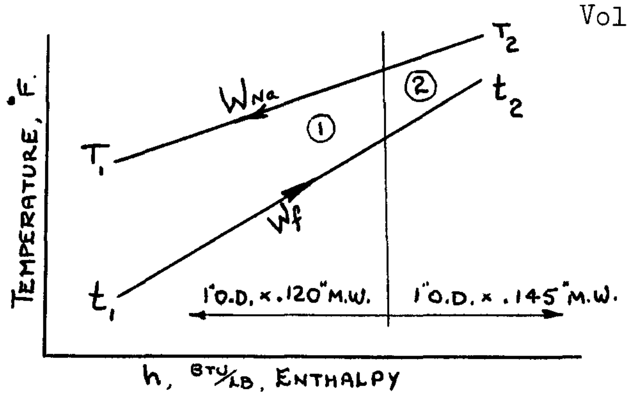
$$T_1 = T_6 - \frac{Q}{W_{na}\, C_{pna}}$$

B - Calculate over-all heat transfer coefficients based on known steam flow and assumed sodium flow. (For a quicker approximation the sodium heat transfer coefficient is considered to be constant since it has little effect on heat transfer.)

C - Knowing T_1, t_1, t_2, Q econ. W_{na}, calculate T_2 from heat balance.

D - Calculate ΔTm of Economizer.

E - Calculate surface requirements of economizer. Since a stepped tube design was used, the heat transfer coefficient changes in the economizer if the tube length required exceeded 59 ft. Two U_o's were required, depending on tube wall thickness (.120" or .145").



$$\frac{Q_{ECON.}}{\Delta T_m} = U_1A_1 + U_2A_2$$

Since A_1 is the known installed surface, solve for A_2.

If A_2 is positive, part of economizer is composed of .145" min wall tubing. If A_2 is negative, nucleate boiling starts in the .120" min wall tubing.

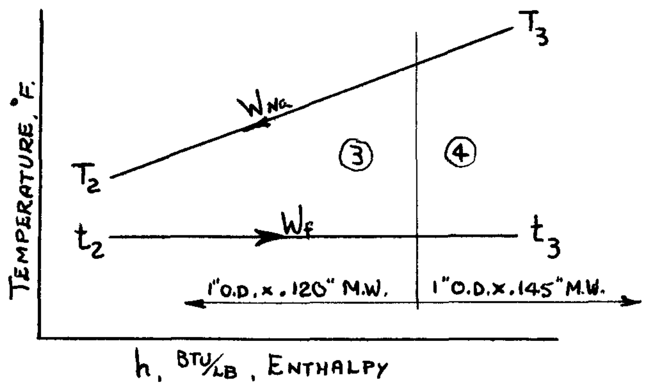
Surface requirement of the economizer is the sum of A_1 and A_2.

F - Determine length of tube required for economizer section.

G - Knowing T_2, t_2, t_3, Q_{NB}, W_{na}, Calculate T_3 from heat balance.

H - Calculate ΔTm of Nucleate Boiling section.

I - Calculate surface requirements of nucleate boiling section.



$$\frac{Q_{N.B.}}{\Delta T_m} = U_3A_3 + U_4A_4$$

Solve for A_4. A_3 is known since it is a function of economizer length.

A_3 = Total surface in 59 feet of tube minus Economizer surface required.

If A_3 is zero or negative, all nucleate boiling occurred in 1" OD x .145" MW tube.

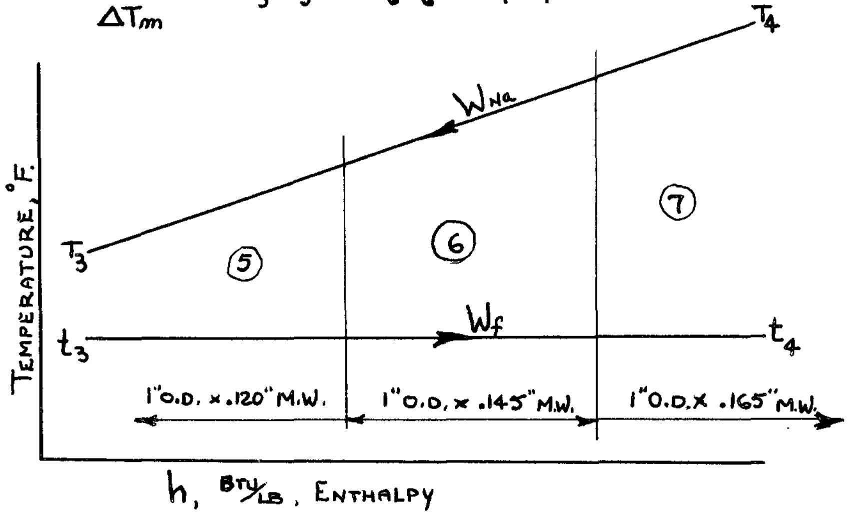
J - Calculate length of tube required for nucleate boiling section.

K - Knowing T_3, t_3, t_4, Q_{FB}, W_{na}, Calculate T_4 from heat balance.

L - Calculate ΔTm of film boiling section.

M - Calculate surface requirements of film boiling section. Since film boiling may span three tube sizes it is necessary to use the following equation:

$$\frac{Q_{F.B.}}{\Delta T_m} = U_5 A_5 + U_6 A_6 + U_7 A_7$$



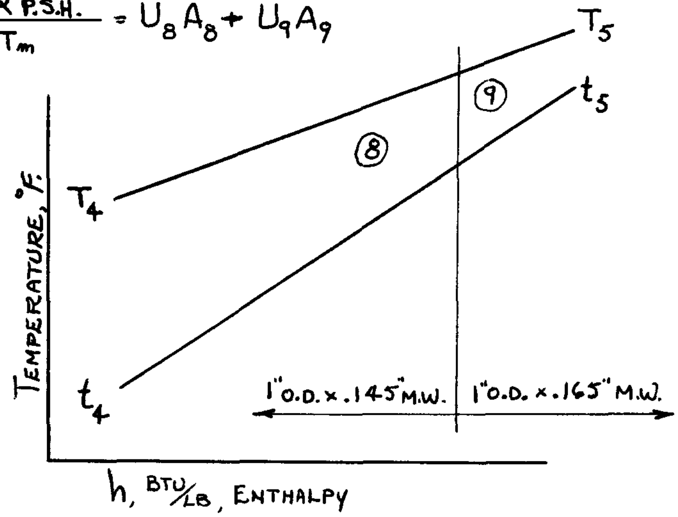
Solve for A_7. If A_7 is zero or negative, 100% steam quality is reached in the 1" OD x 0.145" MW tube.

N - Calculate length of tube required for film boiling section.

O - Calculate ΔTm of primary superheater section knowing T_4, T_5, t_4, and t_5., where T_5 and t_5 are obtained from the secondary superheater performance data (section 2 above) for the sodium flow (W_{na}) assumed.

P - Since the stainless steel superheater has a fixed area and the remaining length of 1" OD x .145" MW tubing is known, calculate length of 1" OD x .165" MW tubing required for the primary superheater section.

$$\frac{Q_{P.S.H.}}{\Delta T_m} = U_8 A_8 + U_9 A_9$$



Solve for A_9.

Q - Calculate length of 1" OD x .165" MW tube required.

R - Add tube lengths for boiler bundle. If this length equals the installed length, the sodium flow assumed is correct. If not assume two or three other flows and repeat the calculation procedure.

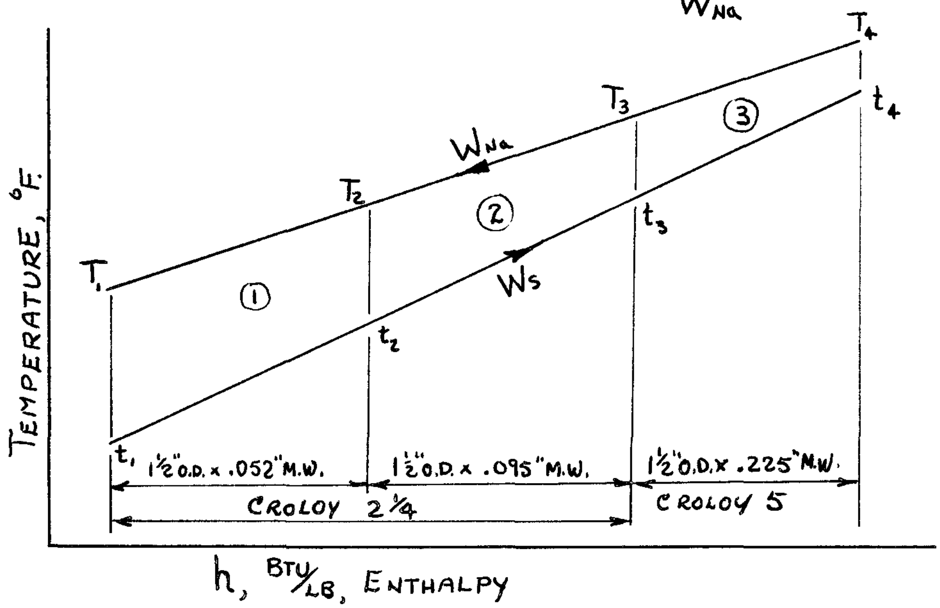
S - Establish a curve of assumed sodium flow vs. length. Correct flow will occur when the tube length is 131 ft.

7.10 Part Load Analysis - Reheater:

The determination of sodium flow to the reheater at part loads was similar to that used in the boiler. In this case there is only one tube bundle with two sizes of Croloy 2-1/4 tubes and a top section of Croloy 5 material.

The procedure for calculation follows:

Knowns	Unknowns
t_1	T_1
t_4	T_2
W_s	T_3
T_4	Q_1
A_1	Q_2
A_2	Q_3
A_3	t_2
Q total	t_3
	W_{Na}



a - Assume a sodium flow and calculate T_1 based on a heat balance.

$$T_1 = T_4 - \frac{Q}{W_{na}\, C_{pna}}$$

b - Calculate over-all heat transfer coefficients, U_o's, based on steam flow, various tube thicknesses and assumed sodium flow. (Since the sodium heat transfer coefficient has little effect on over-all heat transfer it can be assumed constant if a quicker approximation is desired).

c - Calculate ΔTm for entire reheater.

d - Calculate surface requirements of reheater.

$$\frac{Q_{TOTAL}}{\Delta T_m} = U_1A_1 + U_2A_2 + U_3A_3$$

Solve for A_3.

If A_3 is negative or zero, select another sodium flow and repeat calculations.

If A_3 is positive, calculate tube length required in zone 3.

e - Assume several sodium flows so that the calculated A_3 will bracket the actual area installed in A_3. Draw a curve of sodium flow vs. A_3.

f - Determine actual sodium flow required for the installed surface from curve. Determine T_1 from heat balance.

g - This calculation procedure must be repeated for each part load required.

8.0 START-UP SYSTEM:

8.1 Purpose:

In order to bring a once-through type steam generating system into service with either a normal start-up or a hot re-start following a turbine trip-out, an auxiliary start-up system is required. The primary purpose of the start-up system is to protect the steam generating system and the turbine from abnormal temperatures and operating conditions. The primary function of the start-up system is to provide a means, during start-up, of circulating water through the boiler section of the steam generator (but not necessarily through the superheater, turbine, or reheater), in order to establish minimum flow in the circuits to keep tube metal temperatures below the allowable limits; and to allow matching the steam temperature to the turbine nozzle block temperature before admitting steam to the turbine.

Specifically, the start-up system is to be designed to perform the following functions concurrently or sequentially as required:

(a) Provides a means for maintaining at start-up a safe minimum flow through those pressure parts made of Croloy 2-1/4 steel which might be damaged if exposed to high temperature sodium with no flow on the water side.

(b) Provides a means to establish flow through the feedwater system and clean up the water with a by-pass demineralizer while protecting the stainless steel superheater from contact with the boiler water.

(c) Provides a means, without admitting steam to the turbine, for maintaining a flow through the boiler during start-up until condensate in the non-drainable superheater and also the non-drainable reheater has been boiled out.

(d) Provides a means for discharging the steam leaving the superheater at start-up until the steam conditions are satisfactory for admission to the turbine.

(e) Provides a source of steam early in the start-up sequence for equipment such as turbine seals, deaerator, feed-water heaters, and turbine driven pumps.

(f) Recovers heat from the steam by-passing the turbine during start-up, thus saving heat and start-up time.

(g) Provides a means for maintaining during start-up the minimum flow required through boiler pressure parts exposed to high temperature sodium to keep metal temperatures within design limits.

(h) Provides a means for admitting clean, dry saturated steam at the superheater inlet for turbine warming, when the boiler is not yet producing dry steam.

(i) Provides a means for controlling and maintaining pressure in the boiler start-up, while the turbine is out of service, or while the turbine is operating at very low loads.

(j) Provides an auxiliary steam relieving capacity after start-up in the event of excessive pressure build-up in the boiler.

