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PROGRESS REPORT 13

May, 1964
to

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

MASTER

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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SODIUM-HEATED STEAM GENERATOR
DEVELOPMENT

Signed: Paul Probert

THE BABCOCK & WILCOX CO.
BOILER DIVISION
BARBERTON, OHIO

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ABSTRACT

This is the thirteenth Monthly Progress Report on this Contract. The report contains some information on the history and scope of the Contract and tabulated performance data on both the Full-Size Steam Generator and 30 MWt Prototype Steam Generator.

To save time for those who regularly read the Progress reports and are not interested in the background information there is a section entitled "Present Status" in each of the major sections of this report. In the Present Status section is summarized the work that has been accomplished in the past month.

The Preliminary Design work on the Full-Size Steam Generator is complete. The design data on the Steam Generator will be summarized in the Preliminary Design Report, BW 67-2. Design data for the Full-Size Steam Generator will be eliminated from future Progress Reports.

The design work under Phase I of this Contract is approximately 76% complete.

2. INTRODUCTION

This Monthly Progress Report summarizes the status of the work in progress under this Contract as of this date. It is planned to include enough background material in each month's progress report that each report can be understood without reference to all previous reports. In general, each report will have a section describing the Design Work, the R&D Program, and the Critical Path Schedule as outlined in the Table of Contents.

2.1 HISTORY OF CONTRACT

This Contract was received on March 20, 1963, and signed on April 3, 1963. The overall 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 overall objective of developing reliable, economical, large central station nuclear power plants.

2.2 SCOPE OF CONTRACT

The scope of work covered under this Contract is briefly 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 to the Design of the Full-Size Steam Generator.

3. DESIGN WORK

The design work under this Contract is proceeding according to the Critical Path Schedule included with this report. The status of the design work is as outlined below.

3.1 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. The important design criteria are as follows:

1. Once-through type of steam generator.
2. Single tube wall separating the fluids.
3. Tube sheets exposed to inert gas only.
4. Ready access to tube ends for inspection and repair.
5. Design can be extrapolated to larger or smaller sizes as required for a particular central station application.
6. Design can be extrapolated to steam pressures above the critical pressure.
7. Removable tube bundles.
8. Hot restart without thermal shock.

ONCE-THROUGH TYPE STEAM GENERATOR

The overall Commission objective is to develop economical, practical, reliable central station steam generators. To meet this objective the steam generator being designed under this Contract is of a "once-through" type because economic studies have shown that the once-through boiler costs considerably less than a recirculating boiler, especially in large sizes. The once-through steam generator has the ability to follow rapid load changes easily.

SINGLE TUBE WALL SEPARATING THE FLUIDS

A single tube wall will be used for this steam generator because it is felt that adequate safety measures can be provided to protect personnel and to protect the boiler against severe damage in the event of a tube rupture, and by using a single tube wall a considerable saving in cost results. A multiple tube wall design adds cost to the steam generator not only because of the cost of the additional thickness of tubing, but 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.

TUBE SHEETS EXPOSED TO INERT GAS ONLY

Any sodium-heated steam generator will be subjected to rapid sodium temperature changes. Tube sheets are among the thickest metal sections in the steam generator, and therefore are most sensitive to temperature transients. If all the tube sheets are located in the gas space, out of the sodium, transient thermal stresses in the tube sheets can be kept to a minimum.

READY ACCESS TO TUBE ENDS

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 in generating equipment shut down. Any features in a steam generator design which make repairs quick and easy are worthwhile. Removable handhole caps will provide easy access to all tube ends for inspection. If it is desired to do major work within the headers, the interconnecting piping can be removed to give a large access opening into each header.

DESIGN CAN BE EXTRAPOLATED TO LARGER OR SMALLER SIZES

By using a helical coil design of boiler, superheater and reheater

great flexibility is possible in arranging the heat transfer surface to suit the particular needs of the different size reactor plants.

DESIGN CAN 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 higher than the critical pressure as required to take advantage of advancing technology in central station design.

REMOVABLE TUBE BUNDLES

Experience has shown that unforeseen accidents in heat exchangers can result in serious damage to a tube bundle. The boiler, superheater, and reheater tube bundles are individually removable so they can be repaired or replaced if they are damaged from any cause.

HOT RE-START WITHOUT THERMAL SHOCK

Cracking of the shells of high pressure, high temperature steam turbines has been a problem. The cracking is due to thermal stress fatigue and stress-to-rupture from thermal shock during start-up and especially during hot restart after a trip-out. Outages for turbine repair have averaged from two to three months. The repairs have cost from \$14,000 to \$400,000 and the loss in revenue to a utility customer would be approximately \$3,000,000 for one steam generator of the size being designed here.

3.2 FULL-SIZE STEAM GENERATORS (1000 MWe in 3 Units)

The arrangement of one of the three steam generators required for 1000 MWe is shown on Drawing 20950F. Drawings 20951F, 20952F and 20953F show the shell, boiler bundle, and superheater from which this steam generator is assembled. Drawing 20954F shows two typical cross sections through the steam generator. These three pieces would be fabricated separately and assembled into the complete unit in the field.

By referring to Drawing 20950F one can trace the flow paths of sodium and water through the steam generator. The sodium enters through two 24-inch sodium inlet nozzles at the top of the steam generator and flows downward through a distributor system which will assure uniform flow across the tubes at the entrance to the superheater and will prevent local high velocity streams from causing vibration difficulties in the superheater. The sodium flows downward in cross flow across the helical coil superheater and continues down across the helical coil boiler bundle leaving the steam generator at one 32-inch sodium outlet nozzle at the bottom. Feedwater enters the steam generator through four water inlet nozzles distributed around the vessel. Only one of the four nozzles is shown on the drawing. The feedwater flows to the bottom of the boiler bundle in the downcomer tubes then turns and flows upward through the helical coil boiler bundle where it changes to steam and passes upward through the riser tubes to the four boiler outlet nozzles. The steam flows through

interconnecting piping to the four superheater inlet connections, flows downward through the superheater inlet tubes in the annular space around the superheater, then turns and flows upward through the coil superheater and out through the four superheater outlet nozzles.

Since the boiler is made of Croloy 2-1/4 and the superheater is made of Type 316 stainless steel there must be a dissimilar weld in the piping. The boiler is arranged so that the dissimilar weld in the steam piping will be located outside the boiler so the dissimilar weld can be inspected easily and if a leak should occur it will be a leak from the steam to the atmosphere rather than a leak resulting in a sodium-water reaction.

A schematic diagram of the steam generator system is shown on Figure A. This diagram shows one sodium loop, including IHX, boiler, superheater, and reheater. Heat loads, flows, pressures, and temperatures are tabulated at five different loads from 20 per cent to 100 per cent.

It is interesting to note that by the use of a sodium by-pass around the superheater and boiler, it is possible to maintain steam temperature and reheat temperature at design conditions down to 20 per cent load.

