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PRELIMINARY DESIGN REPORT
PROTOTYPE STEAM GENERATOR

Report No BAW-1280-28

Vol. 1 - General
to

(Vol. 1)
Volume 1
of 4 Volumes

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

MASTER

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

November 15, 1965

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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Volume 1 of 4 Volumes

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Vol. 1 - General

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Chicago Operations Office
Lemont, Illinois

June 1, 1965

AEC Contract No. AT (11-1)-1280
B&W Contract No. 610-0067

SODIUM-HEATED STEAM GENERATOR
DEVELOPMENT

Prepared By: J.G. Clark
Approved By: P.B. Probert
Date: June 1, 1965

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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 Prototype Steam Generator.

Phase II:

- A. Detail Design of Prototype Steam Generator.
- B. Fabrication of 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 Prototype Steam Generator, (Phase I-C above). The Prototype Steam Generator has a capacity of 25.2 MWt. '

This report is divided into four major parts:

- Volume 1 - General
- Volume 2 - Stress Analysis
- Volume 3 - Sodium-Water Reaction Study
- Volume 4 - Specifications

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

In Volume 2 are summarized the results of the ASME Code Calculations, the steady-state stress analysis, the earthquake analysis and the transient temperature and stress and stress analysis. A sample calculation showing a typical steady-state and transient analysis is included to illustrate the method of calculation.

In Volume 3 is a dynamic strength study of the steam generator shell and structures based on predicted maximum credible sodium-water reaction pressures, temperatures and volumes. Sample calculations are included in this volume.

In Volume 4 are the design and fabrication specifications. Included in this volume are the acceptance standards for inspections, welding and non-destructive testing.

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 the report are available and will be sent upon request.

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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 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-C, "Preliminary Design of Prototype Generator."

1.2 Design Objectives of Full-Size Steam Generator:

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.

1.3 Design of Full-Size Steam Generator:

The preliminary design of the Full-Size Steam Generator is complete. The design is described in report BW 67-2, Volumes 1 and 2, which were issued July 1, 1964.

2.0 PROTOTYPE MODELING CRITERIA:

The Prototype Steam Generator is a model of the 1000 MWe Steam Generator. The problem areas of the Full-Size Unit have been incorporated into the Prototype to match as nearly as possible, the steady state and transient performance and stress ranges of the larger unit.

The following areas or design conditions found in the full scale unit were modeled as closely as possible in the Prototype.

2.1 Performance:

- 2.1.1 Steam flow per tube in boiler bundle.
- 2.1.2 Steam flow per tube in superheater bundle.
- 2.1.3 Feedwater Temperature.
- 2.1.4 Steam Outlet Temperature.
- 2.1.5 Steam Outlet Pressure.
- 2.1.6 Sodium Inlet Temperature.
- 2.1.7 Sodium Outlet Temperature.
- 2.1.8 Sodium Temperature at various sections of steam generator.
- 2.1.9 Steam and water temperatures at various sections of steam generator.
- 2.1.10 Tube Size.

2.2 Stress:

- 2.2.1 Inlet Tube Sheet - Boiler Inlet.
- 2.2.2 Design Pressure.
- 2.2.3 Design Temperature.
- 2.2.4 Thermal Sleeve at Sodium Inlet.
- 2.2.5 Flanges.
- 2.2.6 Tube Flexibility

2.3 Design Layout and Fabrication:

- 2.3.1 Inside Five Rows of Boiler Bundle.
- 2.3.2 Inside Five Rows of Superheater Bundle.
- 2.3.3 Center Pipe Configuration.
- 2.3.4 Tube Supports and Coil Support Bars.
- 2.3.5 Four Inch Safety Relief Valve.
- 2.3.6 Vibration Supports - Strap-Type.
- 2.3.7 Shroud Thickness.

3.0 DESIGN PARAMETERS:

The Prototype Steam Generator Plant has a full power capacity of 25.2 MWt and is designed in accordance with the following conditions.

3.1 Heat Load:

- 1 - Design and operating load for the Prototype is approximately 86.2×10^6 Btu/hr.

3.2 Steam Flow:

- 1 - High pressure steam flow is 88,750 lb/hr at full load.
- 2 - Variation of steam flow with load is shown on Figure 1.

3.3 Sodium Flow:

- 1 - Sodium Flow is 583,500 lb/hr at full load.

In order to maintain the sodium ΔT across the IHX at part load, some of the sodium must by-pass the steam generator.

- 2 - Sodium flow vs. steam flow is shown on Figure 2 and Figure 2a.