(k) Provides a means for matching steam temperature entering the turbine to the turbine nozzle block temperature during a hot re-start following a turbine trip-out.

(l) Prevents water from entering the stainless steel superheater during hot re-starts to protect high temperature components sensitive to thermal shock.

(m) Provides a convenient means for acid cleaning the boiler, superheater, and reheater, if desirable.

(n) Dissipate flow of energy by-passing superheater and/or turbine and reduce fluid pressure and temperature to conditions suitable for introduction to condenser and auxiliary equipment.

(o) Facilitate the maximum possible rate of water clean up during a start-up and low-load operation.

(p) Provide means for blowing steam lines.

(q) Provide a means of heating up the turbine at the prescribed rate and temperature.

(r) Facilitates heating up the steam generating system to 300 F, before filling sodium side.

8.2 General Description and Design Considerations:

The basic start-up system, as shown on Figure 18 consists of:

(a) Superheater by-pass, consisting of the "boiler start-up valves" and line connecting the boiler outlet to the flash tank ahead of the "Superheater isolation valve." This by-pass from each boiler outlet is piped to the flash tank.

(b) Turbine by-pass, consisting of the "turbine by-pass valves" and lines connecting the condenser and the main steam line ahead of the "turbine stop valves." This by-pass system is used both during start-ups and at very low loads to maintain steam flow through the superheater while steam conditions are not satisfactory for admitting into the turbine.

(c) High pressure "Superheater Isolation Valve," with a pressure reducing by-pass around it, between the boiler and the stainless steel superheater. This permits operating the boiler at high pressure while the superheater is not yet in operation.

(d) Flash tank, which serves as a receiving vessel for the by-passed fluid and separates steam and water. From the flash tank steam and water are returned to the cycle by various paths as shown on Figure 18.

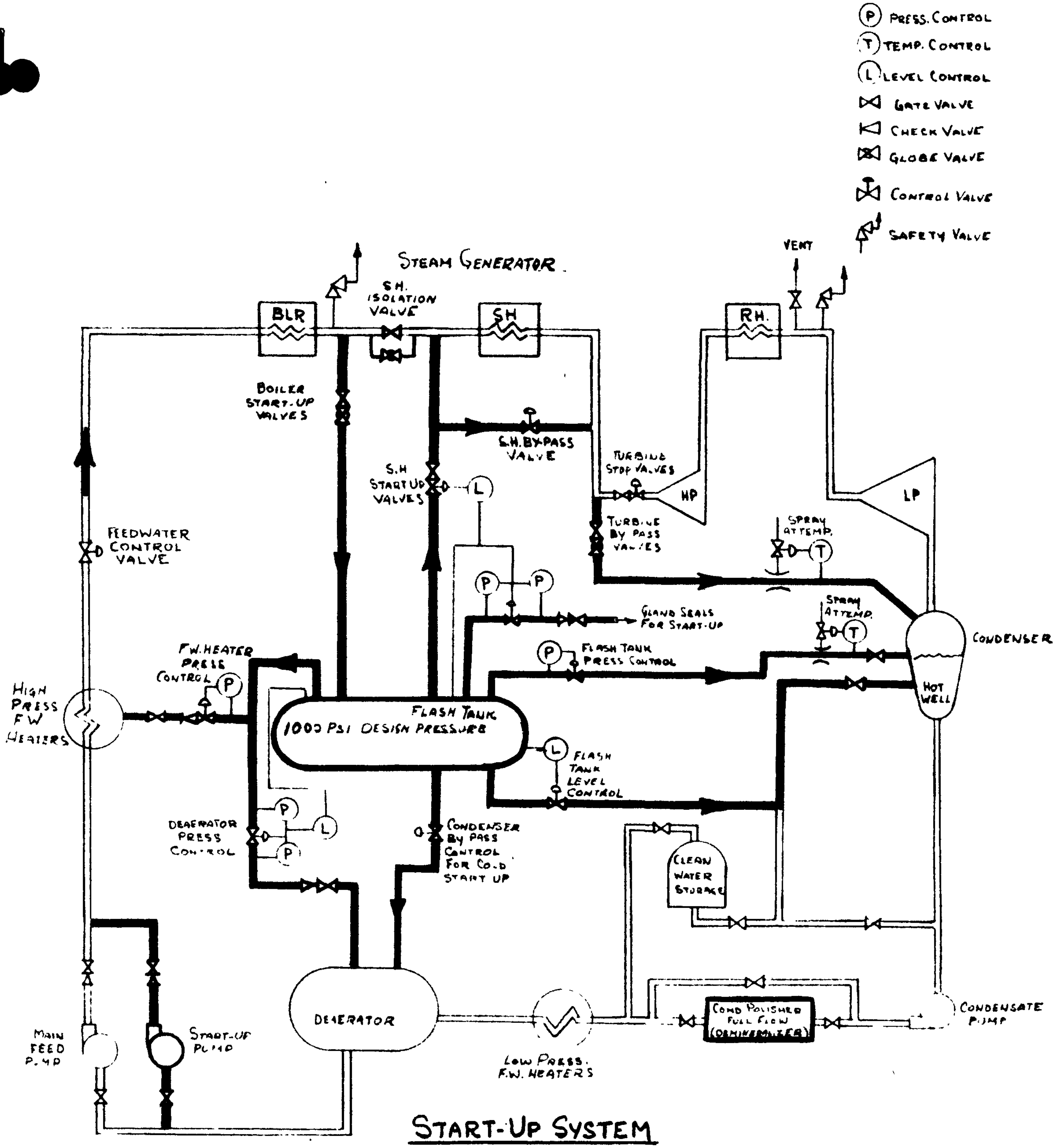
(e) Steam line with "Superheater Start-up Valves" connecting the flash tank with the stainless steel superheater inlet downstream of the "Superheater Isolation Valve." This line permits steam flow from the flash tank through the superheater for warming steam lines and heating up the turbine.

(f) "Superheater by-pass valve and lines around the secondary superheater, permits additional superheater control and is used during initial clean-up of the system.

(g) Flash tank drain line through "flash tank level control" connecting to condenser for maximum heat recovery.

(h) Flash tank drain line through "Condenser by-pass control" connecting to deaerator allows maximum heat recovery by-passing the condenser during early stages of cold start-up.

(i) Steam lines from the flash tank to the deaerator, turbine sealing system, and to the high pressure feedwater heater.



START-UP SYSTEM

for

SODIUM HEATED STEAM GENERATING SYSTEM

610-0067-55

J.P. BUTTI 5-15-64

FIGURE 18

(j) Steam line with "flash tank pressure control" connecting to the condenser. Pressure in the flash tank and start-up system is regulated through the "flash tank pressure control."

(k) Attemperators are located in the turbine by-pass line and the flash tank pressure control line to protect the steam space of the condenser from high temperatures.

(l) The remainder of the start-up system is made-up of the necessary valves, piping, and controls to allow the system to function properly.

(m) One start-up system, interconnected with piping, serves the three steam generating circuits.

(n) Motor-driven start-up pump provides circulation while turbine-driven feed pump is not yet in operation.

8.3 Start-up Sequence:

The following section consists of a "preliminary draft" of start-up sequences for normal "cold" start-up using the start-up system. This draft is only preliminary pending limitations on the reactor and primary sodium system, and other associated components.

610-0067

(Preliminary Draft)

Start-Up Sequences

for

Sodium Heated Steam Generators

By: J. P. Butti 12-12-63

CONTENTS

NORMAL "COLD" START-UP OF FIRST STEAM GENERATOR LOOP

ASSUMPTIONS:

1. The start-up system will be used to start up the steam generator loop.

2. It is assumed that the Primary Sodium Loop (Reactor and Primary side of I.H.X. is filled to normal level with sodium circulating slowly at 300°F.

3. Maximum turbine operative load is 6 to 7% of turbine full load. (equivalent to 20% full load of one steam generator loop.)

4. The non-drainable Superheater and Reheater are to be cleaned up and boiled-out dry before operation.

5. Only one steam generator loop is being started-up in this sequence. The remaining two loops will remain inoperative and isolated from the system while the first steam generator loop is being started up.

6. The remaining two steam generator loops will be started up individually after the first steam generator loop and also the turbine are in normal operation.

7. Any temporary piping or equipment to be used for start-up is installed and ready for operation.

Step 1. INITIAL CONDITIONS

a. Sodium side of the steam generator and the reheater are clean, dry, and purged with argon gas.

b. Steam side of Boiler, S.H., and Reheater have been acid cleaned, flushed, and standing full with demineralized water unpressurized at approx. 80°F. (Steam side of Boiler, S.H., and Reheater are non-drainable.)

c. Adequate clean water (condensate or demineralized) should be available in hot well storage and in clean water storage.

d. Flash tank, deaerator, and connecting piping are cleaned, flushed, and filled with demineralized water.

e. Set points on all automatic controls are properly adjusted.

f. All remote controls and instrumentation checked and in operating condition.

g. All equipment cleaned for operation and circuit breakers in operating position.

h. Primary Sodium loop (Reactor and primary side of I.H.X.) is already filled to normal level with Sodium circulating slowly at 300°F.

Step 2. INITIAL CIRCULATION OF WATER FOR CLEAN-UP IN BOILER

a. Adjust valves so that flow cycle will be as shown in Fig. 1. Flow path will be through start-up pump, high pressure F.W. heaters, boiler tube bundle, boiler start-up valve, flash tank, flash tank level control line, hot well of condenser, condensate pump, demineralizer, low pressure F.W. heaters, and deaerator.

b. Start motor driven start-up pump following Manufacturers instructions with flow control at minimum setting.

c. Increase flow rate to maximum available until one complete system volume has been circulated.

d. Decrease flow rate to minimum setting.

e. The water temperature will begin to rise from heat input of the pump and should be kept below 150°F entering the demineralizer so as not to overheat the resins in the demineralizer.

Step 3. INITIAL CIRCULATION OF WATER FOR CLEAN-UP IN SUPERHEATER

a. Check to be sure that turbine stop valves are closed.

b. Adjust valves so that flow cycle will be as shown in Fig. 2. Flow path will be through start-up pump, high pressure F.W. heaters, boiler tube bundle, S.H. isolation valve, superheater tube bundle, turbine by-pass valve, condenser, condensate pump, demineralizer, low pressure F.W. heaters, and deaerator.

c. Increase flow rate to maximum available until one complete system volume has been circulated.

d. Decrease flow rate to minimum setting.

e. Water temperature entering the demineralizer should be kept below 150°F.

Step 4. INITIAL CIRCULATION OF WATER FOR CLEAN-UP IN REHEATER

a. Using temporary lines, adjust valves so that flow cycle will be as shown in Fig. 3. Flow path will be through start-up pump, high pressure F.W.

heaters, boiler tube bundle, S.H. isolation valve, superheater tube bundle, temporary line to reheater, reheater, temporary line from reheater, boiler start-up line into flash tank, flash tank level control line, hot well of condenser, condensate pump, demineralizer, low pressure F.W. heaters, and deaerator.

b. Increase flow rate to maximum available until one complete system volume has been circulated.

c. Decrease flow rate to minimum.

d. Increase flow rate to maximum available until two complete system volumes have been circulated.

e. Decrease flow rate to 20% full load flow rate for one generator loop.

f. Water temperature entering the demineralizer should be kept below 150°F.

Step 5. FINAL CLEAN UP OF WATER IN STEAM GENERATING LOOP

a. Using start-up pump and flow path as shown in Fig. 3, continue circulation at 20% full load flow rate (step #4.e) until water is cleaned up to less than 1 p.p.m. total dissolved solids.

b. Water temperature entering the demineralizer should be kept below 150°F

NOTE:

If the second and third steam generator loops are also ready for start-up, their components may also be cleaned up at this time to less than 1 p.p.m. T.D.S., by isolating each generating loop individually and cleaning up in accordance with the above procedures before proceeding to start-up the first generator loop. If this cannot be accomplished at this stage temporary piping, pumps, and clean-up equipment will be required for cleaning up the remaining steam steam generator loops while the first generating loop is in operation.

Step 6. DEMINERALIZER BY-PASS

a. Entire system water is now cleaned up to less than 1 p.p.m. total dissolved solids. Non-drainable boiler, superheater, and reheater are full and circulation is continuing per flow cycle. Fig. 3 at flow rate of 20% full load flow rate. Water is unpressurized at approx. 100° to 150°F.

b. Open the by-pass around the demineralizer, then close the demineralizer inlet and outlet valves.

c. Normal circulation will now by-pass the demineralizer except as required in order to maintain purity of water at less than 1 p.p.m. total dissolved solids.