A tabulation of design parameters is included. Table 1 describes the boiler, Table 2 the superheater, and Table 3 the reheater. Table 4 is a plot of pressure drop through various portions of the steam generator at full load, and at 5 per cent over load and 5 per cent over

pressure. Central station steam turbines are customarily designed conservatively so that they can produce additional electrical output if the steam pressure to the turbine is increased 5 per cent. To insure that the steam generator does not limit the maximum capacity of the whole plant, steam generators are usually designed for 5 per cent excess flow and 5 per cent over pressure at the turbine throttle. The design pressure for the various portions of the steam generator are set to be slightly higher than the 5 per cent excess flow and 5 per cent over pressure line. This procedure results in what is known as a "stepped" design pressure for the steam generator. The design pressure for the inlet portions of the steam generator is higher than the design pressure for the outlet. This is a conservative basis for design for a once-through boiler where the safety valves are located at the superheater outlet because the safety valves will limit the pressure at the superheater outlet and the pressure drop through the steam generator will be lower than the values tabulated at any load below 105 per cent load.

Present Status:

Design work on the Full-Size Steam Generator has been completed. The cost estimate for the steam generator is nearly complete and will be included in the design report. It is planned to tabulate the cost data in the Preliminary Design Report in enough detail to allow the designer of a power plant to correct his cost estimates as plant arrangements different from the one in this study are made. Items

such as the interconnecting piping and controls may change as different plant layouts are studied, and these items will be shown separately in the cost tabulation. The Design Report on the Full-Size Steam Generator is nearly completed and will be issued approximately July 1.

3.3 REHEATER:

Economic studies have shown that the fuel cost and demand charge savings possible by using a reheater exceed the cost of the reheater by a considerable amount. For this study the reheater will be located in a separate vessel as close as possible to the steam turbine to save reheat steam piping and pressure drop.

The arrangement of the reheater is shown on Drawing 20955F and 20956F. Three reheaters will be required for the 1000 MWe plant.

The reheaters utilize coil tube bundles generally similar in appearance to the steam generators. Some cost saving has been possible in the reheater by using flat tubesheets and ring headers at the steam inlet and outlet. It was not possible to use flat tubesheets and ring headers for the steam generator because the steam pressure in the steam generator is much higher than the reheater.

Sodium enters the reheater through two sodium inlet nozzles in the upper head and flows through a distributor system downward in cross flow across the coil tube bundle leaving the reheater through the single nozzle at the bottom. Steam coming from the high pressure turbine enters the reheater through the inlet nozzles to the inlet ring header and flows down in the annular downcomer tubes to the bottom of the reheater, turns, and flows upward through the coils of the reheater bundle, flows upward through the vertical riser tubes to the outlet ring header and returns to the low pressure turbine. The shell of the reheater is similar in appearance to the shell of the steam generator,

and both of these components are arranged so that they can stand on their individual support skirts free of any other support structure. The performance data for the reheater is tabulated on Table 3.

Present Status:

The design work on the reheater has been completed for inclusion in the Preliminary Design Report. The cost estimate is proceeding in parallel with the cost estimate for the Full-Size Steam Generator.

REV	DESCRIPTION	DATE

- GENERAL NOTES**
1. VESSEL DESIGNED IN ACCORDANCE WITH THE 1962 EDITION OF ASME PRESSURE VESSEL CODE SECTION VIII AND CODE CASE 1875N-1
 2. OPERATING CONDITIONS:
 - A. STEAM FLOW --- 2403 x 10⁶ LB/Hr
 - B. STEAM PRESSURE AT SUPERHEATER OUTLET --- 2450 PSIG
 - C. STEAM TEMPERATURE AT SUPERHEATER OUTLET --- 1050° F
 - D. SODIUM FLOW --- 15.33 x 10⁶ LB/Hr
 - E. SODIUM INLET TEMPERATURE --- 101° F
 - F. SODIUM OUTLET TEMPERATURE --- 640° F
 3. SUPERHEATER:
 - A. NUMBER OF TUBES --- 1220
 - B. OUTSIDE DIAMETER --- 5"
 - C. EFFECTIVE LENGTH --- 40.6'
 - D. MATERIAL --- SA-213 TP 316 SS
 4. BOILER:
 - A. NUMBER OF TUBES --- 676
 - B. OUTSIDE DIAMETER --- 8 1/2"
 - C. EFFECTIVE LENGTH --- 131'
 - D. MATERIAL --- CROLOY 24 SA-387F
 5. SHELL:
 - A. DESIGN PRESSURE --- 200 PSIG
 - B. MATERIAL --- CROLOY 24 SA-387F

NO.	TITLE	DATE
1	CROSS SECTION OF FULL SIZE 5TH GEN	10/25/54
2	SHELL SECTION OF FULL SIZE 5TH GEN	10/25/54
3	BOILER SECTION OF FULL SIZE 5TH GEN	10/25/54
4	SUPERHEATER SECTION OF FULL SIZE 5TH GEN	10/25/54

THE BABCOCK & WILCOX CO
20950F
REV 0

AEC CONTRACT AT (111) 1280
B&W CONTRACT 610 0067 55
SODIUM HEATED STEAM
GENERATOR DEVELOPMENT

DESIGNED BY	W. R. G. G.
CHECKED BY	W. R. G. G.
APPROVED BY	W. R. G. G.
DATE	3/12/58

APPROVED BY

THE BABCOCK & WILCOX CO
NEW YORK, NEW YORK

**GENERAL ARRANGEMENT
OF FULL SIZE
STEAM GENERATOR**

Code Identifies Drawing No
92439 F 20950F
Scale 3/16" = 1' 0" 20950F

LONGITUDINAL CROSS SECTION OF LOWER SHELL

TOP END VIEW

ENLARGED VIEW A
SCALE 3\"/>

NOTES
1 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 48" INCL	OVER 48" TO 96" INCL	OVER 96" TO 144" INCL	OVER 144" TO 192" INCL
DECIMAL DIM	±.003	±.005	±.005	±.010	±.031	±.031	±.031
FRAC DIM, MACH	±1/64	±1/32	±1/32	±1/16	±1/16	±1/16	±1/8
FRAC DIM UNMACH	±1/16	±1/16	±1/32	±1/8	±3/16	±3/16	±3/16
DIM. FOR BURNING	±1/8	±1/8	±1/8	±1/8	±3/16	±3/16	±3/16
* - MACH. SURFACE T.I.R.	±.001	±.002	±.002	±.003	±.003	±.003	±.003
* PERPENDICULARITY	.004 PER FOOT						
* CONCENTRICITY	1/2 OF TOLERANCE OF DIA						
* ANGULARITY	±.030						
* NON CIRCULARITY	AS 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						
* FABRICATE ONLY WHEN NOTED ON DRAWING - MENS ONS							

AEC CONTRACT AT (111)-1280
B&W CONTRACT 610-0067-55
SODIUM HEATED STEAM GENERATOR DEVELOPMENT

OWN BY: B&W
DRAWN BY: J. A. Symmes
CHECKED BY: J. A. Symmes
APP'D BY: J. A. Symmes
DATE: 3/11/64