3.4 Steam Conditions - Operating:

- 3.4.1 Pressure - Operating steam pressure at the superheater outlet is 2425 psig at full load.
- 3.4.2 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, or by use of the spray attemperator. Feedwater temperature varies from 530F at 100% load to 370F at 20% load. (See Figure 3)

3.5 Sodium Conditions - Operating:

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

3.5.2 Sodium outlet temperature leaving the steam generator and entering the IHX varies between 650F at 100% load and 493F at 20% load. (Figure 4)

3.5.3 Operating sodium pressure is 20 psig maximum.

3.6 Design Conditions - Pressure:

3.6.1 Sodium Side Pressure - 300 psig

3.6.2 Steam Side

The design pressure of the water-steam side of the steam generator tubes is shown on Figure 5. This concept of stepped pressure design is used in central station practice for once-through boilers and has been given ASME Code approval. To model the Full-Size Steam Generator as closely as possible the Prototype Steam Generator is designed on the same basis.

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 superheater outlet is 191 psi. (Figure 6)

The required design pressure at any point in the boiler is defined as 105 percent 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 percent 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 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 = $1.05 (2400) + (1.05)^2 (191) = 2755$ 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.

3.7 Design Conditions - Temperature:

3.7.1 Sodium Side - Temperature - 1200F

3.7.2 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 91.2% of average full load flow. The "worst" tube was 50F superheated with steam leaving the boiler bundle at a temperature of 800F instead of 750F 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 Resistance = .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 730F, for film boiling section, 841F, and the primary superheater section and the outlet riser tubes, 951F. Additional temperature steps were not used, since three different tube wall thicknesses were sufficient to minimize the tube bundle size without increasing the fabri-

cation 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 88.0% of average full load flow. The "worst" tube was 20F superheated with steam leaving the superheater at 1070F instead of 1050F.

It is not necessary to use more than one design temperature in the superheater. The calculated maximum tube wall temperature is 1124F at the superheater outlet. Calculations to determine tube wall temperature for the superheater are included in the Appendix.

3.8 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 the water chemistry specified for the SCTI, but are recommended limits 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.

<u>Item</u>	<u>Limit</u>
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

Vol. 1

Dissolved Oxygen	0.007 ppm Max. Preferably Zero
Carbon Dioxide	Minimum - Preferably Zero
Total Silica (as SiO_2)	0.02 ppm Max.
Total Iron (as Fe)	0.01 ppm Max.
Total Copper (as Cu)	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.

- GENERAL NOTES**
 
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AEC CONTRACT AT (H)-280
 B&W CONTRACT SIO-0067-45
 SODIUM HEATED STEAM
 GENERATOR DEVELOPMENT

THE BARCOCK & WILCOX CO.
 NEW YORK, NEW YORK

GENERAL ARRANGEMENT OF
 STEAM GENERATOR
 PROTOTYPE

READY TO GO 1957 F

SECTION E-E

SECTION C-C

SECTION D-D

NOTES
1. FOR GENERAL NOTES SEE GENERAL ARRANGEMENT DRAWING

REVISIONS	
NO.	DESCRIPTION
1	GENERAL ARRANGEMENT OF STEAM GENERATOR PROTOTYPE
2	SMALL SECTION OF STEAM GENERATOR PROTOTYPE
3	SMALL SECTION OF STEAM GENERATOR PROTOTYPE
4	SUPPLEMENTAL DRAWING OF STEAM GENERATOR PROTOTYPE

AEC CONTRACT AT (H-1) 1280
B&W CONTRACT 610 0087 48
SODIUM HEATED STEAM GENERATOR DEVELOPMENT

T. E. BARCOCK & WILCOX CO.
NEW YORK, NEW YORK
SECTIONS THRU
STEAM GENERATOR
PROTOTYPE

32439 F 20958 F

THE BARCOCK & WILCOX CO.
20958 F

REV	REVISIONS	DATE	APPROVAL
1	GENERAL ARRANGEMENT OF STEAM GENERATOR PROTOTYPE		
2	SECTIONS THRU 5TH GEN PROTOTYPE		
3	2D-2R SECT OF 5TH GEN PROTOTYPE		
4	SUPPLEMENTAL SECT OF 5TH GEN PROTOTYPE		

NOTES

1. FOR GENERAL NOTES SEE GENERAL ARRANGEMENT DRAWING

NO	REFERENCES	DATE
1	GENERAL ARRANGEMENT OF STEAM GENERATOR PROTOTYPE	20957 F
2	SECTIONS THRU 5TH GEN PROTOTYPE	20958 F
3	2D-2R SECT OF 5TH GEN PROTOTYPE	20959 F
4	SUPPLEMENTAL SECT OF 5TH GEN PROTOTYPE	20960 F