Step 7. PREHEATING STEAM GENERATOR, REHEATER, AND SODIUM PIPING IN PREPARATION FOR THE INTRODUCTION OF SODIUM

a. Still using temporary lines to reheater, open condenser by-pass control valve and turn-off condensate pumps.

b. Adjust values for flow cycle as shown in Fig. 4. Flow path will be through start-up pump, low pressure F.W. heaters, boiler tube bundle, S.H. isolation valve, S.H. tube bundle, temporary line to reheater, reheater, temporary line from reheater, flash tank, condenser by-pass control valve, and deaerator. Flash tank pressure control and flash tank level control will operate as required to maintain prescribed pressure and water level in the flash tank. (Circulation is by-passing the condenser, condensate pump, demineralizer, and low pressure F.W. heaters to conserve heat and allow the system water to heat-up faster.)

c. Using the start-up pump, continue circulation Cycle Fig. 4 at 20% full load flow rate for one steam generator.

d. Raise Flash Tank pressure to 67 P.S.I.A. (Saturation pressure at 300°F.)

e. Water temperature will begin to rise from heat input of motor-driven start-up pump.

f. Simultaneously, begin heating up steam generator shell, reheater shell, and Sodium piping with electric heaters at the prescribed rate while purging sodium side with argon gas.

g. Prescribed rate of heat-up for electrically heating shells and piping is to maintain temperature differential between shells and water below 100°F.

h. Continue simultaneous heat-up until steam generator shell, reheater shell, sodium piping, and also water coming out of the reheater are at 300°F.

i. Steam Generator, Reheater, and Sodium piping are now preheated to 300°F for introduction of sodium.

Step 8. FILLING SECONDARY SODIUM LOOP (STEAM GEN., REHEATER, SODIUM PIPING) WITH SODIUM

a. Continue to hold steam generator shell, reheater shell, sec. Sodium piping and water temperatures at 300°F by energizing electrical heaters and circulating water as required.

b. Flow Path will still be as shown in Fig. 4 using temporary lines to and from reheater except that now the condensate pump may be turned on and the condensate by-pass valve closed so that flow from the flash tank will be through the condenser, condensate pumps, by-passing the demineralizer, through the low pressure F.W. heaters, and to the deaerator.

c. Fill secondary sodium loop (Sodium side of Steam generator and reheater, Secondary Side of I.H.X., and Secondary Sodium piping) with 300°F Sodium to normal operating level.

d. Start secondary Sodium pump and establish sodium circulation at minimum flow rate.

e. Now Primary Sodium, Secondary Sodium, and water are all at 300°F.

Step 9. <u>HEATING UP BOILER, BOILING OUT NON-DRAINABLE SUPERHEATER AND REHEATER</u>

a. Adjust valves as required to establish flow cycle as shown in Fig. 5.

b. Reheater will boil out through vent to atmosphere.

c. Superheater will boil out venting through turbine by-pass valve to condenser.

d. Water flow from Boiler will be through flash tank to condensers.

e. Remove temporary piping which was used to preheat the reheater.

f. Establish water circulation at flow rate for 20% full load for one steam generating loop.

g. Increase sodium flow rate and establish flow rate for 20% full load through steam generator, reheater, and I.H.X.

h. Increase flash tank pressure.

i. Bring up reactor temperature at prescribed rate.

j. Turn off electric heaters for steam generator shell, reheater shell, and sodium piping.

k. Boiling will take place in the S.H. and the reheater when vented to boil out.

l. As the sodium temperature increases the boiler temperature will begin to rise, also the superheater and the reheater will continue to boil out.

m. As the sodium temperature continues to increase, a steam-water mixture will be discharged from the boiler to the flash tank, The water level in the flash tank will drop to normal and steam will be separated from the water in the flash tank.

n. As soon as steam becomes available from the flash tank, begin sealing the turbine and pulling a vacuum.

o. As soon as the turbine is sealed, additional available steam may be used to "peg" the deaerator.

p. If further steam becomes available after the deaerator is pegged, the high pressure F.W. heaters will begin to operate to help heat up the feedwater.

Step 10. <u>START UP THE SUPERHEATER</u>

a. After superheater is boiled out dry, open the S.H. start-up valve and dry steam from the flash tank will pass through the superheater and the turbine by-pass valve, to the condenser as shown in Fig. 6.

Step 11. <u>PREHEATING THE TURBINE</u>

a. After steam flow has been established from the flash tank through the supereheater and discharging to the condenser at the required pressure, temperature, and flow rate begin to preheat the turbine. (Fig. 7)

b. Turbine preheat requires 30,000 to 60,000 lb/hr. steam at 1000 PSI and 675°F for approximately 10 to 16 hours.

c. Shut off turbine by-pass as required to maintain steam flow for turbine preheat.

d. Transfer turbine seal steam from start up system to normal steam system.

e. Additional steam control may be obtained by attemperating as required through the S.H. by-pass valve.

Step 12. <u>SHUTTING OF START-UP SYSTEM</u>

a. After turbine has been sufficiently preheated and superheated steam is available from the boiler, open the small by-pass around the S.H. isolation valve and allow pressure to equalize and piping and valve to heat up.

b. Set turbine by-pass valve full open.

c. Open the S.H. isolation valve.

d. Close boiler start-up valve and S.H. start-up valve.

e. Flow Path will be as shown in Fig. 8. Superheated steam will be passing from the boiler directly to the superheater without going through the flash tank.

Step 13. ROLLING THE TURBINE

a. Allow sufficient time for flow cycle shown in Fig. 8 for stabilized flow through boiler and superheater.

b. Be sure that reheater has been boiled out dry, then close valve which rented reheater to atmosphere.

c. Open the throttle valve and roll the turbine.

d. Steam from the H.P. turbine will automatically pass through the reheater to the L.P. turbine as shown in Fig. 9.

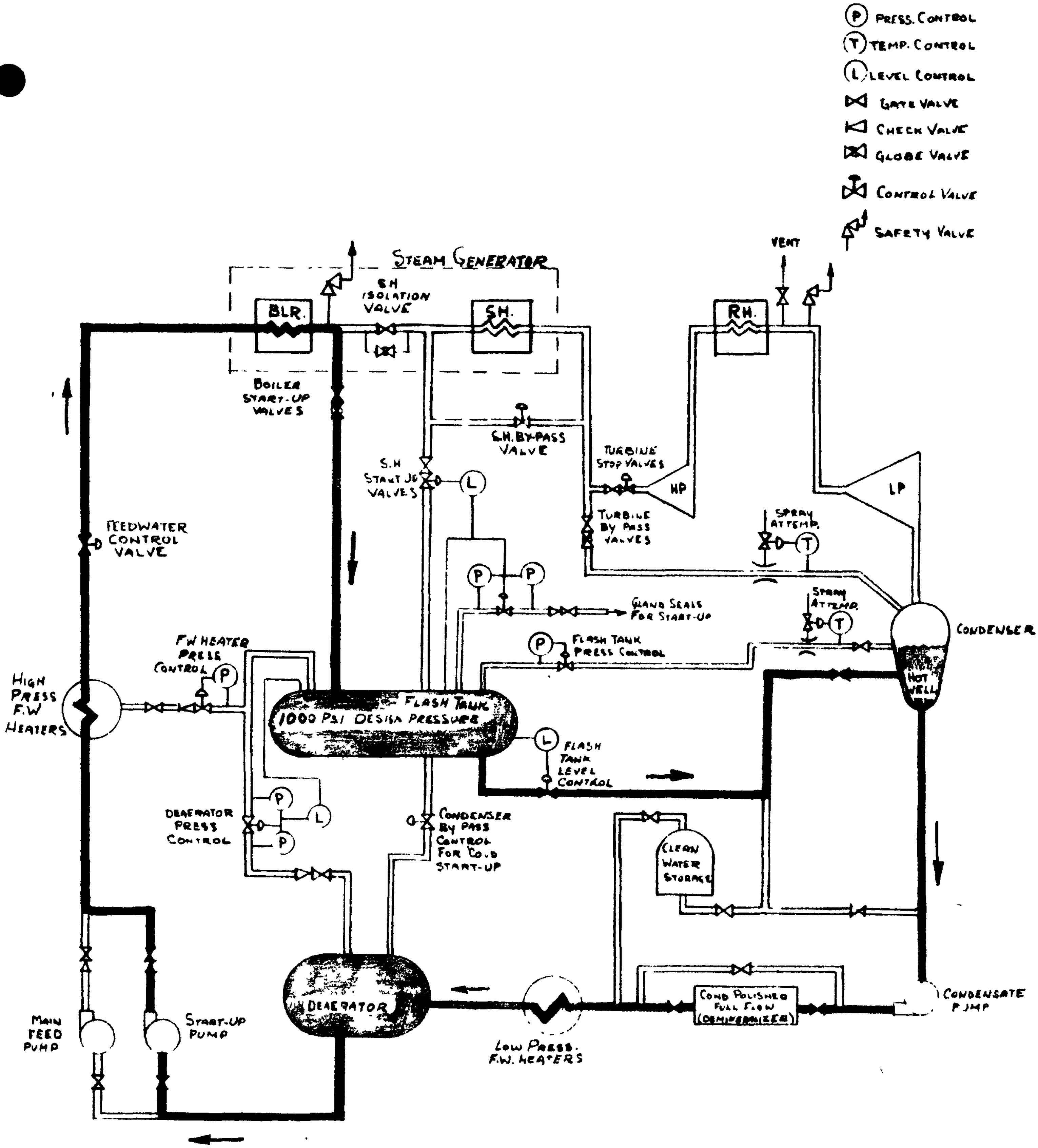
e. After flow has been established through the turbines and reheater close the turbine by-pass valve to bring the steam flow through the turbine up to 20% generator full load flow (equal to 6 to 7% turbine full load flow.)

f. Increase turbine load and synchronize.

g. Transfer feedwater pumping from start-up pump to main feed pumps.

h. Put automatic controls into operation.

i. When turbine by-pass is fully closed, flow path will be "Normal Operating Cycle" as shown in Fig. 10.



SODIUM HEATED STEAM GENERATING SYSTEM

FIG. 1

FLOW CYCLE FOR INITIAL CIRCULATION TO CLEAN-UP BOILER WATER

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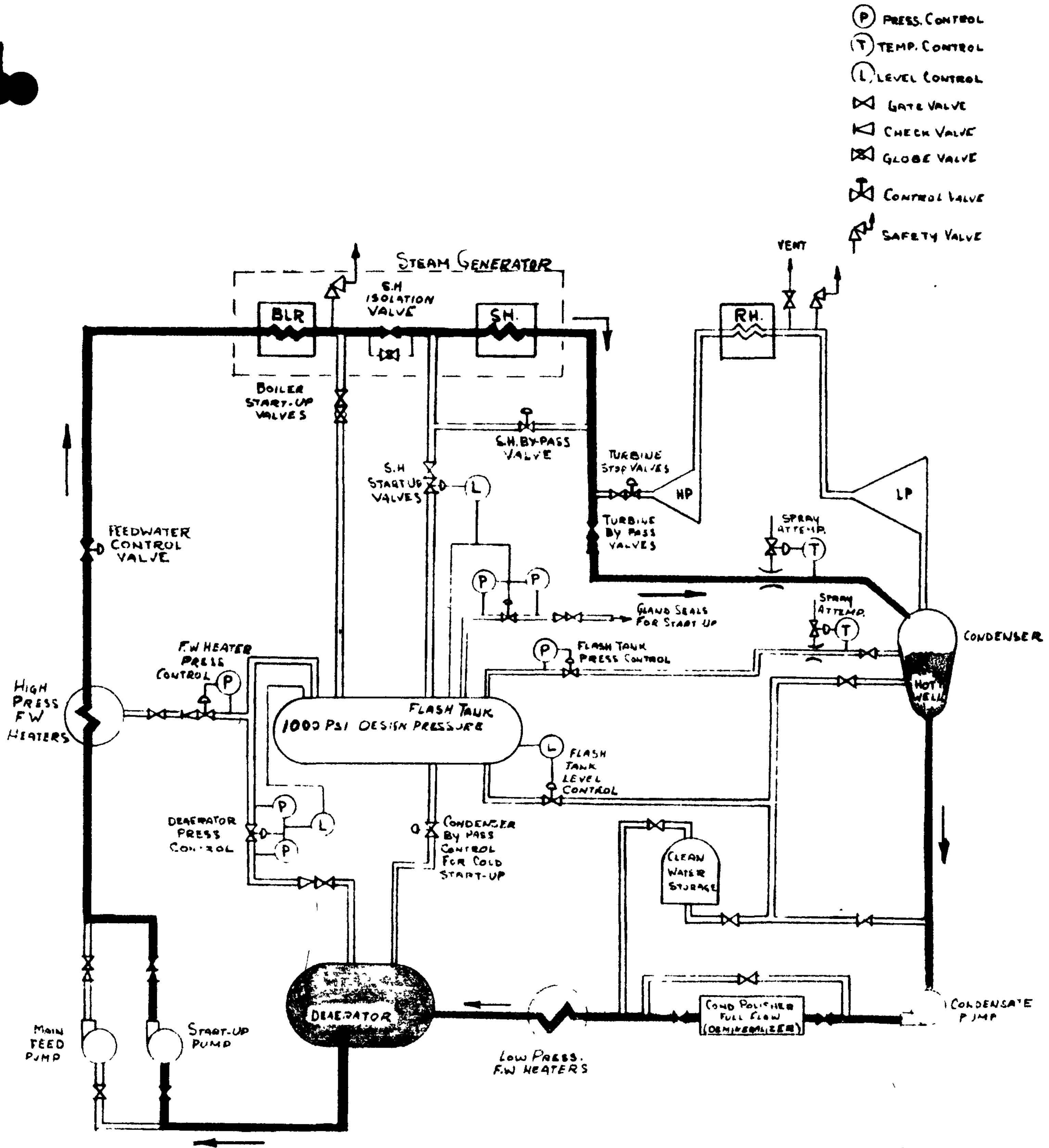

FIG. 2

SODIUM HEATED STEAM GENERATING SYSTEM

FLOW CYCLE DURING INITIAL CIRCULATION TO CLEAN-UP WATER IN NON-DRAINABLE SUPERHEATER (AFTER BOILER AND FLASH TANK WATER HAVE BEEN CLEANED-UP.)