THE BABCOCK & WILCOX CO
NEW YORK, NEW YORK

SHELL SECTION ARRGT OF FULL SIZE STEAM GENERATOR

CDR. ENT. NO. 92439	SIZE F	DRAWING NO. 20951F	REV. 0
---------------------	--------	--------------------	--------

SCALE 1/4\"/>

SECTION 13-13

LONGITUDINAL SECTION A-A

REVISIONS		
REV.	DESCRIPTION	DATE APPROVED

REFERENCES		
No	TITLE	DWG
1	GENERAL ARRANGEMENT OF FULL SIZE STEAM GENERATOR	203
2	SUPERHEATER SECTION OF FULL SIZE 5TH GEN	203
3	SHELL SECTION OF FULL SIZE 5TH GEN	203
4	CROSS SECTION OF FULL SIZE 5TH GEN	203

TOLERANCES						
TEMP AT 48° ± 0.5° UNLESS OTHERWISE SPECIFIED						
	UP TO 4" DIA.	4" TO 6" DIA.	6" TO 12" DIA.	12" TO 18" DIA.	18" TO 24" DIA.	OVER 24" DIA.
1. DIMENSIONAL DIA.	± .0005	± .001	± .0015	± .002	± .0025	± .003
2. DIMENSIONAL HOLE	± .0005	± .001	± .0015	± .002	± .0025	± .003
3. DIA. DIA. COMPOUND	1/16"	1/8"	3/16"	1/4"	3/8"	1/2"
4. DIA. DIA. SURFACES	1/16"	1/8"	3/16"	1/4"	3/8"	1/2"
5. DIA. DIA. HOLE	± .001	± .002	± .003	± .004	± .005	± .006
6. PERPENDICULARITY	DIN 90 PER FOOT					
7. CONCENTRICITY	1/2 OF TOLERANCE OF DIA.					
8. CONCENTRICITY 1/8"	± .002					
9. CONCENTRICITY	± .001					
10. NON-CIRCULARITY	A.S.M.E. CODE TOLERANCE					
11. CHAMFER	1/16" TO 3/8" DIA. HOLE 3/16" OVER 42" DIA. - 3/8"					
12. TRAVEL	UP TO 4" DIA. HOLE 3/16" OVER 42" DIA. - 3/8"					
13. TAPER	1/16" TO 3/8" DIA. HOLE 3/16" OVER 42" DIA. - 3/8"					
14. TAPERLESS	1/16" TO 3/8" DIA. HOLE 3/16" OVER 42" DIA. - 3/8"					
15. TAPERLESS	1/16" TO 3/8" DIA. HOLE 3/16" OVER 42" DIA. - 3/8"					

1/16" NOTED ON DRAWING

AEC CONTRACT AT(111) 1280
B&W CONTRACT 610-0067-55
SODIUM HEATED STEAM
GENERATOR DEVELOPMENT

THE BABCOCK & WILCOX CO.

NEW YORK, NEW YORK

BOILER SECTION AND

OF FULL SIZE

STEAM GENERATOR

CODE IDENT NO	SIZE	DRAWING NO
92439	F	20952F

SCALE 1/2" = 1' WT 350# 7' 4" SUCT 8'

REVISIONS

NO.	DESCRIPTION	DATE	BY
1	AS SHOWN		

GENERAL NOTES

ESSSEL DESIGNED IN ACCORDANCE WITH THE 1965 EDITION OF ASME PRESSURE VESSEL CODE SECTIONS III AND VIII, CASE 2731-T

OPERATING CONDITIONS: 700 PSIG, 540°F

DESIGN PRESSURE: 800 PSIG

DESIGN TEMPERATURE: 540°F

MAINTENANCE: 24 HOURS

REFERENCES

NO.	TITLE	DATE
1	ASME CODE SECTIONS III AND VIII, CASE 2731-T	

THE BADCOCK & WILCOX CO.

NEW YORK, N.Y.

GENERAL ARRANGEMENT OF REHEATER

DRAWING NO. 32439 F

REV. 0

THE BADCOCK & WILCOX CO.
NEW YORK, N.Y.

REVISIONS			
NO.	DATE	BY	REASON

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 48" INCL.	OVER 48" TO 96" INCL.	OVER 96" INCL.
DECIMAL DIM.	±.003	±.005	±.005	±.010	±.015	±.020
FAC. DIM. MACH.	±1/64"	±1/32"	±1/32"	±1/16"	±1/16"	±1/8"
FAC. DIM. UNMACH.	±1/16"	±1/16"	±1/32"	±1/8"	±3/16"	±3/16"
DIM. FOR BURNING	±1/8"	±1/8"	±1/8"	±1/8"	±3/16"	±3/16"
MACH. SURFACE F.T.E.	±.001"	±.002"	±.002"	±.003"	±.003"	±.003"
VERTICALITY & PERPENDICULARITY	.004" PER FOOT					
CONCENTRICITY T.I.R.	1/2 OF TOLERANCE OF DIA					
ANGULARITY	0°-30'					
NON-CIRCULARITY	A.S.M.E. CODE TOLERANCE					
TRAVEL	UP TO 42" DIA. INCL. ±3/16"			OVR 42" DIA. ±3/8"		
STRAIGHTNESS	1/4" PER 20 FEET OF LENGTH					
*APPLICABLE ONLY WHEN NOTED ON DRAWING						

DWN BY *A. G. Evans*
CHKD BY *A. J. Higgins*
EXAM BY *A. J. Higgins*
APPD BY *A. J. Higgins*
DATE *5-21-64*

APPROVED

THE BABCOCK & WILCOX CO.
NEW YORK, NEW YORK

CROSS SECTIONS
OF
REHEATER

CODE IDENT. NO.	SIZE	DRAWING NO.	REV.
92439	F	20955 F	0
SCALE 3/4"=1'-0"	WT.	SECT.

FIG. A

TABLE 1
BOILER SECTION

Parameters for One Unit

Three Units Required
for 1000 MWe

Design Conditions

Sodium Temperature	1200 F
Sodium Pressure	200 psi
Steam Temperature	815 F
Steam Pressure (Nominal)	2725 psi

Operating Conditions (Full Load)

Heat Load	1734 x 10 ⁶ Btu/hr
Sodium Flow	15.59 x 10 ⁶ lb/hr
Sodium Inlet Temperature	1013 F
Sodium Outlet Temperature	644 F
Sodium Pressure Drop	1.8 psi
Steam Flow	2.403 x 10 ⁶ lb/hr
Feedwater Temperature	530 F
Outlet Temperature	750 F
Outlet Pressure	2565 psia

Material

Tubes	Croloy 2-1/4 T-22
Snells, 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.	676	1" O.D. x .120" MW	60 ft.
Film Boiling Section	676	1" O.D. x .145" MW	53 ft.
Superheat Section	676	1" O.D. x .165" MW	18.4 ft.
Total Length			131.4 ft.
Overall Heat Transfer Coefficient			
Economizer			589 B/hr/ft ² F
Boiler			709 B/hr/ft ² F
Nucleate Boiling			464 B/hr/ft ² F
Film Boiling			473 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