AEC CONTRACT AT(11-1)-1280
 D&W CONTRACT G10-0067-45
 SODIUM HEATED STEAM
 GENERATOR DEVELOPMENT

NO	DESCRIPTION	DATE
1	DESIGN	11/1/50
2	CONSTRUCTION	11/1/50
3	OPERATION	11/1/50
4	MAINTENANCE	11/1/50
5	REPAIRS	11/1/50
6	REPLACEMENTS	11/1/50
7	MODIFICATIONS	11/1/50
8	UPGRADES	11/1/50
9	REWORK	11/1/50
10	REDESIGN	11/1/50

THE BABCOCK & WILCOX CO. NEW YORK, NEW YORK	DESIGNED BY DRAWN BY CHECKED BY APPROVED BY DATE
SHELL SECTION ARRANGEMENT OF STEAM GENERATOR PROTOTYPE	DATE 92439 F SCALE 1/4"=1'-0"

THE BABCOCK & WILCOX CO.
 20959 F
 REV

<u>REVISIONS</u>		
<u>DIV.</u>	<u>DESCRIPTION</u>	<u>DATE</u>

NOTES

1 FOR GENERAL NOTES SEE GENERAL
ARRANGEMENT DRAWING.

REFERENCES		
NO.	TITLE	DATE
1	GENERAL ASSESSMENT OF STEAM GENERATOR PROTOTYPE	2088
2	SECTIONS THRU STEAM GEN PROTOTYPE	2088
3	SHAL SECTION OF STEAM GEN PROTOTYPE	2088
4	SUPPLEMENT SECTION OF STEAM PROTOTYPE	2088
5	LONG SECTION J-J OF SUPERHEATER FOR STEAM GENERATOR PROTOTYPE	2088

AEC CONTRACT AT (11-1)-1280
B&W CONTRACT 610-0067-45
SODIUM HEATED STEAM
GENERATOR DEVELOPMENT

		TELEPHONE										OTHER
		1	2	3	4	5	6	7	8	9	0	
NAME	Mr. J. Edgar Hoover	2	1	2	3	4	5	6	7	8	9	
ADDRESS	400 ...	2	1	2	3	4	5	6	7	8	9	
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TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
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TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEPHONE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELETYPE	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEFAX	202-358-5000	2	1	2	3	4	5	6	7	8	9	
TELEVISION	202-358-5000	2	1	2	3	4</						

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DATE	DATE

THE BABCOCK & WILCOX CO.
NEW YORK, NEW YORK

BOILER SECTION
OF STEAM GENERATOR
PROTOTYPE

DOC. IDENT. NO.	92439	CLASS.	F	DRAWING NO.	20961 F
SCALE 1:100					SECT. 2

4.0 GENERAL DESCRIPTION OF STEAM GENERATOR:

The Prototype steam generator is shown assembled on drawing 20957F, with sections shown on drawing 20958F.

4.1 Pressure Shell:

The pressure shell is 6 ft. I.D. stands vertically to an overall height of approximately 44 ft. including the cylindrical support skirt. One sodium inlet nozzle is located in the upper head. One sodium outlet nozzle is located in the lower head. One superheater inlet and one superheater outlet nozzle is arranged opposite each other just below the upper head. Nine feet lower, in the boiler shell spool pieces, one feedwater inlet and one boiler outlet nozzle also are oppositely arranged around the shell. The boiler outlet nozzle is connected to the superheater inlet nozzle by an external pipe.

Drawings 20959F, 20961F, and 20962F, 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 and assembled in the shops. 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 20962F), consists of the upper hemispherical head, top shell, top shell flange, superheater nozzles and tubesheets, the sodium inlet and distribution system, 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 20961F), 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, and the boiler shroud and tube supports. The boiler tubes, shroud and tube support beams are supported from its shell. Unbolting the lower flanges allows the boiler spool section and its tube bundle to be withdrawn from the shell leaving the shell and its liner in place.

The shell section (drawing 20959F) 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 with an intermediate seismic tie to the pit wall.

4.2 Sodium Flow Path (Figures for 100% Load):

By referring to drawing 20957F one can trace the flow path of sodium through the steam generator. Total sodium flow rate through the steam generator is 583,500 lb/hr. Incoming sodium at 1140°F enters through a 10 inch sodium inlet nozzle 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 1016°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 650F through one-12 inch sodium outlet nozzle at the bottom.

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

By referring to drawing 20957F 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 88,750 lb/hr. Feedwater enters the steam generator at 530°F through the boiler inlet nozzle and flows downward in downcomer tubes arranged in an annular boxed 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 750F to the boiler outlet nozzle. Each tube is continuous from the inlet header to the outlet header.