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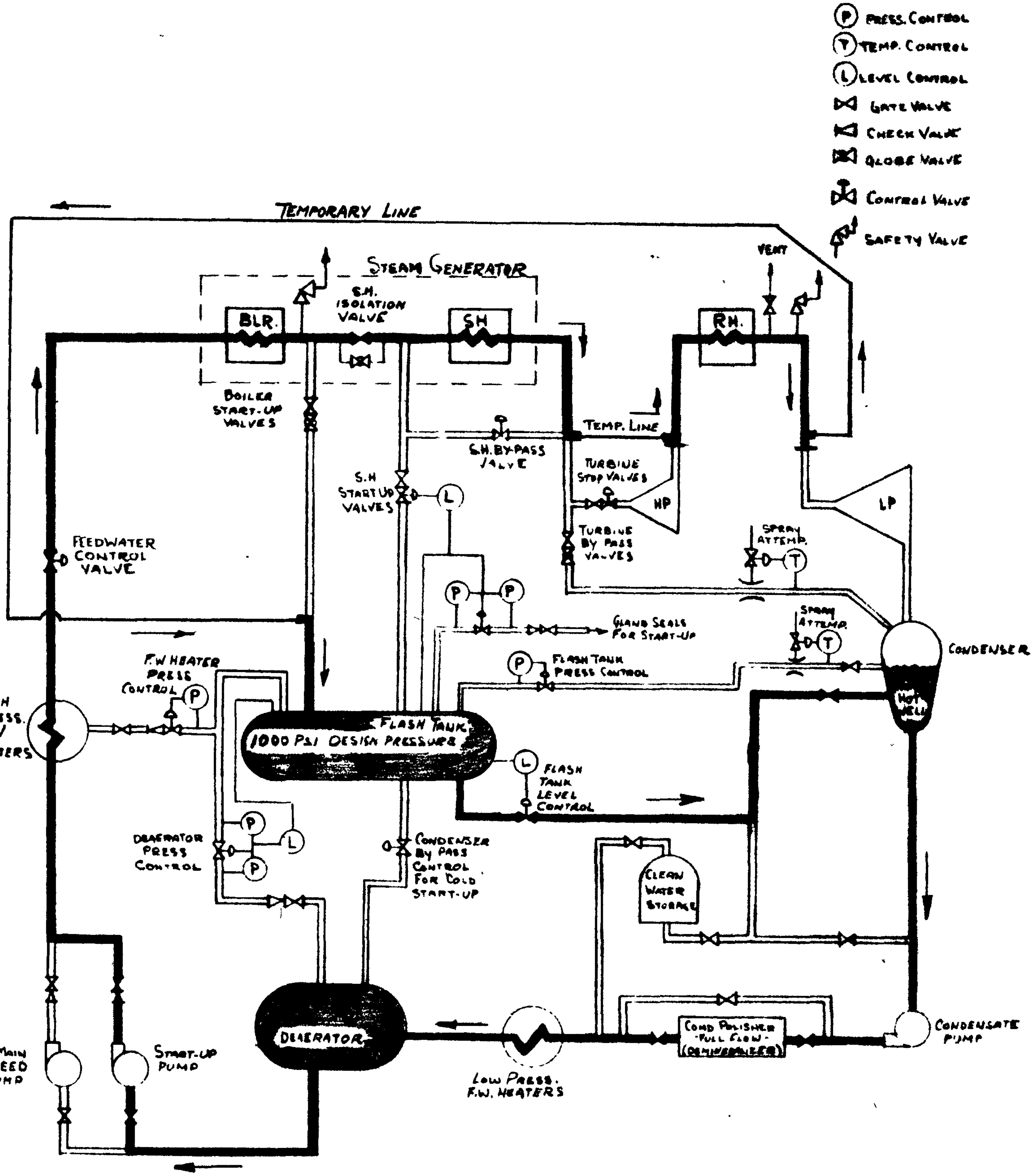

FIG. 3

SODIUM HEATED STEAM GENERATING SYSTEM

FLOW CYCLE DURING INITIAL CIRCULATION TO CLEAN-UP WATER IN NON-DRAINABLE REHEATER (AFTER BOILER, S.H., & FLASH TANK WATER HAVE BEEN CLEANED UP.)

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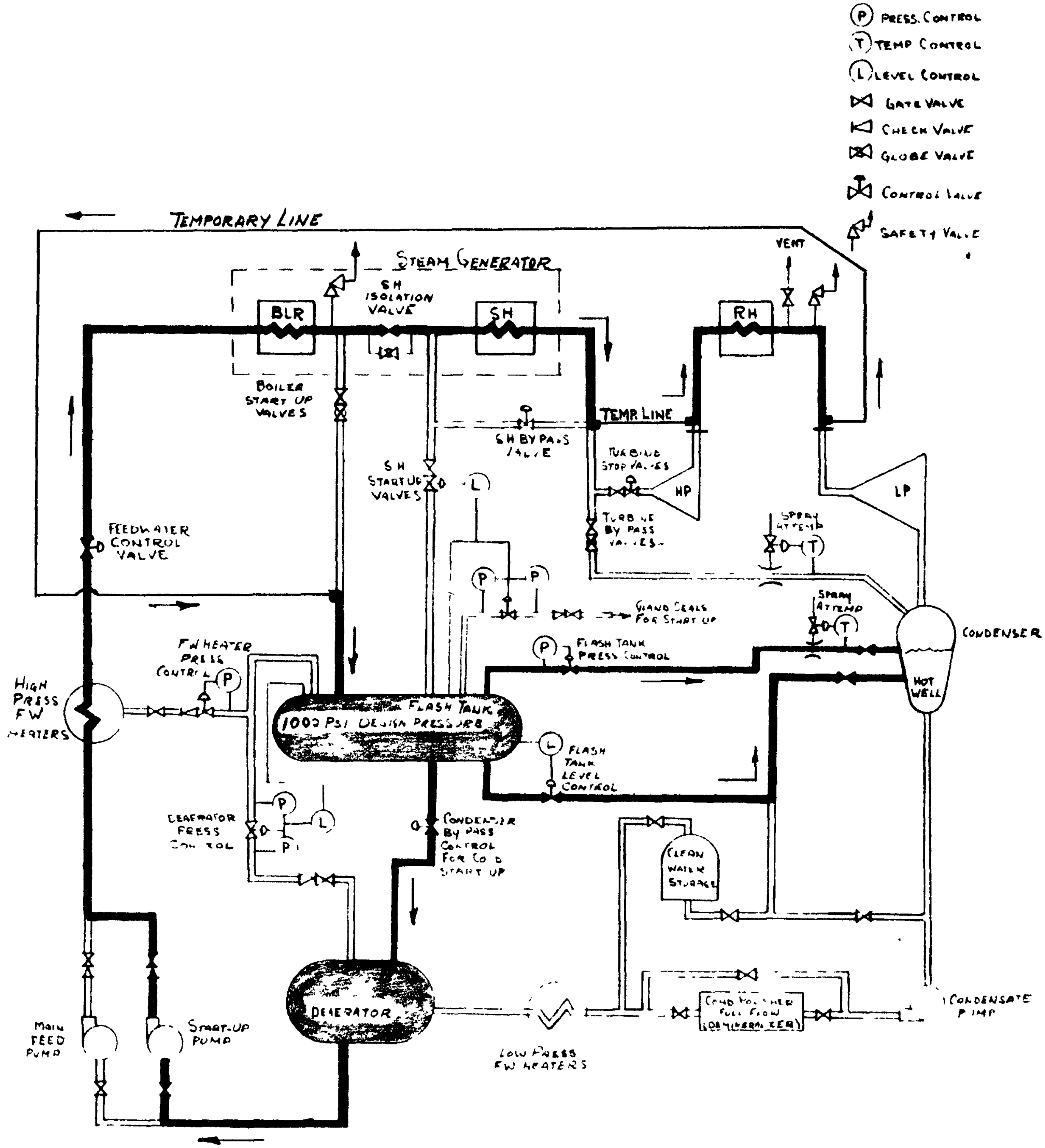

Fig. 4

SODIUM HEATED STEAM GENERATING SYSTEM

FLOW CYCLE DURING INITIAL PREHEATING OF STEAM GENERATOR AND REHEATER – IN PREPERATION FOR INTRODUCTION OF SODIUM.

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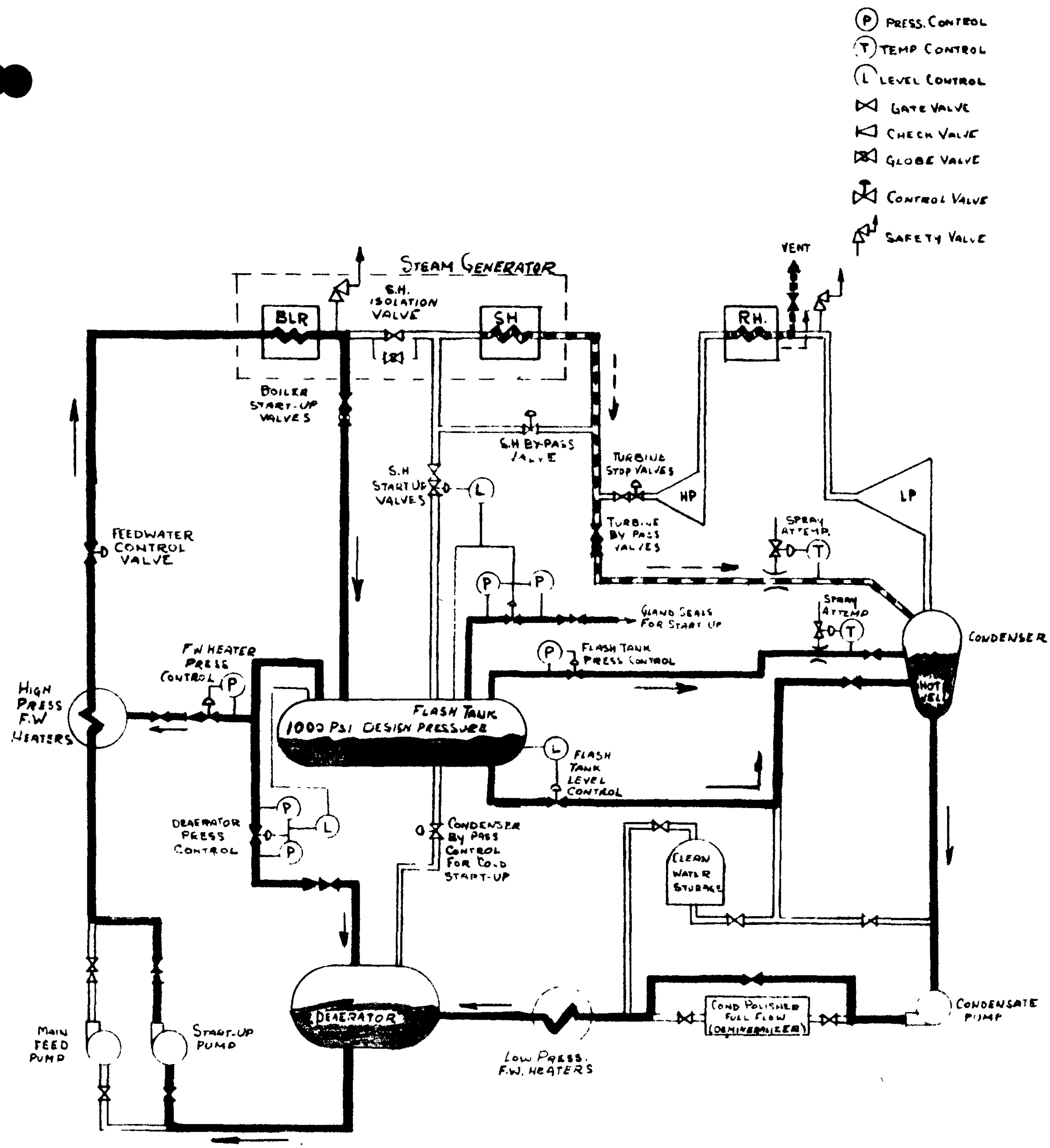

FIG. 5

SODIUM HEATED STEAM GENERATING SYSTEM

FLOW CYCLE HEATING-UP BOILER AND BOILING-OUT NON-DRAINABLE SUPERHEATER AND REHEATER.

