TID-20724

PROGRESS REPORT 12

April, 1964
to

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

NOTICE

This report contains patentable, preliminary, unverified, or erroneous information. For one or more of these reasons the author, or issuing installation and responsible office have limited its distribution to Governmental agencies and their contractors as authorized by AEC Manual Chapter 3202-062. A formal report will be published at a later date when the data is complete enough to warrant publication.

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

~~NOT FOR PUBLIC RELEASE - OFFICIAL~~
~~DISTRIBUTION MAY BE MADE - OFFICIAL~~
~~REQUESTS MAY BE FILLED - REPORT~~
~~CONTAINS NOTHING OF PATENT INTEREST~~
~~PROCEDURES ON FILE IN RECEIVING~~
~~SECTION~~

This report has not been cleared for publication. It is sent to the recipient for official governmental purposes only and should not be published or further disseminated until officially reviewed and released for publication.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PROGRESS REPORT 12

April, 1964
to

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

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

SODIUM-HEATED STEAM GENERATOR
DEVELOPMENT

Facsimile Price \$ 6.60
Microfilm Price \$ 2.30

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

Signed: Paul Perbet

THE BABCOCK & WILCOX CO.
BOILER DIVISION
BARBERTON, OHIO

DISTRIBUTION LIST

R. B. Abderhalden - Baldwin-Lima-Hamilton Corporation
R. U. Blaser - B&W Alliance Research Center
T. M. Campbell - B&W Alliance Research Center
Dr. K. P. Cohen - General Electric Company
G. D. Collins - General Electric Company
R. Cygan - Atomics International
J. K. Davidson - Allis-Chalmers Manufacturing Company
H. F. Dobel - Lynchburg
Dr. O. E. Dwyer - Brookhaven National Laboratory
Dr. D. T. Eggen - Atomics International
F. M. Heck - Westinghouse Electric Corporation
J. Holliday - USAEC, California
W. A. Keilbaugh - B&W Alliance Research Center
K. D. Kuczen - Argonne National Laboratory - R. E. Div.
J. V. Levy - USAEC, California
R. W. Lockhart - General Electric Company
B. MacPherson - UCC - ORNL
F. C. Mattmueller - USAEC, Chicago
D. B. Miller - B&W Production Control
J. Morabito - APDA, Detroit
H. S. Potter - USAEC, New York
C. A. Pursel / G. C. Gower - USAEC, Chicago
J. P. Rowe - B&W Alliance Research Center
W. Savage - ORNL
W. R. Simmons - ANL
G. L. Skinkle - Chicago Sales
C. G. Stevenson - General Electric Company
H. S. Swenson - B&W Alliance Research Center
L. G. Troutman - B&W New York
S. Visner - Combustion Engineering Inc.
Dr. G. W. Wensch - USAEC, Washington
Dr. R. C. Werner - MSA Research Corporation
J. Wise - USAEC, New York
R. Wykoff - LASL

TABLE OF CONTENTS

	PAGE
ABSTRACT	1
INTRODUCTION	2
DESIGN WORK	3
Full Size Steam Generator	6
Reheater	9
Feasibility Study of Integral Reheater Steam Generator Design	10
30 MWt Prototype Steam Generator	11
RESEARCH & DEVELOPMENT PROGRAM	13
Materials - carbon transfer and effect on material properties simulating Full Size Plant	14
Effect on Heat Transfer and Two-Phase Flow of Coiling Tubes	19
Corrosion Rates for Croloy 2-1/4 Steel in Products of a Sodium-Water Reaction	24
Procedure for Welding Tubes to Back Side of Tube Sheet	28
Radiographic Inspection of Tube-to-Tube Sheet Weld	30
Chemical Simulation of Sodium Environment for Leak Testing	31
Sodium-Water Reaction--Engineering Analysis	33
CRITICAL PATH SCHEDULE	36

ABSTRACT

This is the twelfth Monthly Progress Report on this Contract. This report contains some information on the history and scope of work on this Contract in addition to a description of the present status of the work.

The tabulations of design and operating characteristics have been revised to bring them up-to-date.

In order 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" included in each of the major sections of this report. In the Present Status is summarized the work that has been accomplished in the past month.

Design Work under Phase I of this Contract is approximately 72% complete. The Preliminary Design Report for the Full Size Steam Generator is being written and should be completed by the end of May. Design work on the Prototype Steam Generator is in progress.

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 & 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 supercritical 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 SK-520. Drawings SK-513, 514, and 515 show the shell, boiler bundle, and superheater from which this steam generator is assembled. These three pieces would be fabricated separately and assembled into the complete unit in the field.

By referring to SK-520 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 downward in tubes arranged in the annular space between the boiler bundle and the shell liner. 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.