The steam flows at 750°F from the boiler outlet nozzle to the superheater inlet nozzle through an external interconnecting pipe, 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 superheater outlet nozzle.

4.3.1 Steam Flow During Start-Up

The start-up system is described in Section 6.0. 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 an existing flash tank in the SCTI feedwater 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 pipe. 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 pipe.

4.4 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 418 ft³ 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 small values.

4.5 Access to Tube Ends:

Access to the steam and water side of the tube sheets is provided through three 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.

4.6 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 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. 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 45-7/8" I.D. x 3/8" thick above the sodium level. Below the sodium level it changes to a double shroud whose inner wall is 45-7/8" I.D. x 3/8"

thick and whose outer wall is 46-5/8" I.D. x 3/8" thick. A double shroud is used below the sodium level to reduce heat transfer to the superheater 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 boiler shroud is 62-1/4" I.D. x 3/8" thick. The annulus between the superheater and boiler shroud contains the superheater downcomer tubes, the boiler riser tubes and the boiler downcomer tubes. Each of the groups of tubes is contained in its own box as shown on drawing 20958F, Section D-D. The downcomer box is made of double plate to reduce heat transfer. A double shroud is used between the boiler bundle and the shell liner 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.

4.7 Sodium Distributor System:

Sodium entering the steam generator through one sodium inlet nozzle flows into a 8 SCH 40 I.D. round ring type header then flows downward in four - 3-1/2" SCH 40 I.D. Sodium downcomer pipes which terminate in four distributors. The sodium flow from each of the four sodium downcomers is distributed into the area above the superheater tube bundle, but below the normal sodium level. The distributors at the outlet ends of the sodium downcomers are arranged to assure that local velocity streams leaving the downcomers will not cause superheater tube vibration or carry inert gas down with the sodium into the sodium pump. 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 1.09 ft/sec

4.8. Interconnecting Piping:

In order to conduct steam from the boiler section to the superheater section, an interconnecting pipe is installed, carrying steam from the boiler outlet nozzle to the superheater inlet nozzle. The interconnecting pipe is located outside the steam generator. 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. A spray desuperheater and a flow measuring orifice are located in this pipe. The pipe size is 5" double extra heavy.

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 from water to sodium.

This interconnecting pipe also serves as a location for superheater by-pass control during start-up. The interconnecting pipe has a superheater isolation valve and two connections leading to the start-up system. The start-up system is described in Section 6.0.

The steam pressure drop at 100% load through this interconnecting piping from the boiler outlet headers to the superheater inlet headers is approximately 29 psi.

4.9 Design of Tube Bundle:

The boiler and superheater sections are made up of helical coiled tubes. These 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 1-5/8" transverse spacing and 1-3/8" parallel spacing. The pitch angle on each tube is approximately three degrees. The tubes are arranged in 5 rows with the number of tubes per row set to give nearly equal tube lengths of 133.8 ft. With 25 tubes in the bundle the inner coil diameter is 32-1/8 inches and the outer coil diameter is 45-1/8 inches. The number of tubes per row varies from 4 on the inner row to 6 on the outer row.

The superheater tubes are 7/8" O.D., SA-213, TP-316, Stainless Steel, on 1-1/2" transverse spacing and 1-1/4" parallel spacing. The pitch angle on each tube is approximately 5-1/2 degrees. The tubes are arranged in 5 rows with the number of tubes set to give nearly equal tube lengths of 43 ft. The number of tubes per row varies from 8 on the inner row to 10 on the outer row. (total 45 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.

4.10 Description of Mechanical Parts of Steam Generator:

4.10.1 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 drawing 20961F). Four coil supports are equally spaced around the coil. Each coil support is similar to those used on the Full-Size Steam Generator and consists of a hanger bar attached to the beam supports through an adjustable hanger rods, and individual coil support bars suspended from the four 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.

4.10.2 Superheater Tube Supports

The superheater tube supports are similar to the boiler tube supports.