Total

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

Boiler Inlet Tubes

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

Boiler Outlet Legs

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

Pressure Drop (Steam Side)

Boiler Inlet Legs	25.2 psi
Economizer	6.52 psi
Boiler	1.00 psi
Nuclear Boiling Section	26.30 psi
Film Boiling Section	19.54 psi
Superheater	47.54 psi
Outlet Legs	127.40 psi
Total	

Transverse Tube Spacing S _T	1.50"
Parallel Tube Spacing S ₁₁	1.375"

TABLE 2
SUPERHEATER

Parameter for One Unit	Three Units Required for 1000 MWe
------------------------	--------------------------------------

Design Conditions

Sodium Temperature	1200 F
Sodium Pressure	200 psi
Steam Temperature	1100 F
Steam Pressure	2675 psi

Operating Conditions (Full Load)

Heat Load	596 x 10 ⁶ Btu/hr
Sodium Flow	15.59 x 10 ⁶ lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	1013 F
Sodium Pressure Drop	6.7 psi
Steam Flow	2.403 x 10 ⁶ lb/hr
Steam Inlet Temperature	750 F
Steam Outlet Temperature	1050 F
Outlet Pressure	2465 psia

Material

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

Heat Transfer Results

Tubes - Number	1220
Size	7/8" O.D. x .120" MW
Effective Length	40.6 ft.
Overall H.T. Coefficient	361.5 B/hr/ft ² F
IMTD	161.3 F
Surface	11,330 ft ²

Superheater Inlet Tubes

Size	7/8" O.D. x .120" MW
Material	TP-316 SS
Length	28 ft.

Outlet Tubes

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

SUPERHEATER
TABLE 2 (CONT'D)

Pressure Drop (Steam Side)

Downcomer Tubes	15.64 psi
Tube Bundle	28.30 psi
Outlet Tubes	<u>21.26</u> psi
Total	65.20 psi

Transverse Tube Spacing S _T	1.25"
Parallel Tube Spacing S ₁₁	1.25"

TABLE 3

REHEATER

Parameters for One Unit

Three Units Required
for 1000 MWe

Design Conditions

Sodium Temperature	1200 F
Sodium Pressure	200 psi
Steam Temperature	1050 F
Steam Pressure	625 psi

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 1-22
Tubes (Section C, Outlet Tubes)	Croloy 5 T-5
Shell	Croloy 2-1/4
Tube Sheets, Heads	Croloy 2-1/4

<u>Heat Transfer Results</u>	<u>Number</u>	<u>Size</u>	<u>Effective Length</u>
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 .055" M.W.	26.06 ft
Section C	752	1-1/2" O.D. x .225" M.W.	18.90 ft
			100.16 ft
	Heat Transferred	<u>L.M.T.D.</u>	Overall Heat Transfer Coef.
	(BTU/hr)		(Btu/hr./ft ² F)
Tube Bundles 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°	166.7
Total	326.7×10^6		

Fouling Factor 3333 Btu/hr/ft² F.

Corrosion Allowance 0.009 inches.

REHEATER
TABLE 3 (CONT'D)

Heat Transfer Surface

Section A	15,780 ft ²
Section B	8,280 ft ²
Section C	<u>5,580 ft²</u>
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	<u>7.83 psi</u>
Total	25.68 psi

Transverse Tube Spacing S_T	2"
-------------------------------	----

Parallel Tube Spacing S_{11}	2"
--------------------------------	----

TABLE 4

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

3.4 FEASIBILITY STUDY OF INTEGRAL REHEATER STEAM GENERATOR DESIGN:

A study is in progress of locating the Reheater within the same shell as the boiler and superheater. By making optimum use of the temperature difference between the sodium and the steam it may be possible to decrease the overall cost of the steam generator unit. By having the sodium flow in parallel through the superheater and reheater, then mix and flow through the boiler the log mean temperature difference for the reheater will be improved. Less heat transfer surface will be required for the reheater although some additional boiler surface will be required.

Drawing SK-1000-1 shows one concept of an integral reheater steam generator. The steam generator is designed to have the same performance as the Full-Size Steam Generator, including the Reheater. This design concept has tube sheets in the sodium at the boiler inlet and outlet.

Present Status:

This design depends on having tubesheets for the boiler inlet and outlet submerged in the sodium. Stress calculations show that the temperature stresses for the boiler outlet tubesheets are too high if these tubesheets are not provided with some protection on the sodium side. Thermal blocks have been used on sodium-heated steam generators in the past, and testing of these steam generators has shown that in some cases the thermal blocks did not provide the protection expected. On reviewing these previous designs it appears that clearances between

the thermal blocks and the tubesheets or shells were excessive so that sodium could circulate behind the thermal block by natural convection. From the studies that have been made so far it appears that the clearance between the thermal block and the tubesheet is a very critical item. The study of this portion of the design is continuing.

DESIGN DATA
STEAM SIDE

STEAM FLOW RATE - 180,000 LBS/H
 " " " " - 15,000 LBS/H S.H.
 " " " " - 3,000 LBS/H R.H.
 DESIGN PRESSURE - 2,500 PSIG
 " TEMPERATURE - 1,050°F
 HEATING SURFACE (EFFECTIVE):
 BOILER - 34,573 SQ. FT.
 S.H. - 12,574 SQ. FT.
 R.H. - 8,348 SQ. FT.
 REHEATER PRESS. - 1,500 PSIG
 " TEMP. - 1,000°F

SODIUM SIDE

SODIUM FLOW RATE - 10,000 LBS/H TOTAL
 " " " " - 15,000 LBS/H S.H.
 " " " " - 3,000 LBS/H R.H.
 DESIGN PRESSURE - 300 PSIG
 " TEMP. - 1,100°F

INTEGRAL SODIUM HEATED
NUCLEAR STEAM GENERATOR
 (BOILER - SUPERHEATER - REHEATER)
 1000 MWE
SK-1000-1

8-25-1963
 REVISED 9-17-

3.5 30 MWt PROTOTYPE STEAM GENERATOR:

Design work on the Prototype Steam Generator is in progress. To model the performance of the Full-Size Steam Generator as closely as possible the tube diameters and lengths will be the same in the Prototype as in the Full-Size Steam Generator. The number of tubes will be scaled down to give the smaller capacity of the Prototype. Since the layout drawings have not been completed for the Prototype Sketch SK-051568 is included in this report. This drawing shows the general size and arrangement of the Prototype Steam Generator. The design and performance data for the Prototype Steam Generator are tabulated on Tables 5 and 6. The Prototype will have twenty-five 1" O.D. tubes in the boiler bank and forty-five 7/8" O.D. tubes in the Superheater. Only one tubesheet and thermal sleeve will be required for each boiler inlet, boiler outlet, superheater inlet and superheater outlet. It is not planned to build a Prototype of the Reheater because the problems of the Reheater will be essentially the same as the problems in the Superheater, and in the Superheater the problems will be more severe because the pressures and temperatures are higher.