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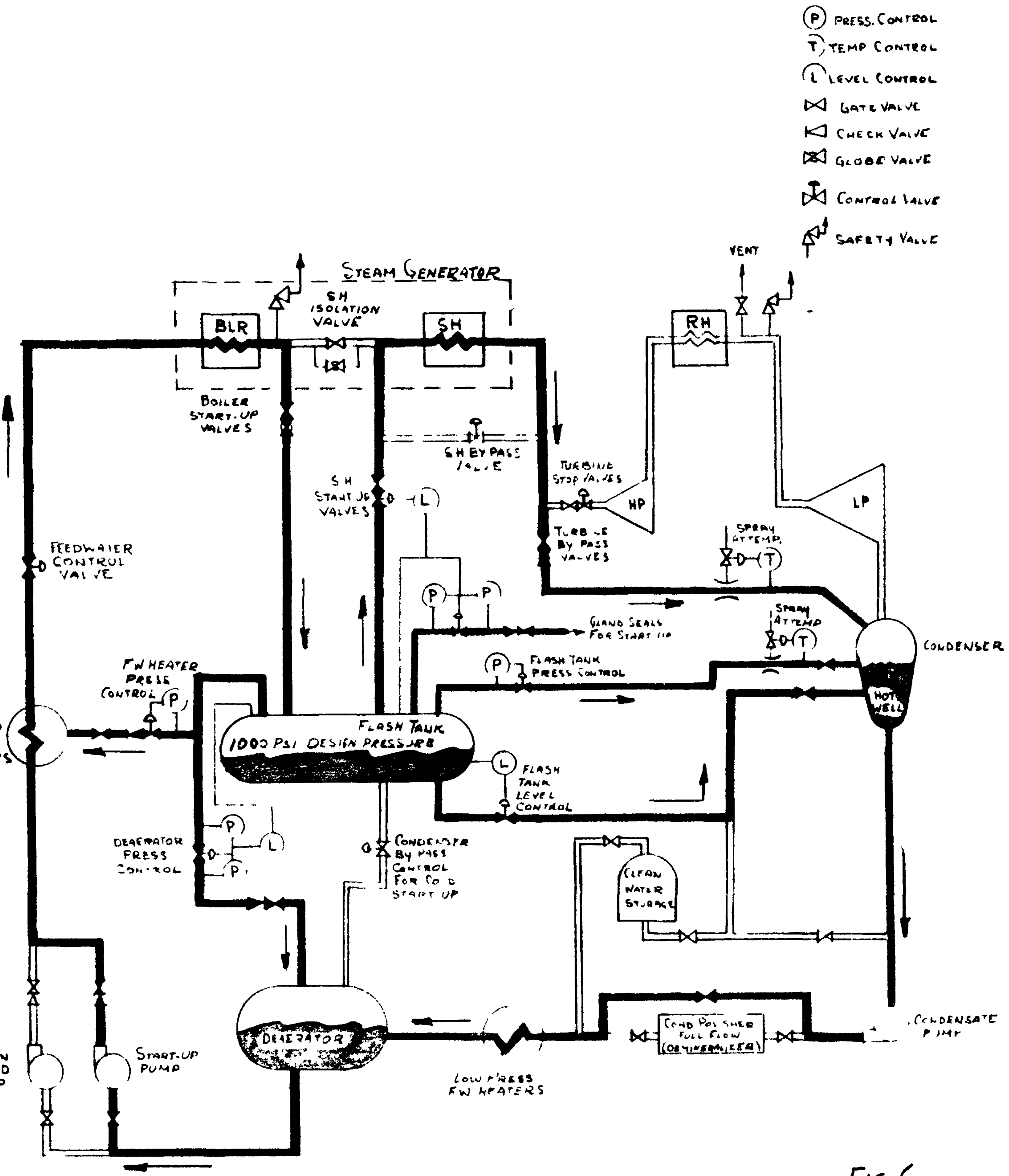

Fig. 6

SODIUM HEATED STEAM GENERATING SYSTEM

FLOW DURING HEAT-UP CYCLE AFTER SUPERHEATER & REHEATER HAVE BOILED OUT. DRY STEAM FROM FLASH TANK IS PASSING THROUGH SUPERHEATER.

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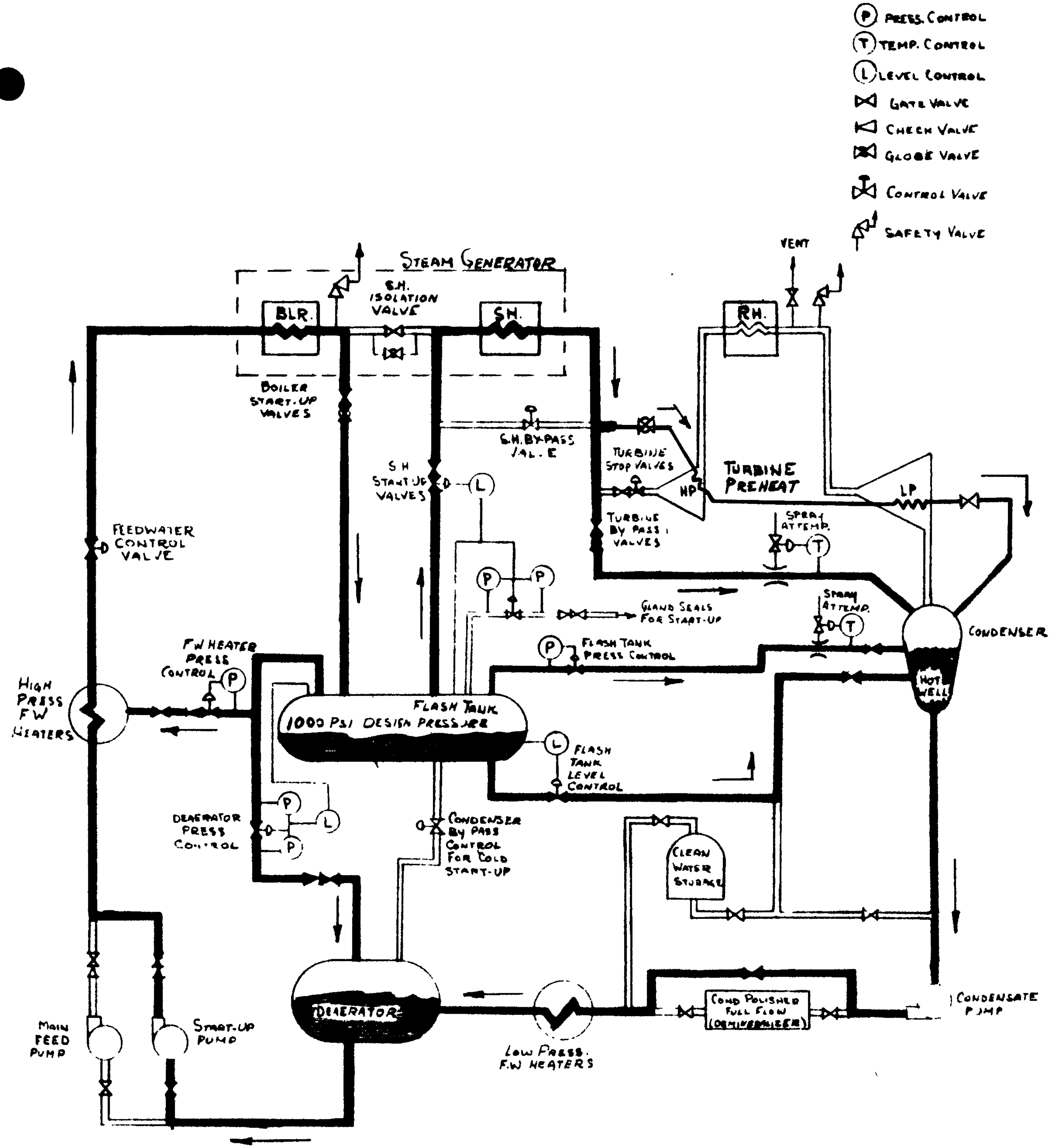

SODIUM HEATED STEAM GENERATING SYSTEM

FIG. 7

FLOW CYCLE DURING TURBINE PREHEAT. GLAND SEAL STEAM TRANSFERRED FROM FLASH TANK TO NORMAL SYSTEM.

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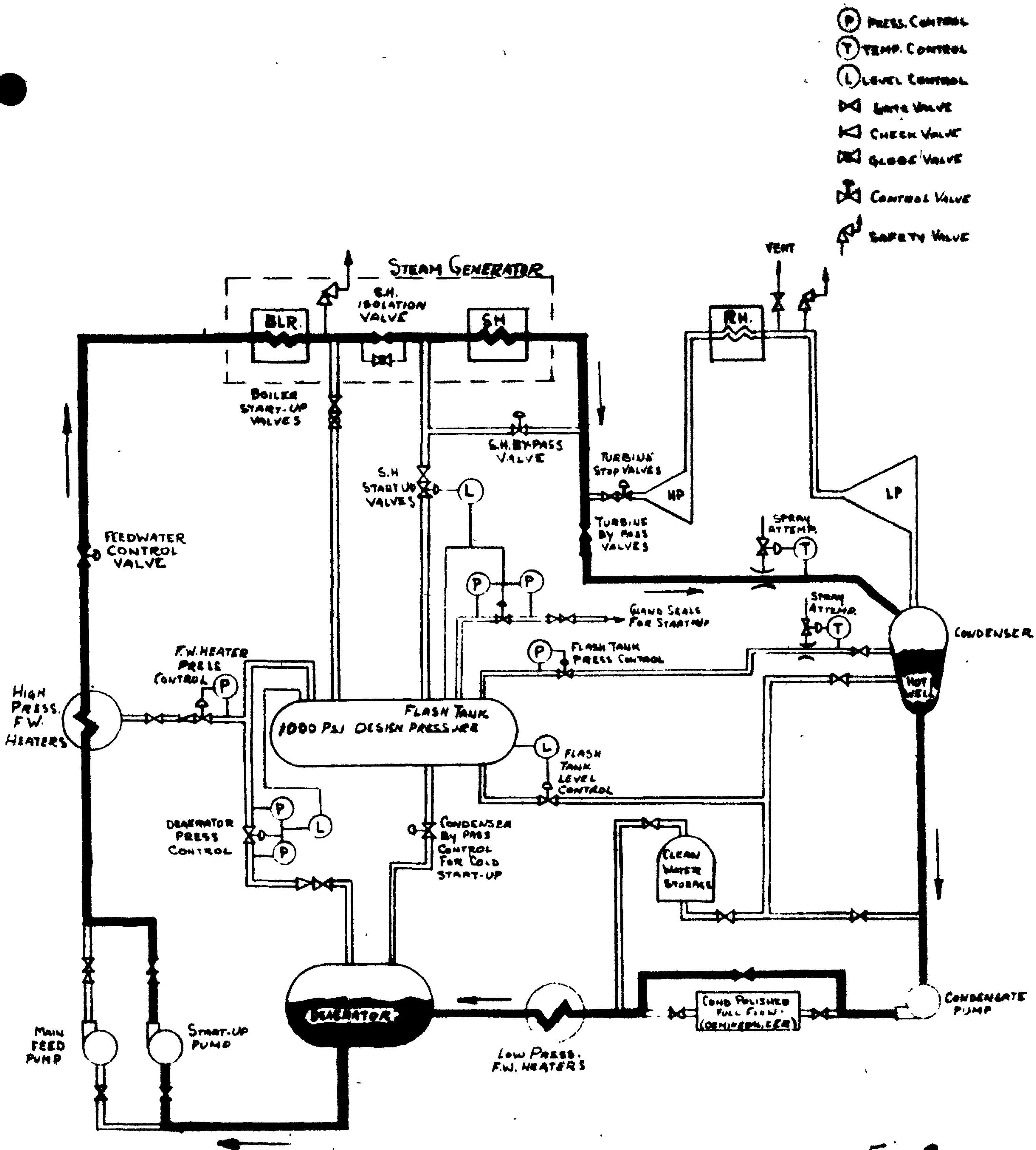

FIG. 6

SODIUM HEATED STEAM GENERATING SYSTEM

START-UP SYSTEM CUT OUT, AFTER TURBINE HAS BEEN PREHEATED. GLAND SEALS ON NORMAL STEAM SYSTEM.