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 1

PERCENT LOAD VS. STEAM FLOW

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 2

SODIUM FLOW VS. STEAM FLOW

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 2a

SODIUM FLOW VS. STEAM FLOW

0.85 S.G. SODIUM

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 3

STEAM TEMPERATURE VS. STEAM FLOW

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 4

SODIUM TEMPERATURE VS. STEAM FLOW

PROTOTYPE DESIGN PRESSURE

STEPPED DESIGN PRESSURE FOR 5%
OVERFLOW AND 5% OVERPRESSURE
FIGURE 5

DESIGN PRESSURES

DOWNCOMERS TO ECONOMIZER	2825 PSI
ECONOMIZER AND BOILER	2750 PSI
PRIMARY SUPERHEATER	2725 PSI
RISERS	2725 PSI
INTERCONNECTING PIPE	2675 PSI
SECONDARY S.H.	2625 PSI

SODIUM-HEATED STEAM GENERATOR DEVELOPMENT

AEC Contract No. AT (11-1)-1280

B&W Contract No. 610-0067

PROTOTYPE STEAM GENERATOR

FIGURE 6

STEAM SIDE PRESSURE DROP VS. STEAM FLOW

SCHEMATIC ARRANGEMENT
(and performance data)
for
PROTOTYPE STEAM GENERATOR
By: J.G. CLARK
Cont. No. - 610-0067
11-30-65 FIGURE 7

TABLE 1

PROTOTYPE STEAM GENERATOR
BOILER SECTION

Design Conditions

Sodium Temperature	1200 F
Steam Temperature	800 F
Steam Pressure (Nominal)	2750 psi

Operating Conditions (Full Load)

Heat Load	64.35×10^6 Btu/hr
Sodium Flow	583,500 lb/hr
Sodium Inlet Temperature	1016 F
Sodium Outlet Temperature	650 F
Sodium Pressure Drop	.138 psi
Steam Flow	88,750 lb/hr
Feedwater Temperature	530 F
Outlet Temperature	750 F
Outlet Pressure	2507 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

	<u>Number</u>	<u>Size</u>	<u>Effective Length</u>
Tubes - Econ. & Nucleate Boiling Sec.	25	1" O.D. x .120" MW	57.27 ft.
Film Boiling Section	25	1" O.D. x .145" MW	55.53 ft.
Superheat Section	25	1" O.D. x .165" MW	21.00 ft.
Total Length			133.80 ft.
Overall Heat Transfer Coefficient			
Economizer		571 B/hr/ft ² F	
Boiler		642 B/hr/ft ² F	
Nucleate Boiling		449 B/hr/ft ² F	
Film Boiling		450 B/hr/ft ² F	
Superheater		3333 B/hr/ft ² F	
Fouling Factor		0.009 inches	
Corrosion Allowance			

BOILER SECTION
TABLE 1 (CONT'D)Heat Transfer Surface Installed

Total	874.8 ft ²
Economizer	375.0 ft ²
Boiling	362.2 ft ²
Superheater	137.6 ft ²

Boiler Inlet Tubes

Size	5/8" O.D. x 0.076" MW
------	-----------------------

Boiler Outlet Legs

Size	1" O.D. x 0.165" MW
------	---------------------

Pressure Drop (Steam Side)

Downcomers	14.82 psi
Economizer	6.21 psi
Boiling Zone	31.15 psi
Superheater	19.95 psi
Boiler Risers	27.10 psi

Transverse Tube Spacing S _T	1.625"
Parallel Tube Spacing S ₁₁	1.375"

Departure from Nucleate Boiling

100% Load - Quality	69.39%
---------------------	--------

TABLE 2

PROTOTYPE SUPERHEATER
SECTION

Design Conditions

Sodium Temperature	1200 F
Steam Temperature	1070 F
Steam Pressure	2625 psi

Operating Conditions (Full Load)

Heat Load	21.82 x 10 ⁶ Btu/hr
Sodium Flow	583,500 lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	1016 F
Sodium Pressure Drop	.081 psi
Steam Flow	88,750 lb/hr
Steam Inlet Temperature	750 F
Steam Outlet Temperature	1050 F
Outlet Pressure	2425 psia

Material

Tube	SA-213 TP 316
Shell	Croloy 2-1/4
Tube Sheets, Heads	TP 316 SS

Heat Transfer Results

Tubes - Number	45
Size	7/8" O.D. x .120" MW
Effective Length Installed	43.1 ft.
Overall H.T. Coefficient	347.0 B/hr/ft ² F
LMTD	162.5 F
Surface Installed	444 ft ²

Superheater Inlet Tubes

Size	7/8" O.D. x .120" MW
Material	TP 316 SS

PROTOTYPE SUPERHEATER
SECTION
TABLE 2 (CONT'D)

Outlet Tubes

Size
Material

7/8" O.D. x .120" MW
TP 316 SS

Pressure Drop (Steam Side)

Tube Bundles

58.08 psi

Transverse Tube Spacing S_T
Parallel Tube Spacing S_{11}

1.5"
1.25"

5.0 SUMMARY OF PERFORMANCE:

The steam generator was sized on the basis of full load conditions shown in Figure 8. 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 7, the heat requirements of the SCTI Test Facility, and the modeling criteria in Section 2.0 of this report.