Present Status:

A layout drawing of the 30 MWt Prototype Steam Generator has been made. An accurate cost estimate is being made of the Prototype as rapidly as possible in order to compare the cost of the Prototype with the original estimate contained in the Proposal on which this Contract

was based. This cost estimate will be completed approximately on
July 1.

51'-2 $\frac{3}{8}$ " OVERALL LENGTH (APPROX)

GENERAL ELEVATION SECTION

DESIGN PRESSURES

SHELL SIDE (SODIUM SIDE) = 300 PSIG
 FEEDWATER INLET (WATER SIDE) = 2825 PSIG
 BOILER OUTLET (") = 2725 PSIG
 SUPERHEATER INLET (") = 2700 PSIG
 OUTLET (") = 2675 PSIG

MATERIAL

SHELL & HEADS - CROLOY 2 1/4
 BOILER BANK & TUBE SHEETS - CROLOY 2 1/4
 SUPERHEATER BANK & TUBE SHEETS - TYPE 316 ST ST
 SODIUM INLET & BY-PASS SYSTEM - TYPE 316 ST ST

CODE

ASME SECTION VIII WITH NUCLEAR CASE RULINGS

PLAN VIEW

SECTION "A-A"

PROPOSITION DRAWING OF PROTOTYPE

25 MWT SODIUM STEAM GENERATOR

ALE 5-15-63

ORDER NO G10 0067-45

THE BABCOCK-WILCOX CO
 BARBERTON OHIO

SK-051508

TABLE 5

30 MWT PROTOTYPE STEAM GENERATOR
BOILER SECTION

Parameters for One Unit

Design Conditions

Sodium Temperature	1200 F
Steam Temperature	800 F
Steam Pressure	2725 psi

Operating Conditions (Full Load)

Heat Load	64.0×10^6 Btu/hr
Sodium Flow	583,000 lb/hr
Sodium Inlet Temperature	1013 F
Sodium Outlet Temperature	650 F
Sodium Pressure Drop	1.8 psi
Steam Flow	88,750 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.	25	1" O.D. x .120" MW	59 ft.
Film Boiling Section	25	1" O.D. x .145" MW	53 ft.
Superheat Section	25	1" O.D. x .165" MW	19 ft.
Total Length			131 ft.
Overall Heat Transfer Coefficient			
Economizer			584 B/hr/ft ² F
Boiler			618 B/hr/ft ² F
Nucleate Boiling			455 B/hr/ft ² F
Film Boiling			459 B/hr/ft ² F
Superheater			3333 B/hr/ft ² F
Fouling Factor			0.009 inches
Corrosion Allowance			

BOILER SECTION
TABLE 5 (CONT'D)

Heat Transfer Surface

Total	857.6 ft ²
Economizer	331.5 ft ²
Boiler Nucleate Boiling	52.4 ft ²
Film Boiling	352.0 ft ²
Superheater	121.7 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)

Economizer	6.3 psi
Boiler Nuclear Boiling Section	1.26 psi
Film Boiling Section	30.9 psi
Superheater	19.95 psi

Transverse Tube Spacing ST	1.50"
Parallel Tube Spacing S ₁₁	1.375"

TABLE 6
30 MWT PROTOTYPE SUPERHEATER
SECTION

Parameters for One Unit

Design Conditions

Sodium Temperature	1200 F
Steam Temperature	1090 F
Steam Pressure	2675 psi

Operating Conditions (Full Load)

Heat Load	22.1×10^6 Btu/hr
Sodium Flow	583,000 lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	1013 F
Sodium Pressure Drop	6.7 psi
Steam Flow	88,750 lb/hr
Steam Inlet Temperature	750 F
Steam Outlet Temperature	1050 F
Outlet Pressure	2465 psia

Material

Tube	SA-213 TP 316 SS
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	41.9 ft.
Overall H.T. Coefficient	348.5 B/hr/ft ² F
LMTD	161.2 F
Surface	432 ft ²

Superheater Inlet Tubes

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

Outlet Tubes

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

Pressure Drop (Steam Side)

Tube Bundles	68.9 psi
Transverse Tube Spacing S _T	1.25"
Parallel Tube Spacing S ₁₁	1.25"

4. RESEARCH AND DEVELOPMENT PROGRAM:

Research and development work has been approved under this Contract on the following projects:

1. Materials - carbon transfer and effect on material properties
simulating Full-Size Steam Generator.
2. Heat Transfer - Effect on heat transfer and two-phase flow of
coiling tubes.
3. Corrosion of Croloy 2-1/4 in products of sodium-water reaction.
4. Procedure for welding tube to back side of tube sheet.
5. Radiographic inspection of back side tube welds.
6. Chemical simulation of sodium environment for leak testing.
7. Sodium-Water Reaction - Engineering Analysis

The problem to be solved and the general scope of each project is described on the following pages along with a short description of the present status of each project.

4.1 MATERIALS - Carbon transfer and effect on material properties simulating

Full-Size Steam Generator:

Background Information

There are actually two problems relating to materials and their application for a sodium-heated steam generator. There is the problem of carbon and mass transfer on the sodium side of a tube, and also the problem of possible accelerated corrosion at the location of Departure from Nucleate Boiling on the steam side of the tube.

It is well known that materials used in sodium systems above 900 F undergo mass transfer whereby materials are dissolved from the tube walls in the hot zones and deposited in the cooler zones. In addition to this, there is a tendency for ferritic materials such as Croloy 2-1/4 to decarburize in sodium and for the carbon to deposit out on austenitic stainless steel surfaces in the same sodium circuit. Considerable work has been done on mass transfer and carburization-decarburization problems, but it is evident that further work is required to determine if these problems will be of concern in a closed loop with the relative quantities of Croloy 2-1/4 and Type 316 Stainless Steel involved in this design.

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 24 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 in a zone of low heat flux. The relatively low heat flux at the DNB point comes about because of the necessity of protecting the tube from overheating ("burnout") when nucleate breaks down and film boiling sets in.

In this sodium-heated boiler there are no extremely high temperatures such as found on the gas side of a fossil fuel fired boiler, but because sodium is so much better a heat transfer medium than gas there can be very high heat fluxes with moderate temperature differences between sodium and water.

Tests which have been conducted on model once-through sodium-heated steam generators at temperature levels below those for which this boiler is being designed showed a small amount of corrosion had taken place. It is felt that further experimentation is required at the temperature levels of interest for this steam generator to be able to say with assurance that serious corrosion will not occur.

Objective

The purpose of this program is to study the carbon and mass transfer effects in a sodium-heated steam generator containing both austenitic and ferritic materials, and to determine that these materials will be satisfactory on both the sodium and the water side for use under the planned operating conditions.