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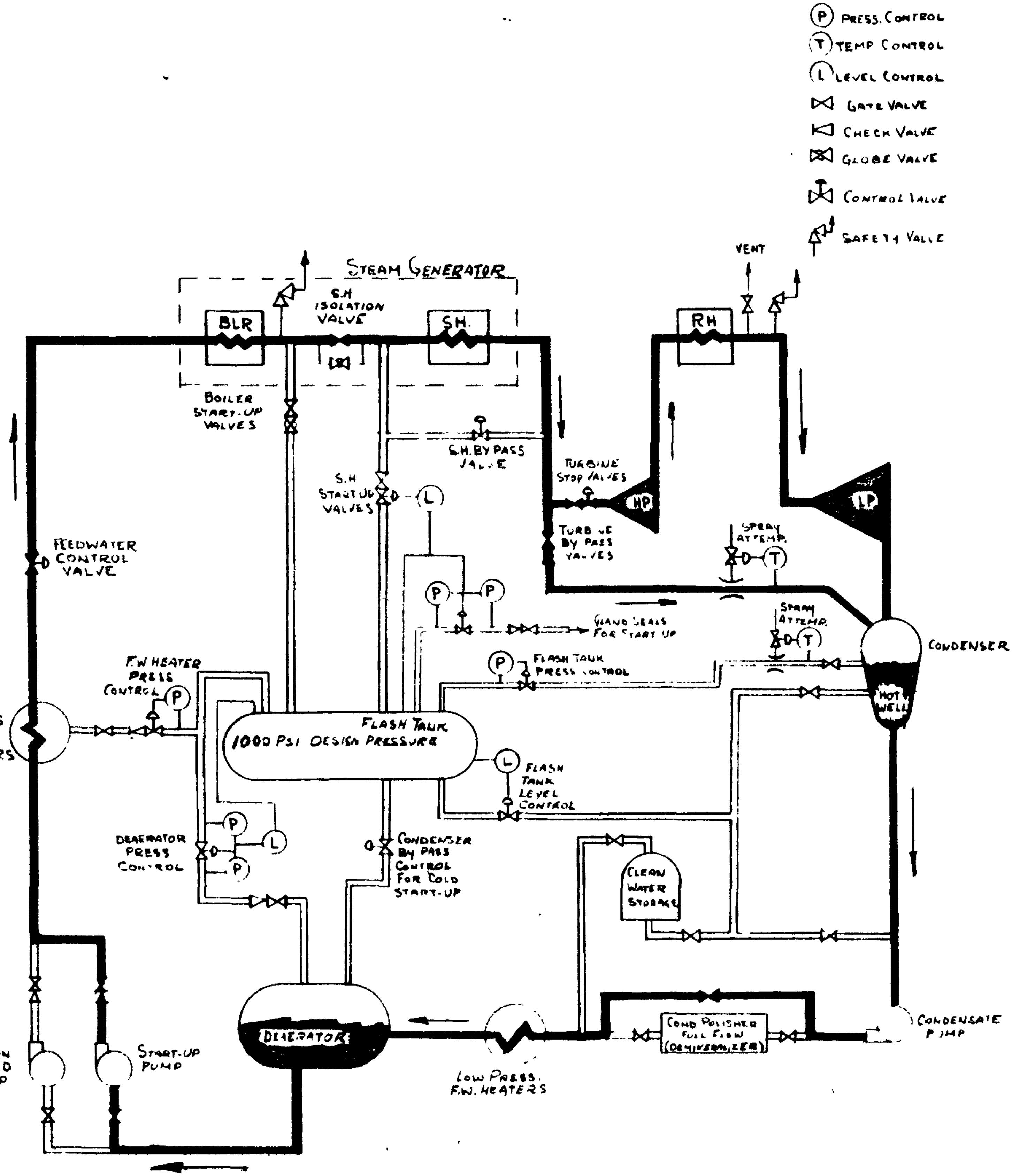

FIG. 9

SODIUM HEATED STEAM GENERATING SYSTEM

ROLLING THE TURBINE

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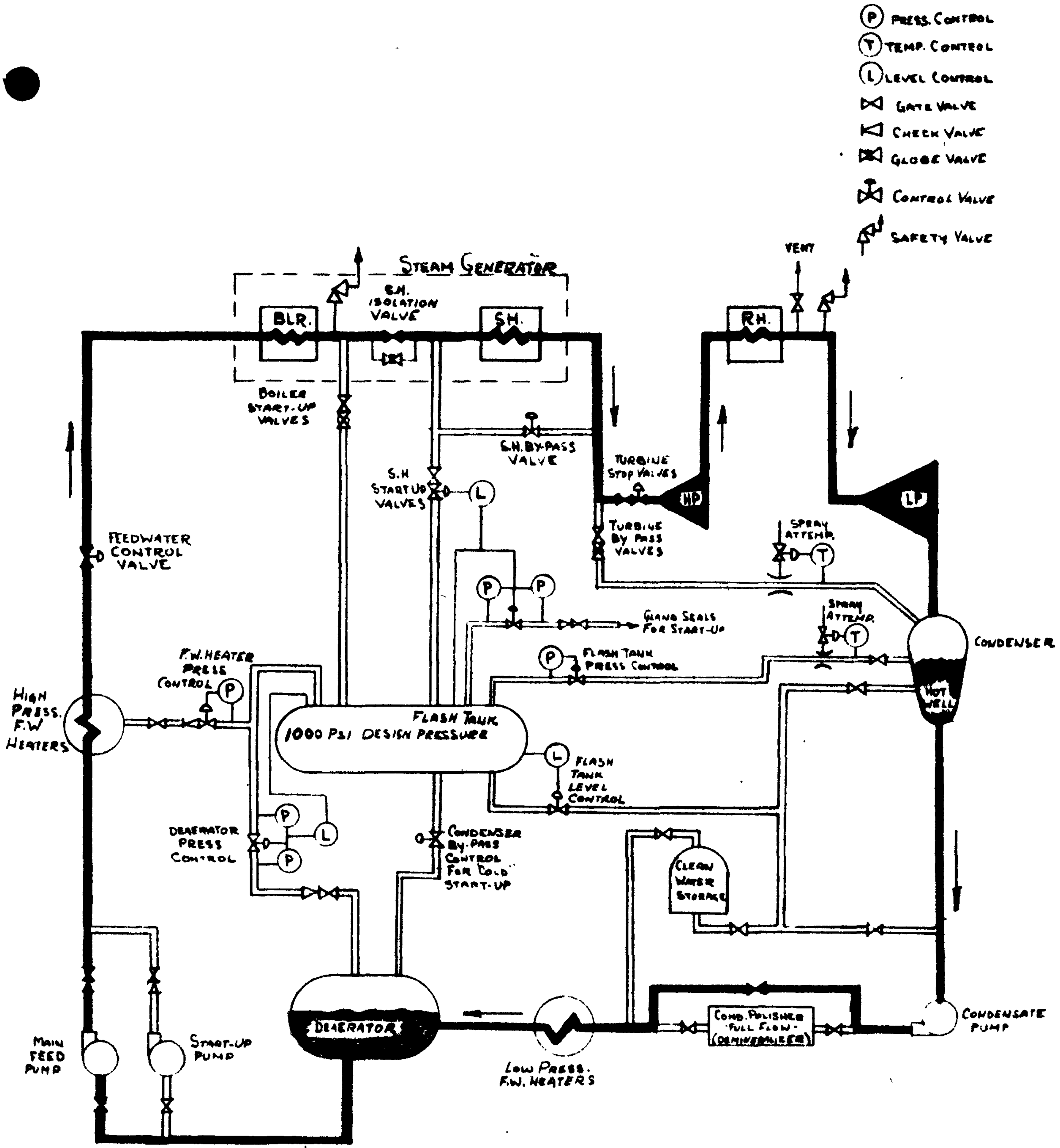

SODIUM HEATED STEAM GENERATING SYSTEM

FIG. 10

NORMAL OPERATING CYCLE

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NORMAL "COLD" START-UP OF

SECOND STEAM GENERATING LOOP

Note: This sequence is written to cover the basic philosophies only for getting a second or third steam generating loop on the line after the first loop is at normal operation.

The details such as piping, valves, temperatures, flows, etc. are to be developed after the basic philosophies are agreed to be acceptable to all concerned.

INITIAL CONDITIONS & ASSUMPTIONS

a. For illustrative purposes, we will assume that steam generating loop #1 is in normal operation and loop #2 is to be started up.

b. The turbine is operating at 1/3 full load from steam supplied by loop #1. Loop #1 is operating at its 100% full load. (F.W. Temp. = approx. 370°F)

c. Loop #2 steam side has been acid cleaned, flushed, and non-drainable boiler tube bundle #2, superheater tube bundle #2, and reheater tube bundle #2 are standing full with clean water at room temperature of approx. 80° to 100°F.

d. Secondary sodium loop #2 (Steam generator, reheater, secondary side of I.H.X. and secondary sodium piping) is clean, dry and purged with argon gas.

e. Primary sodium loop #2 is full to normal operating level with sodium circulating at minimum flow rate.

f. Sodium in primary loop #2 is at reactor outlet temperature and no heat is being removed at the I.H.X.

g. Water side of non-drainable superheater #2 and reheater #2 need to be boiled out dry before steam generator loop #2 goes into operation.

h. Secondary sodium loop #2 (including Steam Gen. #2, reheater #2, and sodium piping) to be preheated to at least 300°F prior to filling with sodium.

i. After filling, sodium in secondary sodium loop #2 will be circulated through steam generator, reheater and by-pass the I.H.X. while being heated up with external heaters to temperature suitable (approx. 650° to 700°F) for admitting into secondary side of I.H.X.

Step 1. FINAL CLEAN-UP OF WATER SIDE OF STEAM GENERATING LOOP #2

a. Slowly admit boiler feedwater 370°F to steam generator #2, routing through boiler tube bundle #2, pressure reducing station, into flash tank, out of flash tank through superheater tube bundle #2, through turbine by-pass line to condenser at prescribed heat up rate.

b. Simultaneously with (a) slowly admit steam (approx. 500°F) from outlet side of H.P. turbine through reheater tube bundle #2, through temporary line to turbine by-pass and condenser at prescribed heat-up rate.

c. Simultaneously with (a) and (b) turn on electric heaters to heat up shell of steam generator #2 and reheater shell #2 and also secondary sodium piping at prescribed rate.

d. Simultaneously adjust turbine load to suit because steam from loop #1 is being extracted to heat up loop #2, and loop #1 is already operating at its full load.

e. Use full flow demineralizer as required to clean up circulated water to less than 1 p.p.m. T.D.S.

f. Adjust water flow and electric heaters to #2 generating loop to maintain no more than 100°F temperature difference between metal temperature and water temperature.

Step 2. HEAT UP, BOIL-OUT, AND FILL WITH SODIUM

a. As the temperature rises in steam generating loop #2, the water will boil out of the non-drainable reheater and be replaced with steam. Also the non-drainable superheater will be boiled out to the condenser and the superheater will be filled with dry steam from the flash tank.

b. At some pre-determined temperature for steam generating loop #2 (say, approx. 300 to 400°F) fill the sodium side to normal level with sodium which has been preheated to approx. 50°F higher than the generating loop temperature. Secondary sodium by-pass should be used to keep low temperature sodium from entering hot I.H.X. The use of the secondary sodium by-pass should protect the I.H.X. from thermal shock. Filling the sodium side of the steam generating loop with sodium at slightly higher temp. than the generating loop temperature should keep water from condensing in the tubes.

c. After filling sodium side of loop #2, start sodium circulation and apply electric heat to heat up sodium at prescribed rate.

d. Cut steam & water flow through steam generator #2 and reheater #2 to minimum and continue to heat up secondary sodium with electric heaters until sodium temperature at outlet of secondary sodium pump #2 reaches 650°F.

e. Slowly open sodium valves to admit 650°F sodium into I.H.X. #2 and close the sodium by-pass. Set sodium circulation at minimum flow and allow temperatures to stabilize.

f. After sufficient time for temperatures to stabilize, increase sodium flow rate and feedwater flow rate. Now sodium is being heated by I.H.X. #2. Shut off electric heaters.

g. Continue to heat-up until superheated steam becomes available from the boiler. Then open S.H. stop valve and close valves to flash tank. Superheater and reheater still venting to condenser through turbine by-pass.

h. Continue to heat up until steam conditions match #1 steam generating loop. Steam conditions may be matched more quickly if power on #1 loop is reduced to minimum for turbine operation.

i. After Steam conditions are matched, transfer steam outlets of superheater #2 and reheater #2 to line with #1 steam generator and adjust turbine. Then put automatic controls into operation.