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

5.1 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 5.3

This correlation does not fit this 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 $\pm 10\%$. 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 $0.0003 \frac{\text{hr ft}^2 \text{ F}}{\text{Btu}}$ 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 same basis as the Full Size Steam Generator). The allowable stress for the Croloy 2-1/4 material was reduced to allow for the affect of sodium on design stress. This is discussed in the Preliminary Design Report of the Full Size Steam Generator, report No. BW 67-2.

For vessels used in steam service 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. Although the Prototype Steam Generator will not see 30 years operation the same corrosion allowance was used for the Prototype as was used for the Full Size Steam Generator.

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

The tube wall heat transfer conductance is $h_m = K/t_e$ where K is the thermal conductivity (Btu/hr-ft²-F/in) tube wall temperature.

4. Water-Steam Side:

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:

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

$$h_i^* = 0.023 \left(\frac{G^{.8}}{D^{.2}} \right) \left(\frac{c_p^{.4} K^{.6}}{\mu^{.4}} \right) \text{ (Modified Form)}$$

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.

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

$$C = \left[\frac{\mu h_{fg}}{\sqrt{g(\rho_l - \rho_v)}} \right] \left[\frac{c_p}{.013 h_{fg} \left(\frac{c_p \mu}{K} \right)^{1.7}} \right]^3$$

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.

$$h_{FB} = 0.5(0.023) \left(\frac{G^{.8}}{D^{.2}} \right) \left(\frac{c_p^{.4} K^{.6}}{\mu^{.4}} \right)$$

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.

$$h_{sh} = 0.023 \left(\frac{G}{D^{0.2}} \right) \left(\frac{c_p \mu^{0.4} k^{0.6}}{\mu^{0.4}} \right)$$

5.2 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 $\Delta P = \frac{f L}{D} \frac{V^2}{2g}$

This equation has been modified to a more convenient form.

$$\Delta P = \left(\frac{f L}{D} + \frac{V_h}{12} \right) \mu \left(\frac{G}{105} \right)^2$$

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

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

²Martinelli, 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.

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

5.3 Definition of Terms:

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

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

$\bar{h}$ = Average heat transfer coefficient, BTU/hr ft² 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-ft²

W = Flow rate of sodium - lb/hr

A = Cross sectional flow area of tube bundle exposed to sodium flow, ft²

¹Heat 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

= 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

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

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

G = Mass flow of water or steam = $\frac{W}{A}$, lb/hr-ft²

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

A = Flow area of inside of tubes, ft²

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-ft²F

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.

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

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

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

²Heat 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

h_{fg} = 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/ft³

ρ_v = Density of saturated vapor, lb/ft³

C_p = 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 Factor¹

¹Friction 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

$$5 - \Delta p = \left[f \frac{L}{D} + \frac{V_n}{12} \right] \mu \left[\frac{G}{10^5} \right]^2$$

ΔP = Pressure drop - psi

f = Moody friction factor for cold drawn tubes.

L = Tube length, ft.

D = Inside diameter of tube, in.

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

μ = Specific volume of fluid, ft³/lb

G = Mass flow of fluid, lb/hr-ft²

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

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

6.0 START-UP SYSTEM:

6.1 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.

In order to model some of the effects of a start-up system, the Prototype Steam Generator has been arranged to permit a simplified start-up procedure, but still closely duplicates the start-up of the Full-Size Unit.

The start-up system will consist of two 1-1/2" pipes, one leading from the boiler outlet to an existing high pressure flash tank in the SCTI test loop and the second line from the high pressure flash tank to the superheater inlet. A superheater shut-off valve is provided between the two lines in the inter-connecting pipe. Start-up procedure will be established at a later date.

7.0 SODIUM LEVEL CONTROL

7.1 Level Variation

One of the possible problems investigated is that of control of sodium level in Prototype Steam Generator and the SCTI expansion tank and the secondary sodium pump.

The steam generator is not particularly sensitive to sodium level variations. The operating sodium level above the superheater bundle can vary from 1-1/2" above the sodium discharge plane of the distributor to 24 inches above the sodium discharge plane. Normal level at 20% load will be 10 inches above the sodium discharge plane. As sodium flow is increased from 20% load to full load the sodium level will rise approximately seven inches to accommodate the increase in volume of sodium due to the temperature change of the bulk sodium. At full load, the sodium level above the superheater bundle will be about six inches above the level in boiler annulus, and three inches above the superheater downcomer annulus. These levels reflect the sodium pressure drop across the boiler bundle and superheater bundle.