Scope

A schematic diagram of the test apparatus is shown on Figure 1. The test boiler will consist of a one-tube model steam generator having

a Croloy 2-1/4 boiler section and a Type 316 Stainless Steel superheater section. The proportion of Croloy 2-1/4 and Stainless Steel will be arranged to simulate the proportions of these materials in the Full-Size Steam Generator, and the ratio of surfaces exposed to volume of sodium will be made to duplicate the full-size boiler as closely as possible. Sodium will be circulated outside the tube in the model boiler at full rates and temperatures simulating the full-load boiler, and steam will be generated within the tube at pressures and temperatures similar to the full-load boiler. The sodium system consists of an electromagnetic pump, flow meter, sodium heater, plugging indicator, cold trap, and pump. The water-side system includes a reservoir, pump, heater, boiler and superheater, condenser-cooler section and a back pressure regulator.

In operation, water will be circulated from the reservoir by a recirculating pump into the boiler section at a pressure of 2450 psi and 600 F. Steam will leave the superheater at 2400 psi and 1050 F. The superheated steam is passed through a condensing cooler section, through a back pressure regulator to control the system operating pressure, and back into the reservoir for recirculation.

The sodium system will include the necessary accessory components to provide the required operating conditions and to maintain any sodium purity.

The test operation will continue for approximately one year during which the unit will be subjected to steady-state conditions as

well as transient operation. In this way, the full range of anticipated service will be duplicated. Samples will be removed and examined during the test operation to get preliminary test results. Following the test, the unit will be disassembled and the materials examined by appropriate techniques such as metallographic, electron microprobe, electron microscope, and spectrographic means.

Program Schedule

The following tables shows the estimated schedule for the program described above:

<u>Program Schedule</u>	<u>No. of Weeks</u>
Design & Construction	16
Testing	52
Analysis & Report	<u>6</u>
Total	74

Present Status:

On April 2, 1964 initial operation was started for purposes of debugging the equipment, and instrument and control evaluation. Early in the initial operation, it was determined that the desired sodium temperature could not be achieved due to the low power factor (approximately 0.5) of the main sodium heater. The cause of the low power factor was determined to be a highly inductive circuit produced by a high self-inductive reactance due to the specific geometry of the sodium heater piping. To reduce the effect of this reactance, it was decided to increase the electrical resistance of the heater by inserting

a 3/4-inch pipe inside the existing 1-1/4-inch pipe to allow the sodium to flow through the annulus formed by the two pipes. Measurements subsequent to this modification showed that the power factor had been increased to about 0.8, thereby satisfactorily providing the required heat input for the sodium temperature.

Operation of the modified heater at full load conditions revealed a severe vibrational problem. In effect the 3/4-inch pipe fixed at each end had a natural frequency for the first harmonic of approximately 63 cycles per second and was in resonance with the current flow. To eliminate this vibrational problem, it was decided to pack the 3/4-inch pipe with sand which would reduce its natural frequency for satisfactory operation. This was accomplished and subsequently improved by replacing the sand with a magnesium oxide having a higher density and further eliminated vibration effects.

Operation at full loop test conditions indicated that the overall heat transfer surface of the boiler and superheater were adequate. However, the steam temperature at the boiler outlet was higher than the desired 750 F. Heat transfer analysis of temperatures through the boiler and superheat circuit indicated that the superheated steam film conductance was considerably less than calculated. To eliminate this problem, the boiler and superheat surfaces were reproportioned.

Continuous operation of the model loop was achieved at all desired test conditions on May 20, 1964. It is planned to operate the test loop for approximately one year at full temperature, shutting down

periodically to remove samples for analysis, but not adding any new material to the loop. The first shut down is scheduled for mid-July following approximately 1000 hours of loop operation.

FIG. 1

3-20-64

4.2 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 available in the cylindrical steam generator vessel.

Objective

The purpose of this program is to determine the effect of making a tube in a coil configuration on:

- 1) The location of the Departure from Nucleate Boiling,
- 2) The nucleate and film boiling heat transfer conductances.

The results of this program are essential to be able to determine accurately the amount of heat transfer surface required for the steam generator being designed under this Contract and to be assured the tubes will not suffer fatigue or corrosion failure due to temperature fluctuations at the DNB point.

Scope

In this R&D Program we are fortunate that the test facility is already in existence at B&W's Alliance Research Center. This facility has been in use for a number of years investigating boiling problems, and the operation of the facility and techniques for obtaining reliable data have already been proven out.

A schematic diagram of the test facility is shown on Figure 2. It will be noted that there are two separate water loops in this test facility. Each has pumps, flow measuring devices, and a flow control valve. One loop flows through the once-through boiler to the mixing tee. By adjusting the flow in this loop and the heat input to the gas fired once-through boiler it is possible to obtain steam at various enthalpies entering the mixing tee. The other water loop is unheated and flows directly to the mixing tee. By mixing the flow from these two loops it is possible to adjust the enthalpy of the mixture entering the electrically heated test section over a wide range. This allows independent control of the location of the DNB point in the test section,

and the heat input. The versatility of this test facility has proven to be of great value in the study of the DNB problems and film boiling. The steam leaving the electrically heated test section passes through a throttle valve then is condensed and recirculated through the test facility. A demineralizer and deaerator are installed to maintain the purity of the water in the facility.

For this program, a curved test section will be fabricated and installed in this test facility. This test section will be operated over a range of heat fluxes and water velocities simulating the operating conditions of the Full-Size Boiler. The test section will be instrumented with thermocouples and voltage taps. The location of the point of DNB will be determined, and the effect on tube temperature recorded. These data will be compared with similar data for straight tubes to determine the effect on boiler design.

Program Schedule

The following table shows the estimated schedule for the proposed program:

<u>Program Schedule</u>	<u>No. of Weeks</u>
Design & Construction	20
Testing	20
Analysis & Report	<u>16</u>
Total	56

Present Status:

Data taking is complete for this project. Two different radii of

helical coils have been tested. One was a 16" radius simulating the inner coil of the Full-Size Steam Generator and one was a 65" radius coil simulating the outer coil of the Full-Size Steam Generator. These data are being compared with data at similar pressures, heat fluxes and mass flows for a straight vertical tube as reported by Swenson, Carver and Szoke of B&W Alliance Research Center in ASME paper Number 61-WA-201 entitled, "The Effects of Nucleate Boiling versus Film Boiling on Heat Transfer in Power Boiler Tubes").

Figure 3 shows a typical section of a coil with the location of the thermocouples indicated. It will be observed that thermocouples are located at each six inch interval along the heated length of the coiled test section and at each six inch location there are six thermocouples distributed around the hole. Between each thermocouple location is a voltage tap for measuring heat input. Figure 4 is a development of the 65" radius coil for one set of test conditions as if it were split lengthwise and opened out flat. This sketch shows very clearly the Departure from Nucleate Boiling occurring earliest at the zero and 360° positions which is the side of the tube toward the center of curvature, and shows the DNB occurring latest at the 180° position which is the side of the tube farthest from the center of curvature.