9.0 SODIUM-WATER REACTION:

Introduction and Statement of Problem:

In any steam generator heated by sodium one must face the possibility of a sodium-water reaction. Designing the steam generator with double tube walls does not insure against a sodium-water reaction. (As an example, Adams, et.al, KAPL - P - 1512, describes sodium-water reactions in double tube steam generators having mercury in the annulus).

One of the objectives of this sodium-heated steam generator development contract is to develop an economical, practical, large central station steam generator. Since double tube wall construction does not insure against a sodium-water reaction and does multiply the cost of the heating surface by a factor of about four, the steam generator under this contract is being designed with a single tube wall separating the sodium and water. It is felt that, if sodium-heated steam generators are ever to be economical, ways must be found to provide adequate safety from sodium-water reaction using single tube walls.

The over-all problem of sodium-water reaction can be divided into large and small leak problems in which the hazards are quite different. In the case of a large leak of water into sodium there is a problem of relief of heat and reaction products, and the safety of nearby personnel. In the case of the small leak the problem is one of early detection and protection of the steam generator from damage. Also in the small leak problem is the concern if the small leak will become a large leak under some circumstances.

History:

Of the sodium-water reaction testing which has been done, most effort has been spent on what can be considered large leaks. Until the tube failures on December 12, 1962, at Enrico Fermi Station, very little thought had been given to the small leak problems. The Fermi tube failures shows that relieving of the reaction products, from a leak in that location at least, was no particular problem; but that severe corrosion of the tubes in a zone surrounding the initial leak had occurred.

Since the Proposal that resulted in this Contract was made before the Fermi failure had occurred the R&D projects under this Contract on sodium-water reactions originally described only investigation of a large leak. As a result of the Fermi failures the scope of work was redirected. A relatively small project was begun at B&W Alliance Research Center on corrosion of Croloy 2 1/4 material in the products of a sodium-water reaction, and a subcontract was negotiated with Atomic Power Development Associates to do an engineering analysis of sodium-water reaction problems in the B&W

Prototype Steam Generator and the Full Size Steam Generator. In addition, APDA has a contract with the Commission for R&D work, including actual leak testing, to investigate small leaks of water into sodium. Atomics International has a contract with ESADA for investigating large leaks of water into sodium in a modular type steam generator.

To proceed with the Preliminary Design of the Full Size Steam Generator before the R&D work is completed it is necessary to make what are felt to be conservative assumptions with regard to relieving the products of a sodium-water reaction.

Each Steam Generator is provided with one 4" relief valve set for 50 psi and two 20" relief diaphragms. Each Reheater is provided with one 4" relief valve and with one 18" relief diaphragm. The 4" relief valves are protected from build-up of sodium or oxides in the valve by a 4" relief diaphragm between the steam generator or reheater and the relief valve. These valves are used commercially and should present no problems in this service.

Attempts were made to calculate the reaction pressure and temperature using simplifying assumptions. Steady state reaction calculations did not adequately represent the problem of an actual sodium-water reaction. Transient pressure calculations accounting for the inertia of the sodium, assumed a step change in energy input at the beginning of the reaction and resulted in an infinite calculated hydrogen bubble pressure. This only demonstrates the importance of the assumptions used in making these calculations.

The scope of work under the Sub-Contract with APDA is to do an engineering analysis of sodium-water reaction problems in the B&W Full Size and Prototype Steam Generators. The Sub-Contract was not signed early enough to complete the analysis of the Full-Size Steam Generator for this Report. The analysis of sodium-water reaction problems in the Prototype Steam Generator was begun first to have this work completed for inclusion in the Preliminary Design Report.

When the pressure-time plots have been made for leaks assumed to occur at various locations in the steam generator a dynamic shock type analysis will be made of the structural adequacy of the vessel, liner, and internal parts of the steam generator.

The analysis of the Full Size Steam Generator will be done later, but will be included in the Final Design Report on the Full Size Steam Generator.

10.0 STEAM GENERATOR CONTROL SYSTEM:

The details of the control system for the Full Size Steam Generator cannot be designed until the reactor, intermediate heat exchanger, and steam turbine characteristics are known. This section is a brief description of some of the important criteria in the control system. The Full Size plant will have three IHX's, three steam generators and three reheaters operating in parallel. There is a possibility of control instability among the three parallel loops.

When the design of the Full Size plant is being made, the control system will be designed. A simulation of the control characteristics should be made to prove out stable control of the multi-loop plant.

The control system for this steam plant is divided into two parts; a start up system and a control system for normal operation. The start up system is described in section 8.0. The control system used during the normal operation must meet the following requirements.

1. The control system must follow load changes quickly, but must be stable and not cycle or hunt after a disturbance.
2. Main steam pressure and temperature must be maintained at 2425 psi and 1050F for all loads from 20% to 100% load.
3. The reheat temperature must be held at 1000F for all loads above 20%.

10.1 Load Control:

This control scheme is an Integrated Boiler-Turbine Generator Control System as shown on Figure 19. The basic requirement of the integrated control system is the matching of megawatt generation to unit load demand, by properly coordinating the turbine throttle valve position.

The basic boiler requirements are the maintenance of balanced ratios of feedwater to steam flow, Btu input to Btu output, and reheater absorption to high pressure superheater absorption.

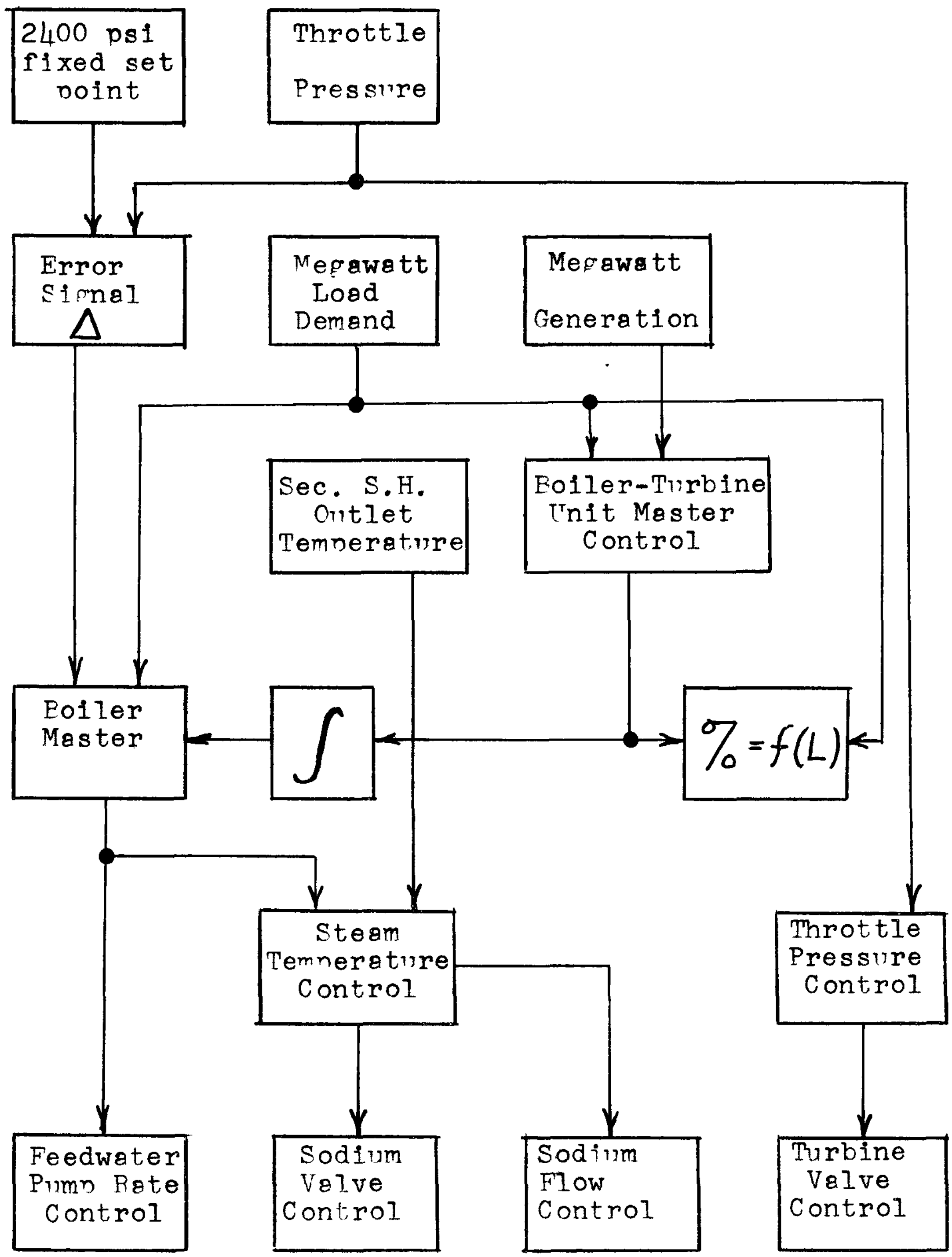
To change load on this type of system, the megawatt demand signal is given to the master boiler control and the turbine valve control, so the boiler can anticipate the change in steam flow. This same demand signal initiates a change in sodium flow in both primary and secondary sodium flow and reactor power level. The total heat flow in each loop is measured and kept in continuous balance as load is changed.

10.2 Superheat and Boiler Control:

The feedwater flow rate to the steam generator is adjusted to meet steam demand while maintaining a constant turbine throttle pressure. As an index of heat load on the steam generator, the feedwater flow and temperature and superheater outlet temperature are measured. This heat load is compared with the heat load calculated by using the sodium flow and sodium

Figure 19

Simplified Control Scheme



inlet and outlet temperatures. Sodium flow is adjusted to equalize the heat balance on each side of the steam generator, and maintain superheater outlet temperature.

The sodium flow is adjusted by two valves. One is the sodium bypass valve in the boiler. This valve bypasses the excess sodium flow in the secondary loop not required to maintain a heat balance. A sodium flow control valve is installed in the pipe to the intermediate heat exchanger to regulate the total sodium flow in the loop as a function of system load.

10.3 Reheat Control:

The function of reheat control is to maintain a constant reheat outlet temperature of 1000 F at all loads above 20%. Sodium flow is adjusted to hold the outlet temperature by means of a sodium flow control valve in the inlet sodium to the reheater. Reheater absorption is calculated using steam flow and the steam inlet and outlet temperature. The sodium flow is adjusted to balance this heat absorption from the sodium to the steam. This absorption is kept within a specific percentage of steam generator absorption by means of a ratio control.

11.0 PROBLEM AREAS AND R&D PROGRAM DIRECTED TOWARD SOLVING THESE PROBLEMS:

As design work has progressed on a full-size steam generator, a number of problem areas have been uncovered in which adequate design data is not available. These problem areas are as follows:

1. Material selection and utilization.
2. Heat Transfer -- Effect of coiling tubes on the location of the Departure from Nucleate Boiling, and the effect of this on steam generator performance.
3. Corrosion of steam generator materials in the products of a sodium-water reaction.
4. Welding of the tubes to the sodium face of the tubesheet.
5. Radiographing of these tube-to-tubesheet welds.
6. Chemical simulation of a sodium environment for shop leak testing.
7. Safe relieving of the products of a sodium-water reaction.
8. Uniform distribution of sodium over the heating surface in the steam generator, and protection of the tubes from high velocity impacting.
9. System control stability in a multi-loop plant.

Of these nine problem areas, R&D work is already in progress on seven items under this Contract. The following is a brief description of each of the problems and the R&D work being carried on to solve these problems. A more detailed description of the various R&D projects is contained in the Progress Reports and Topical Reports on this Contract.

11.1 Materials - Selection and Utilization:

Background Information

To meet the Commission objective of economical nuclear power, the steam generator must be designed to utilize inexpensive material up to its safe use limits. This makes it very important to know the use limits for each material in the environment it will see in a sodium heated steam generator, and for the 30 year design life specified in this Contract.

It is well known that mass transfer occurs in sodium systems whereby the ferritic alloys, such as Croloy 2-1/4, are decarburized and the stainless steel portions are carburized. Although considerable R&D work has been done on the mass transfer problem, it is evident that further work is required to determine if these problems will be of concern in a closed loop with the quantities of Croloy 2-1/4 and Type 316 Stainless Steel involved in this design. A related problem is what effect the composition of the materials has on their mechanical properties after mass transfer has occurred, and what design stress the steam generator designer could use to account for these modified properties.

In addition to the above problems on the sodium side, tests have shown that accelerated corrosion can occur in boiler tubes at the location of DNB under certain conditions. Under some conditions a boiler tube can fail by corrosion at the DNB point in less than twenty-four hours.

This corrosion is controlled on fossil-fuel fired boilers by careful control of water chemistry and by designing the boiler to have the DNB point occur at a zone of low heat flux. In this sodium-heated steam generator the sodium is so much better a heat transfer medium that there can be high heat fluxes with moderate temperature differences between sodium and water. With these high heat fluxes the tube metal temperature can cycle over a wide enough range at the DNB point to be of concern from thermal stress and stress-accelerated corrosion.