The surge tank at SCTI is located on the suction side of the secondary sodium pump. The pump and surge tank are connected together on the sodium side and operate essentially in parallel. See Figure 9. To keep sodium from flooding the steam generator, a gas pressure of approximately 20 psi higher than the expansion tank pressure will have to be kept over the sodium in the steam generator.

FIGURE 10

SODIUM LEVELS AT VARIOUS LEVELS

FIGURE 11

As load is increased to full load, the gas pressure in the steam generator will increase about four psi, due to the volumetric increase in the sodium. It appears that sodium levels and gas pressures can be established at 20% load and will change only slightly. This will minimize the need for adding and bleeding out cover gas to maintain proper sodium levels.

When the steam generator is being filled, the bulk temperature of the sodium will be 350F. As this sodium is heated up to 900F the volumetric change in the sodium will be approximately forty cubic feet. In order to accommodate this change in volume, the fill level in the steam generator should be about twelve inches below the sodium discharge plane. At this condition the sodium distributors will be uncovered, but due to the low flows during this heat up period, this should not present any major problems.

7.2 Level Indication

The primary sodium level indicator will be a double coil, eddy current instrument that depends on liquid sodium as a coupling medium. The coil is completely enclosed in a stainless steel tube. As sodium surrounds the tube, there is a coupling between the two coils through the sodium. This coupling is read out on instruments which indicate sodium level. There are two such level indicators in the Prototype Steam Generator; one in the sodium above the superheater bundle, and the other in the annulus between the superheater shroud and the boiler shroud.

As a back-up for the primary level indicators it is proposed to mount

an external float type level indicator of stainless steel construction.

Connection to the gas space would be through a presently unused instrument connection. The sodium connection to the instrument would be in the sodium pipe leaving the bottom of the steam generator. This float type level indicator has been used successfully in sodium service.

DATA REQUIRED FOR EVALUATION OF PROTOTYPE

I. <u>WATER SIDE</u>	NUMBER OF MEASUREMENTS
A. FLOW	
1. Feedpump speed, rpm	1
2. Water flow to boiler (presently measured at inlet of high pressure heater)	1
3. Steam flow leaving boiler before desuperheater (required to determine time rate of mass storage in boiler during a transient)	1
4. Superheater attemperator spray flow	1
5. Steam flow leaving secondary superheater	<u>1</u>
	5
B. ABSOLUTE PRESSURE MEASUREMENT	
1. Fluid pressure where water flow to boiler is measured	1
2. Steam pressure at boiler outlet where flow is measured	1
3. Steam pressure at superheater outlet header	1
4. Steam pressure where steam flow leaving secondary superheater is measured	<u>1</u>
	4
C. PRESSURE DROP	
1. Boiler inlet to boiler outlet (boiler ΔP)	1
2. Superheater inlet to superheater outlet (superheater ΔP)	1
3. Boiler outlet to superheater inlet (interconnecting pipe ΔP)	1
4. Boiler inlet to superheater outlet (steam generator ΔP)	1
	<u>4</u>
D. TEMPERATURES	
1. Fluid temperature where water flow to boiler is measured	1
2. Steam temperature where steam flow leaving secondary superheater is measured.	1
3. Attemperator spray water temperature	1
4. Fluid temperature at boiler inlet header	1
5. Fluid temperature at boiler outlet header	1
6. Fluid temperature at superheater inlet header	1
7. Fluid temperature at superheater outlet header	1
8. Steam temperature of each tube at boiler outlet (OD of tube in gas space)	25
9. Boiler coil inlet (OD temperature of tube)	<u>1</u>
	33

II. SODIUM SIDE

A. FLOW

- 1. Sodium flow into steam generator 1

B. SODIUM LEVEL INDICATIONS

- 1. Sodium level above superheater bundle 1
- 2. Sodium level in annulus between superheater shroud and boiler shroud 1
2

C. TEMPERATURES

- 1. Inlet sodium temperature 1
- 2. Sodium temperature where flow is measured 1
- 3. Sodium at midpoint of superheater bundle 4
(one per quadrant)
- 4. Sodium at outlet of superheater bundle 4
(one per quadrant)
- 5. Sodium temperature upset in one superheater quadrant 7
- 6. Sodium temperature at inlet to boiler bundle 4
(one per quadrant)
- 7. Sodium temperature at start of nucleate boiling and 8
start of superheat
- 8. Sodium temperature leaving boiler bundle 4
(one per quadrant)
- 9. Sodium temperature in superheater downcomer annulus box - 2
two levels
- 10. Sodium temperature in boiler riser annulus box - two 2
levels
- 11. Sodium temperature in boiler downcomer annulus box - 4
four levels
- 12. Sodium temperature between superheater and boiler shrouds - 4
two levels, two quadrants
- 13. Sodium temperature between boiler shroud and shell liner - 4
superheater level
- 14. Sodium temperature in boiler annulus at boiler bundle 4
53