Figure 5 is a plot for a mass flow of 1.0×10^6 lbs/hr/sq.ft. and a pressure of 2600 psi showing the earliest and latest DNB points for various heat fluxes, in a straight tube, a 65" radius coil, and a 16"

radius coil. This is typical of the data which has been obtained for the various mass flows.

Figure 6 shows a plot of the temperature of the tube where DNB is first observed for the straight tube, the 65" radius coil and the 16" radius coil. It will be observed that the temperature excursion experienced at the DNB point is much less for either coil than for the straight tube. This is felt to be due to the way the transition of film boiling is spread out along a considerable length of tube and also the fact that the curvature of the tube has improved the heat transfer conductance under film boiling conditions.

These data are being written up and will be reported in B&W Research Report 4438.

SCHEMATIC OF HIGH PRESSURE BOILING WATER
HEAT TRANSFER APPARATUS

THERMOCOUPLE AND VOLTAGE TAP LAYOUT

PRESSURE = 2600 PSIA
 $Q/A_i = 200,000$ BTU/HR-SQ FT
 MASS FLOW, $G = 1.0 \times 10^6$ LB/HR-SQ FT
 65 INCH RADIUS COIL

DISTRIBUTION OF NUCLEATE BOILING & FILM BOILING SURFACE

EFFECT OF COILED TUBE ON DEPARTURE OF NUCLEATE BOILING(DNB)

COMPARISON OF INSIDE
SURFACE TEMPERATURE PROFILES

4.3 CORROSION RATES FOR CROLOY 2-1/4 STEEL IN PRODUCTS OF A SODIUM-WATER REACTION

Background Information

Tube failures, due to sodium-water reactions, can result from stress corrosion cracking, apparent metal fatigue, and bulk transcrystalline corrosion. Considerable interest has been generated in this latter type of metal failure, and little is known of its rates under the widely varying environmental conditions which can exist.

Examples of such corrosion can be found in the tube failures at Enrico Fermi Power Plant. In one area where a sodium-water reaction occurred, blisters with longitudinal cracks were noted. The wall thickness of the tube at the point of the reaction was reduced by about 1/2.

With such effects on tubes in a steam generator during a sodium-water reaction, it is necessary to know as much as possible about this corrosion caused by the products of reaction. This knowledge affects two areas of sodium-heated steam generator design — operation and materials selection.

During normal operation, hot sodium is circulated through the steam generator. If a sodium-water reaction occurs with its associated products of reaction, the station operator has two choices in regard to sodium flow, (1) shut off the sodium flow to the steam generator and permit sodium temperature to decay to the isothermal condition, or (2) keep the sodium flowing and maintain a specific temperature in the unit. Since the products and rates of reaction are temperature dependent, it may be advantageous to maintain a predetermined sodium temperature to lessen the corrosion effects of a sodium-water reaction.

The program described below is directed toward the assembly of the necessary test equipment, and the determination of corrosion rates for Croloy 2-1/4 steel in hot aqueous solutions of sodium hydroxide, and in suitably equilibrated solutions of sodium hydroxide in molten sodium. Corrosion rates in pure sodium will be determined in order to establish base values for this work.

Croloy 2-1/4 steel is used for this project since it is more susceptible to gross corrosion in a sodium environment than any of the stainless steels to be used for other parts of the system. Although the austenitic steels are more susceptible to stress corrosion, extensive work has already been done in this area by B&W and others. This data is available for use in the Sodium-Heated Steam Generator Development Program.

Objective

The objective of this program is to provide information pertaining to the rate of corrosion of Croloy 2-1/4 steel with reaction products of water-to-sodium leak. A second objective is to be able to postulate the mechanism of reaction between Croloy 2-1/4 steel and the sodium-water reaction products. With such information, it will be possible to determine if there are operational procedures which will reduce the corrosion effect of a sodium-water reaction on the tube material. Also, the tests will indicate what products of corrosion will affect the tube material and to what extent.

Scope

In a sodium-water reaction, the resulting products are sodium hydroxide, sodium monoxide, and at a temperature less than 300 F — sodium hydride. The most corrosive compound resulting from this

reaction is sodium hydroxide (aqueous). The rates of corrosion of Croloy 2-1/4 steel in hot aqueous solutions of sodium hydroxide will be determined. Corrosion products caused by the reaction can exist in almost any concentration. Therefore, the concentrations of sodium hydroxide will be varied from approximately 25 to 98 per cent, and corrosion tests will be made at five different temperatures for each concentration. Corrosion tests in these solutions will be made to temperatures as high as their boiling points at atmospheric pressure.

The corrosion testing of sodium hydroxide in sodium will be conducted on Croloy 2-1/4 at the saturation level at five temperatures varying from 400 to 1500 F. These tests will be made under a dry inert atmosphere. The solution will be stirred to renew the solid-to-liquid interface. Other tests will be performed with a partial pressure of hydrogen over the sodium-sodium hydroxide solutions to stimulate the presence of sodium hydride in the solutions.

In order to have a basis for comparison of tests, Croloy 2-1/4 specimens will be subjected to pure molten sodium at the same temperature as those used in the test.

Metallographic examinations of the specimens will be performed to ascertain any change which may occur in the grain structure of the metal, as well as the form of metallurgical damage. These specimens will be weighed before and after the corrosion tests are conducted to determine the loss of weight during the test period.

The experimental work outlined above will do two things. First, it will establish the effect of sodium hydroxide on Croloy 2-1/4 steel as a function of concentration and temperature of the sodium in a steam generator. Since the bulk temperature of the sodium in steam generator can be controlled, operating procedures can be written to minimize the

temperature effects of corrosion resulting from a sodium-water reaction.

Second, the amount and nature of corrosion can be determined. With this information, the extent of damage to a boiler tube bundle caused by sodium-water reaction can be estimated, and tube bundle life can be predicted.

Program Schedule

The time to complete this project will be approximately 56 weeks.

Present Status:

Some preliminary data have been obtained for the corrosion of Croloy 2-1/4 steel at 1250° F for periods of 48 hours and of 72 hours in sodium to which 0.25 weight percent NaOH was added. Calculations from these data indicate a rate of corrosion of approximately 40 mils per year under these conditions.

4.4 PROCEDURE FOR WELDING TUBES TO BACK SIDE OF TUBE SHEET

Background Information

An expanded and seal welded tube-to-tube sheet 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 the 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.

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

The Company has a machine under development for making inexpensive tube-to-tube sheet butt welds. The development of this welding machine, welding processes, and the quality control procedures will be completed to demonstrate a commercially feasible process for making the tube-to-tube sheet welds on the subject steam generator.

Scope

The development work under this program is to complete the development of the welding machine and quality control procedures and demonstrate the ability to produce sound welds in tubes of the sizes and materials used in the boiler being designed under this Contract.