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

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 that the dissimilar weld can be inspected easily and so that 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 pressures 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.

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

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.

3.2 Present Status:

Design work on the Full Size Steam Generator has been completed. The arrangement drawings are completed and have been photographed for the Preliminary Design Report. Cost estimates of the steam generator, with the exception of the Reheater, have been completed. The writing of the Preliminary Design Report on the Full Size Steam Generator is approximately 70% completed, and it is expected that the design report will be issued in the latter part of May.

3.3 REHEATER

The reheater will be located in a separate vessel situated as close as possible to the steam turbine to save reheat steam piping and pressure drop. Because of the comparatively high specific volume of the reheat steam, the steam piping is large and expensive. It will be less expensive to pump the sodium to the reheater located near the turbine than to take the steam from the turbine a long distance to the reheater.

3.3 Present Status:

Stress analysis work is completed on the Reheater. The arrangement drawings are nearly completed. As soon as the drawings are completed they will be photographed for inclusion in the design report. Cost estimating work is under way on the Reheater. As soon as the cost estimates are completed they will be included in the Preliminary Design Report.

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.

3.4 Present Status:

Since this design depends on having tube sheets in sodium at the boiler inlet and outlet the study work has concentrated on analyzing the feasibility of having boiler outlet tube sheets exposed to sodium. Calculations which have been made so far show that the steady-state thermal stresses in the tube sheet are quite high, although they have not ruled out the use of tube sheets in sodium. If ways can be found to have satisfactory life under both steady-state and transients additional design work will be begun on this concept.

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 tube sheet 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.

3.5 Present Status:

The layout drawing of the 30 MWt Prototype Steam Generator is being made in parallel with the preliminary stress analysis calculations. It has been found possible to make the boiler outlet and superheater inlet and outlet tube sheets the same size so that one set of dies can be used for making the forgings for these three tube sheets and covers. The material for the boiler outlet tube sheet will be Croloy 2-1/4 and the

material for the superheater inlet and outlet tube sheets will be Type 316 stainless steel, however. The boiler inlet tube sheet will be made full size of one tube sheet of the Full Size Steam Generator to model the stress problems at the thermal sleeve connecting the tube sheet to the steam generator shell.

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.
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

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-,/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 flow 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 table 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

4.1 Present Status:

This test loop is in the "shake down" phase of operation. When the sodium and water circuits had been filled and the loop was being brought up to temperature it was found that the power factor for the electric heater was very low and the current capacity of the power transformer was exceeded before the loop reached the desired temperature. Analysis of the electrical characteristics of the test loop showed that the loop piping had a significant inductive reactance for the high currents used in this heater. This was the cause of the low power factor and high, lagging current.

The sodium heater is a direct resistance heater utilizing the resistance of a section of the stainless steel piping and the contained sodium to generate the required heat. Electrical connections are welded to the pipe walls and connected to the power transformer. An analysis of the electrical characteristics of the loop indicated that if the resistance of the sodium heater could be increased and a higher voltage tap on the transformer used, the power factor would be improved. Since the current flows in parallel through the pipe walls and the contained sodium in the sodium heater, displacing some of the sodium from the heater would increase its resistance.

A sealed, air-filled core tube was fabricated and installed within the sodium pipe in the sodium heater. This core tube displaced enough sodium to increase the electrical resistance of the contained sodium in the heater and also increase the resistance of the over-all heater configuration. This increase in resistance, with a constant inductive reactance, improved the power factor so that the test loop could be brought up to temperature without exceeding the current capacity of the transformer.

When the heater was operated at high loads a severe 120 cps vibration was observed in the heater. Calculations showed that the core tube had a natural frequency near 120 cps so that the 60 cps ac power supply caused it to vibrate badly and the locating lugs on the core tube were banging against the inside of the sodium pipe. To add mass to the core tube and lower its natural frequency below the inherent 120 cps magnitization frequency the core tube was removed and filled with sand. The core tube was sealed and reinstalled in the test loop. With these modifications the test loop could be brought up to full operating temperature without difficulty.

As soon as the loop temperatures have been adjusted to model the temperature conditions of the Full Size Steam Generator as closely as possible the loop will be put on 24 hour per day 7 days per week operation.

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 failures 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

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 tube. 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.

4.2 Present Status:

These data are being written up in a Topical Report that will complete this R&D project. It is expected that this report will be issued in early June, 1964.

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 later 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 800 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 innerface. 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.

4.3 Present Status:

During the month of April a modification was made in the electrical circuit of the apparatus so that the stirrer and the heaters for the sodium are inactivated if either a high or a low-temperature signal is received.