R&D Project

A sodium-heated model steam generator has been constructed to simulate both the problems of the sodium side and the water side of the Full-Size Steam Generator. This model steam generator is now in operation in an electrically heated test loop at B&W Alliance Research Center.

The one-tube model steam generator was designed to simulate the ratios of Croloy 2-1/4 to stainless steel surface exposed to sodium, and to model the surfaces to volume ratios of the secondary sodium system of the Full-Size Steam Generator and I.H.X. Since it is felt that temperatures and temperature gradients are important parameters in mass transfer, the model steam generator was designed to simulate the tube temperatures and temperature gradients of the Full-Size Steam Generator. The test loop is arranged so that small samples can be removed from the pipe walls at intervals during the test operation without adding any new surface exposed to the sodium. These samples will indicate the rate at which material transport is taking place, and after the completion of approximately one year of operation the model steam generator will be removed and cut up for more complete examination.

The model steam generator will have heat fluxes somewhat higher than the Full-Size Steam Generator so the water side of the model steam generator will undergo more severe duty than is expected for the full-size unit. Destructive examination of the model steam generator after the completion of the test operation will show whether there is any evidence of thermal fatigue or accelerated corrosion on the inside of the tube.

A more complete description of the scope of work under this project and present status is contained in the Progress Reports for this Contract, and in B&W Research Report No. 5452.

11.2 Heat Transfer - Effect on Heat Transfer and Two-Phase Flow of Coiling Tubes:

Background Information

In any once-through boiler, water enters subcooled and leaves as superheated steam; so somewhere in the boiler, nucleate boiling will break down and film boiling set in. The heat transfer conductance under film boiling conditions is much lower than under nucleate boiling so that, with a constant sodium temperature outside the tube, the tube wall temperature will increase sharply when film boiling begins. The DNB fluctuates up and down the tube so that a point on the tube wall will see a cycling, boiling conductance and a cycling inner wall temperature. This resulting cycling thermal stress is of concern since it may cause fatigue failures of the tube wall.

In addition to the thermal stress considerations, the amount of heat transfer surface area required for a boiler will be in error if predictions of the location of DNB and film boiling conductance are in error.

A great amount of work has been done over the past 15 years by the B&W Company and others on film boiling problems, but all of the prior work has been done on straight tubes. The boiler being designed under this Contract has helical coil tubes to make optimum use of the space.

R&D Project

Background Information

Coiled tubes simulating the inner row and outer row of the Full-Size Steam Generator was fabricated and tested in an existing test facility at B&W Alliance Research Center. These coil test sections were instrumented for measuring temperatures along the length of the test section and at six locations around the tube at each position along the tube. Voltage taps along the length of the tube were used to calculate the heat flux at each thermocouple location. The coil test sections were tested over a range of qualities, heat fluxes, and mass flows simulating the full operating range for the Full-Size Steam Generator.

The test operation has been completed and the results are reported in detail in B&W Research Report No. 4438. Very briefly, this program shows that the coiling of a tube prolongs nucleate boiling to a much higher quality than is observed for a straight tube operating under the same conditions. Film boiling begins earliest at the portion of the tube nearest the center of curvature and occurs later toward the side away from the center of curvature. The drawings for the Full-Size Steam Generator have not been corrected based on the results of this project, but the improved heat transfer because of prolonging nucleate boiling, will allow using less heat transfer surface in the steam generator and will save approximately $100,000. in the cost for a 1000 MWe plant.

11.3 Corrosion of Steam Generator Materials in Products of a Sodium-Water Reaction:

Background Information

Severe corrosion has been observed under some circumstances in the zone where a sodium-water reaction has occurred. Some of the early investigators of sodium-water reactions observed failures of test equipment by either stress corrosion or bulk transcrystalline corrosion of the test apparatus. After the tube failure and subsequent sodium-water reaction at Enrico-Fermi Station in December, 1962, severe corrosion of the steam generator tubes in the zone of sodium-water reaction was observed. Some of the tubes had lost approximately one-half of their wall thickness in a very short time.

It is felt that it is vital to know the conditions under which this extremely rapid corrosion can occur in order to set operating procedures to follow after discovery of a tube leak in a steam generator to protect the steam generator against extensive damage.

R&D Project

A small project is in progress at B&W Alliance Research Center to study the corrosion rates of Croloy 2-1/4 steel in various concentrations of aqueous sodium hydroxide at various temperatures, and various concentrations of sodium hydroxide in sodium at various temperatures, up to 1500 F. Preliminary results from this project indicate that the corrosion rate for some concentrations of aqueous sodium hydroxide would result in the amount of corrosion observed after the Fermi tube leak.

11.4 Procedure for Welding Tubes to the Sodium Face of the Tubesheet: Background Information

An expanded and seal welded tube-to-tubesheet joint can develop a crevice exposed to the sodium side. Sodium vapor will collect in this crevice. When the steam generator is shut down for maintenance, moisture laden air finding its way into the sodium side of the unit will result in a formation of a strong caustic solution concentrated in the crevice, thus presenting the classical conditions for stress corrosion of stainless steel or "caustic embrittlement" of ferritic alloys. In addition to this, if a small leak should develop in the sealed weld of an expanded and seal welded joint, the strong caustic solution will be formed similar to above and could destroy the tubesheet.

One way to eliminate the above problem is to machine a projection on the sodium face of the tubesheet at each tube and butt weld the tube to this projection.

R&D Project

One of the R&D Projects under this Contract is the development of a welding process and quality control procedures that will demonstrate a commercially feasible process for making this type of tube-to-tubesheet weld in the materials and thicknesses of the Full-Size Steam Generator.

11.5 X-Ray Inspection of Tube-To-Tubesheet Welds:

Background Information

By welding the tube to the backside of the tubesheet, it becomes possible to x-ray the weld to prove its integrity, whereas an expanded and seal welded tube-to-tubesheet joint cannot be x-rayed. The best way to radiograph these welds is to wrap the film around each tube and put a source within the tube to radiograph the whole weld at one shot. The alternate method is to take at least two angle shots from outside the tube.

R&D Project

A small project was undertaken under this Contract to look into the feasibility of constructing a radioactive source that would produce x-rays emanating from a point source. This source could be inserted within the tube and x-ray the tube-to-tubesheet weld. Vendors of radioactive sources have stated that such sources will be commercially available, and therefore no R&D work was required under this project. These sources will be purchased as required to fabricate the Prototype Steam Generator.

11.6 Chemical Simulation of Sodium Environment for Leak Testing:

Leaching out of minute slag or oxide inclusions by sodium is well known. Even though metal components are tested by ultrasonics and magnetic particle methods and found to be metallurgically sound, oxide inclusions may still be present. When hot sodium comes in contact with these oxide inclusions, the oxide leaches out leaving areas that are subjected to accelerated attack and ultimate failure.

In a previous sodium-heated boiler proposal, the Company considered shop tests whereby the boiler would be immersed in sodium at operating temperature for approximately three days to leach out any inclusions. The boiler would then be subjected to a mass spectrometer test and any leaks repaired before shipment. However, the many problems associated with handling sodium in a manufacturing facility, together with the problems of cleaning the sodium from the boiler after the test to prevent the absorption of water from the air and possible setting up of stress corrosion, make this test undesirable.

Recent studies have indicated that it may be possible to find a solution that will react in the same manner as sodium in leaching out oxide but will be easier to handle in a manufacturing facility.

The program is in progress at B&W Alliance Research Center to investigate the feasibility of several reagents that will be safe to handle in a manufacturing facility, and that can be used at temperatures not exceeding perhaps 150 to 180 F.

11.7 Sodium-Water Reaction -- Engineering Analysis:

Background Information

In any steam generator heated by sodium one must face the possibility of a sodium-water reaction. Designing the boiler with double tube walls does not insure against a sodium-water reaction. (As an example, Adams, at al, KAPL-P-1512, describes sodium-water reactions in double tube steam generators having mercury in the annulus). Since double tube wall construction does not insure against a sodium-water reaction and does multiply the cost of the heating surface by a factor of about 4, the steam generator under this Contract is being designed with a single tube wall separating the sodium and water. It is felt that if sodium-heated steam generators are ever to be economical, ways must be found to provide adequate safety from sodium-water reactions using single tube walls.

The over-all problem of sodium-water reaction can be divided into two problems:

1. Small leaks and corrosion.
2. Large leaks and relieving reaction products safely.

   Work on the problem of corrosion in the products of a sodium-water reaction is underway and is described in Section 4.3 of this report.

To design a sodium-heated steam generator which can withstand a large leak without being a hazard to personnel the designer needs to know:

1. The maximum energy release rate vs. time and position in the steam generator.
2. The split of this energy between pressure effects and temperature.

If it were possible to know these things the effect on the steam generator could be predicted by thermodynamic and hydrodynamic techniques. Neither of the two basic relations is known with any certainty at this time. The sodium-water reaction at the time of a leak is a complex one. The reaction itself is almost instantaneous so the over-all limit is the mixing of the reactants. The hydrogen formed from the reaction tends to blow the reactants apart and they may come together again some distance from the leak. The reaction is not a steady one, but is very eradic.

Basic research on sodium-water reaction is underway under other Contracts, but there are certain needs for information for this design Contract that will not be met in time for the building of the Prototype Steam Generator.

R&D Project

The purpose of this program, which is a Subcontract to Atomic Power Development Associates, is to analyze existing sodium-water reaction test data and apply this analysis to the design of the B&W Full-Size and 30 MWt Prototype Steam Generator.

Scope

The scope of work under this Subcontract is as follows:

1. Analyze existing sodium-water reaction data and write a mathematical model representing the reaction fundamentals.
2. Use this model to analyze the design of the B&W 30 MWt Prototype Steam Generator with respect to sodium-water reaction problems.
3. Revise the mathematical model as further test data is accumulated under other R&D Programs.
4. Using the revised mathematical model to analyze the problems of the Full-Size Steam Generator.

11.8 Distribution of Sodium over Tube Bundles:

Background Information

Uniform distribution of sodium over the heat transfer surface of a sodium-heated steam generator is of great importance. High local velocity has caused vibration and wear of the tubes of the Enrico-Fermi steam generators, and of the Hallam intermediate heat exchangers. The distributor system for the steam generator being designed under this Contract is designed as carefully as possible with existing data to distribute the sodium uniformly and to prevent local high velocity streams.

Distribution devices are extremely difficult to design accurately by analytical methods but are usually relatively simple to prove out with simple water models. The duct work and flow distributors for many conventional fossil-fuel fired boilers are proved out in water models before the Full-Size Steam Generators are constructed. Since sodium and water have similar flow properties, a simple water model at room temperature will model the sodium flow very accurately.

R&D Project

An estimate is being prepared of the cost to make a small-scale water model of the flow distributor of the 30 MWt Prototype Steam Generator.

11.9 System Stability and Control:

Background Information

In any multi-loop plant, such as the Full-Size Plant that will use the steam generators described herein, there is a possibility of control instability or oscillation between the several loops. As central station power plants have become larger, and the equipment becomes more expensive it has become necessary to simulate the plant performance, including the control system, on a differential analyzer type of analog computer and prove out the control response characteristics of the plant prior to putting the actual plant in operation. This has prevented control difficulties after the plant goes into service, and has prevented interruptions in service for control adjustments or possibly damage to equipment.

R&D Project

A simulation of the performance of the sodium-heated steam generators for the Full-Size Plant should be performed before the Full-Size Steam Generators are built. Some of the information necessary for simulating the operation of the Full-Size Steam Generator can best be obtained from the actual test data when the 30 MWt Prototype Steam Generator is built and tested. For this reason, the work on control simulation should be started with a small effort during the time the Prototype Steam Generator is being fabricated with the major amount of the work and the actual simulation of the control system taking place after the completion of testing of the Prototype.

12.0 COST ESTIMATE:

The estimated cost for the Full-Size Steam Generators to supply steam to produce 1000 MWe is as follows:

	First Plant	Subsequent Plants
Three Steam Generators	$14,181,400.	$11,864,000.
Three Reheaters	5,148,550.	4,600,000.
Sub Total	19,329,950.	16,464,000.
Freight 1	230,000.	230,000.
Erection 1	146,000.	146,000.
Price, Delivered & Erected	19,705,950.	16,840,000.
Control System	534,050.	500,000.
Inert Gas System	10,000.	10,000.
Feedwater Heaters2	1,250,000.	1,250,000.
Total	21,500,000.	18,600,000.

1. Freight and Erection are based on delivering to and installing the steam generators at the hypothetical site described in "Guide to Nuclear Power Cost Evaluation", TID-7025.

2. The feedwater heating cycle for this plant is based on 8 stages of feedwater heating. These heaters were not designed in detail, but an average cost of $1.25/KW for these heaters was used.