For use with this welding machine, the tube sheets will be machined with projections or lips around each tube hole on the sodium face. A rod with an expanding grip will reach through the tube hole in the tube sheet into the end of the tube. An air cylinder will

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exert a pull on the rod to draw the end of the tube lightly against the projection on the tube sheet. A carefully controlled current will be passed through the rod and grip to the tube through the lip to the tube sheet and to ground. The resistance where the tube is held against the tube sheet will cause heating at this location and the air cylinder will force the tube against the lip and produce a weld. (This general procedure has been used in making tube-to-tube welds in the B&W shops for a number of years.)

Program Schedule

It is estimated that this program will be completed in approximately 12 months.

Present Status:

Demonstration welds have been made on the tube diameters and thicknesses of the Full-Size Steam Generator using a mock-up of this welding machine on a welding development apparatus. Making the welds has proven to be of no particular problem but making a weld that can be proven by x-ray techniques has been a problem. The metal that is extruded outward during the welding process has made it extremely difficult to distinguish a crack in a weld by x-ray techniques. Work has been held up on this project. A report is being written evaluating the results that have been obtained to date and outlining possible future work. This report will be reviewed with the Commission before further work is undertaken under this project.

4.5 RADIOGRAPHIC INSPECTION OF TUBE-TO-TUBE SHEET WELD

Background Information

By welding the tube to the back side of the tube sheet, it becomes possible to x-ray the weld to prove its integrity whereas an expanded and seal-welded tube-to-tube sheet 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. A conventional gamma ray source inserted inside the tube gives off its rays from too large a volume to give good definition in the picture. What is needed is a point source of x-rays located within the tube.

Scope

This program is to demonstrate the feasibility of constructing a point source for radiographing the tube-to-tube sheet welds.

If a small (1/16" diameter) sphere of some heavy element is bombarded with electrons, x-rays will be produced emanating from this 1/16" point. The source of electrons can be a Beta emitter such as Promethium 147. The heavy element target may be surrounded by the Promethium 147 to produce a composite source yielding x-rays from a 1/16" diameter point and the whole source will fit within a steam generator tube.

Present Status:

During discussions with a Subcontractor about developing this type of x-ray source this Subcontractor stated that he has such a source developed and will build one on a fixed-price basis. A request has been sent to this vendor for a quotation on a source suitable for x-raying the tubes of the Full Size Steam Generator or the Prototype Steam Generator. If this x-ray source can be purchased the development work planned under this project will not be needed.

4.6 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 to find a suitable reagent to leach out oxide inclusions in Croloy 2-1/4 and Type 316 stainless steel will proceed in the following two phases:

Phase I - Feasibility of various reagents for removing oxides:

The two reagents that appear attractive at this time are EDTA (Ethylene Diamine Tetracetic Acid) and Sulfamic Acid. It is planned to do rough-screening testing of the ability of these reagents to remove

oxides from Croloy 2-1/4 and stainless steel material.

Weld deposits on Croloy 2-1/4 and Type 316 stainless steel flat plate will be made under inert atmosphere. No fluxing material will be used. The weld beads will consist of oxides of elements present in the flat plate material. In addition to these, beads of molten slag will be deposited on flat plate specimens. Several different fluxes will be used to produce slags of different characteristics.

The ease of removal of the oxides in the beads by either EDTA or Sulfamic Acid will be determined. EDTA is more effective at higher temperatures, so the tests will be conducted at temperatures approaching the breakdown temperature of EDTA, (approximately 350 F). Semi-quantitative evaluation will be made by visual and low-power magnification (10x) study of the test specimens after treating with the solutions.

Phase II

If either of these two reagents appear feasible for this application, test specimens can be made up with known oxide inclusions and more exacting techniques used in evaluating the effectiveness of these solutions.

Present Status:

This project is a small one with a long span time. Work is not carried on continuously and no work was done during the month of March.

4.7 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, et 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 relationships is known with accuracy 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 erratic.

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.

Objective

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.

Present Status: Subcontract No. 1 AEC Contract No. AT(11-1)-1280

(Quoted from APDA Report to B&W)

Review of the literature concerning sodium-water reactions is near completion. Fifty six references have been accumulated to date which deal with various aspects of the reaction between water and the alkali metals. Forty-five of these have been examined with respect to reaction chemistry, thermal effects, pressure effects, corrosion effects and application to steam generator design. Upon completion of the review, a summary of the information relevant to this study and a bibliography will be presented.

References to six separate failures of NaK-and sodium-heated steam generators have been found in the literature. Also nine NaK-and sodium-water reaction test series have been conducted in relation to steam generator design. Tabulations of these tests and failures will be presented in the summary referred to above. A review of the data from various tests has been initiated.

5. CRITICAL PATH SCHEDULE

One of the requirements of this Contract is to schedule the work according to a PERT schedule or equivalent.

A Critical Path Schedule has been prepared for the design work of Phase I. (This is the preliminary design of the Full-Size Unit and preliminary design of the 30 MWt Prototype). The schedule will be expanded to include the R&D work as soon as the various projects are laid out in enough detail. The schedule for Phase II (detail drawings, procurement of materials, fabrication and delivery of the 30 MWt Prototype) will be added as soon as possible to facilitate the Commission's planning for SCTI.

In preparing the portion of the schedule for Phase I, the design work was broken down into individual tasks and an arrow diagram made showing the inter-relation of these tasks. The time to complete each task was estimated. In general, the statistical mean time,

$$T_{\text{mean}} = \frac{T_{\text{min}} + T_{\text{max}} + 4 T_{\text{avg}}}{6}$$

was used, although this was modified in some cases based on experience.

The schedule and times were run on a Critical Path Method program on the Burroughs 220 Computer. This program developed the Critical Path Schedule that was plotted with a time scale as the ordinate to portray the schedule as clearly as possible.

The critical path can be recognized easily as the dark line, and tasks along this line set the overall time span for the whole project. Other tasks have "float" time — shown as dotted lines. These tasks can float over a considerable time period to make optimum use of manpower without affecting the completion of the overall project. A wavy line above the regular task arrows indicates the progress of the task in relation to the calendar times found at the bottom of the chart.

A short vertical line in front of the wavy line indicates the task started, and two short vertical lines at the end of the wavy line indicate the task finished. Delayed starts are possible for all tasks which have "float" time and are not on the critical path. If a task on the critical path is started late and not finished on time the whole project may be delayed.

By comparing the status of each task with the large arrow indicating the date of this report it can easily be seen if the task is ahead, on, or behind schedule.

The chart of the complete Critical Path Schedule for the Preliminary Design of the Full-Size Steam Generator and 30 MWt Prototype Steam Generator was included in Progress Report #1 for May, 1963, and was again in Progress Report #6 for October, 1963. The intervening progress reports contained a portion of the schedule chart showing work in progress.

Present Status:

The design work on Phase I of this Contract is approximately 76% complete. The design work on the Full-Size Steam Generator is completed and the design work on the Prototype Steam Generator is approximately 25% completed. The Critical Path Schedule Chart is being revised to include the manufacturing of the Prototype Steam Generator and detail drawings. When the new chart has been drawn up it will be included in the Progress Report.