Preliminary corrosion data have been obtained for Croloy 2-1/4 steel in pure sodium at 900°F for periods of 12 hours and of 48 hours. Specimens were exposed to pure sodium at 1250°F for 3-1/2 hours. Croloy 2-1/4 specimens have been corroded in sodium saturated with sodium hydroxide at 900°F for 48 hours and for 72 hours. Preliminary results indicate only a slightly greater rate of corrosion of Croloy 2-1/4 steel in sodium saturated with sodium hydroxide at 900°F than with pure sodium at 900°F.

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

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.

4.4 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.

4.5 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.

4.6 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 relations is known with any certainty at this time.

The sodium-water reaction at the time of a leak is a complex one. The reaction itself is almost instantaneous so the over-all limit is the mixing of the reactants. The hydrogen formed from the reaction tends to blow the reactants apart and they may come together again some distance from the leak. The reaction is not a steady one, but is very 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.

4.7 Present Status:

The Subcontract with APDA has been drawn up and is in the process of being approved. Work is proceeding in the meantime on the project as described above. A review of all existing sodium-water reaction test data is being made in preparation to writing the mathematical representation of the reaction fundamentals.

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.

5. Present Status:

One of the requirements of this Contract is to schedule the work according to a PERT schedule or equivalent. The design work on Phase I of this Contract is approximately 72% completed. The design of the Full Size Steam Generator is nearly completed and the design of the Prototype Steam Generator is just beginning. The Critical Path Schedule Chart is being revised to more closely represent the rest of the design work, and to include the manufacturing of the Prototype Steam Generator. When the new Critical Path Chart has been drawn it will be included in the Progress Report.

LAYOUT OF SHELL SECTION

SK-513

LAYOUT OF BOILER SECTION

SK-514

LAYOUT OF SUPERHEATER SECTION

SK - 515

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

Material

Tubes	Croloy 2-1/4 T-22
Shells, Heads	Croloy 2-1/4
Tube Sheets, Nozzles	Croloy 2-1/4

Heat Transfer Results

	Number	Size	Effective Length
Tubes - Econ. & Nucleate Boiling Sec.	676	1" O.D. x .120" MW	60 ft.
Film Boiling Section	676	1" O.D. x .145" MW	53 ft.
Superheat Section	676	1" O.D. x .165" MW	<u>18.4</u> 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

23,255 ft²

Economizer

9,380 ft²

Boiler

Nucleate Boiling

1,240 ft²

Film Boiling

9,380 ft²

Superheater

3,255 ft²

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

Nuclear Boiling Section

1.00 psi

Film Boiling Section

26.30 psi

Superheater

19.54 psi

Outlet Legs

47.54 psi

Total

127.40 psi

Transverse Tube Spacing S_T

1.50"

Parallel Tube Spacing S₁₁

1.375"

TABLE 2

SUPERHEATER

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

Material

Tube	SA-213 TP 316 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
LMTD	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.

SUPERHEATER
TABLE 2 (CONT'D)

Outlet Tubes

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

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 x 10 ⁶ Btu/hr
Sodium Flow	2.41 x 10 ⁶ lb/hr
Sodium Inlet Temperature	1140 F
Sodium Outlet Temperature	690 F
Sodium Pressure Drop (approximately)	4 psi
Steam Flow	1.71 x 10 ⁶ lb/hr
Steam Inlet Temperature	655 F
Steam Outlet Temperature	1000 F
Outlet Pressure	490 psia

Material

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

Heat Transfer Results

	<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 .095" M.W.	28.06 ft.
- Section C	752	1-1/2" O.D. x .225" M.W.	<u>18.90</u> ft.
			100.16 ft.

	<u>Heat Transferred</u> (BTU/hr)	<u>L.M.T.D.</u>	<u>Overall Heat Transfer Coef.</u> (Btu/hr./ft ² F)
Tube Bundle Section A	117.6 x 10 ⁶	52.1 F°	160.9
Section B	108.6 x 10 ⁶	89.3 F°	165.5
Section C	<u>101.2 x 10⁶</u>	122.8 F°	166.5
Total	326.7 x 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

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"

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

SK-1000-1

[illegible]

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 1/2

BOILER BANK & TUBE SHEETS - CROLOY 2 1/2

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

PROPOSITION DRAWING OF PROTOTYPE

25 MWT SODIUM STEAM GENERATOR

ALT 5-15-63

ORDER No 610-0067-45

THE BABCOCK-WILCOX CO
BARBERTON OHIO

SK-051568

FIG. 1

3-20-64

**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

LEAD ANGLE
 $6^\circ - 15'$

DISTRIBUTION OF NUCLEATE BOILING & FILM BOILING SURFACE

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

COMPARISON OF INSIDE
 SURFACE TEMPERATURE PROFILES