D. PRESSURE

- 1. Argon gas pressure 1

III. STRUCTURAL AND PRESSURE PARTS (Internal)

A. UPPER HEAD

1. Cold face temperature of internal insulation	3
2. Inside surface temperature of flange	<u>4</u>
	7

B. SPOOL SECTION

1. Inside surface temperature of upper flange	4

C. VESSEL SHELL AND LINER

1. Outside surface temperature of shell liner	4

IV. EXTERNAL TEMPERATURES

A. UPPER HEAD

1. Outside surface temperature of shell	4
2. Flange temperature where inside surface temperature is measured	4
3. Rupture disc flange	1
4. Outside surface of external insulation where shell surface temperatures are measured	4
5. Flange stud temperature	<u>2</u>
	15

B. SPOOL PIECE

1. Flange surface temperature where ID surface temperature is measured	3
2. Outside surface of shell - 90° from tubesheets	<u>2</u>
	5

C. VESSEL FLANGE

1. Outside shell surface temperature	4
2. Support skirt attachment	<u>4</u>
	8

V. STRAIN GAGES

	<u>Number of Measurements</u>	
	Strain Gages	Temperature
A. Superheater outlet header (for location see Sketch #1)	22	9
B. Boiler inlet header (for location see Sketch #2)	18	7
C. Sodium inlet nozzle (for location see Sketch #3)	14	7

V. STRAIN GAGES (CONTINUED)

<u>Number of Measurements</u>	
Strain Gages	Temperature
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
 
97	97
98	98
99	99
100	100

D. Sodium outlet nozzle
(for location see Sketch #4)

12

7

E. Tubes

1. Superheater coil at bottom. Biaxial gages and thermocouple midway between downcomer leg and first support (in sodium)

2

1

2. Boiler coil at top. Biaxial gages and thermocouples midway between the last support and the riser leg (in sodium)

2

1

3. Boiler Coil at bottom. Biaxial gages and thermocouple midway between the downcomer leg and the first support (in sodium)

2

1

4. Superheater riser tube near first vibration support from header and (in gas space)

2

1

5. Superheater downcomer tube near first vibration support from header end (in gas space)

2

1

6. Boiler riser tube near first vibration support from header end (in gas space)

2

1

7. Boiler downcomer tube near first vibrations support from header end (in gas space)

2

-

80

37

VI. MISCELLANEOUS

1. Ambient air temperature of pit

SUMMARY LIST OF INSTRUMENTATION

I.	STRAIN GAGES	
	OUTSIDE OF VESSEL	48
	STEAM OR WATER SIDE	12
	SODIUM SIDE	
	In Gas Space	12
	In Sodium	<u>8</u>
		80
II.	THERMOCOUPLES AND TEMPERATURE MEASUREMENTS	
	OUTSIDE OF VESSEL (Metal Temperatures) -	54
	STEAM & WATER SIDE	7
	SODIUM SIDE	
	In Gas Space	47
	In Sodium	<u>58</u>
		166
III.	FLOW MEASUREMENTS	
	STEAM & WATER SIDE	4
	SODIUM SIDE	<u>1</u>
		5
IV.	PRESSURE MEASUREMENTS	
	STEAM & WATER SIDE	
	Absolute Pressure -	4
	Pressure Drop -	4
	SODIUM SIDE	<u>1</u>
		9
V.	LEVEL INDICATIONS (Sodium)	2
VI.	MISCELLANEOUS	2

- + BIAXIAL STRAIN - 2 GAGES
- ! UNIAXIAL STRAIN - 1 GAGE
- THERMOCOUPLE

BABCOCK & WILCOX COMPANY ✓

DEPARTMENT

BY N.G.D.

DATE: 6-16-64

30 MWT PROTOTYPE

GNL

JOB NO.

GUIDED HEATER OUTLET HEAD

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BABCOCK & WILCOX COMPANY
DEPARTMENT

BY N.G.D.

DATE 6-24-64

30 MWT PROTOTYPE

GNL

JOB NO.

BOR 10 INLET HEADER

SHEET 20 OF

SODIUM OUTLET NOZZLE

+ BIAXIAL STRAIN - 2 GAGES

• THERMOCOUPLE

BABCOCK & WILCOX COMPANY

DEPARTMENT

BY N.G.D.

DATE 7-1-64

30 MWIT PROTOTYPE

5196

JOB NO.

SODIUM OUTLET NOZZLE

SHEET 109 OF