PROGRESS REPORT

BAW - 1280 - 15

July, 1964

to

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

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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Signed: Paul Probert

THE BABCOCK & WILCOX CO.
BOILER DIVISION
BARBERTON, OHIO

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ABSTRACT

This is the fifteenth Monthly Progress Report on this Contract. This report contains some background information on various phases of the work being done.

The Preliminary Design of the Full-Size Steam Generator is complete. Information on this design, including cost information, is included in the Preliminary Design Report on the Full-Size Steam Generator, BW 67-2. Data on the Full-Size Steam Generator has been deleted from the Progress Report, but can be found in either report BW 67-2 or in Progress Report 13.

Preliminary Design of the Prototype is in progress. The design work under Phase I of this Contract is approximately 89% 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, and the R&D Program.

2.1 HISTORY OF CONTRACT:

This Contract was received on March 20, 1963, and signed on April 3, 1963. The over-all 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 over-all 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 Phase I of this Contract is proceeding according to the Critical Path Schedule. 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 over-all 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 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 dèsign.

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 GENERATOR:

The Preliminary Design of the Full Size Steam Generator and Reheater is complete. Cost estimates were made and are included in the Design Report.

Preliminary copies of the Design Report on the Full-Size Steam Generator were submitted for comments. The report will be corrected based on these comments and will be issued within the next few weeks.

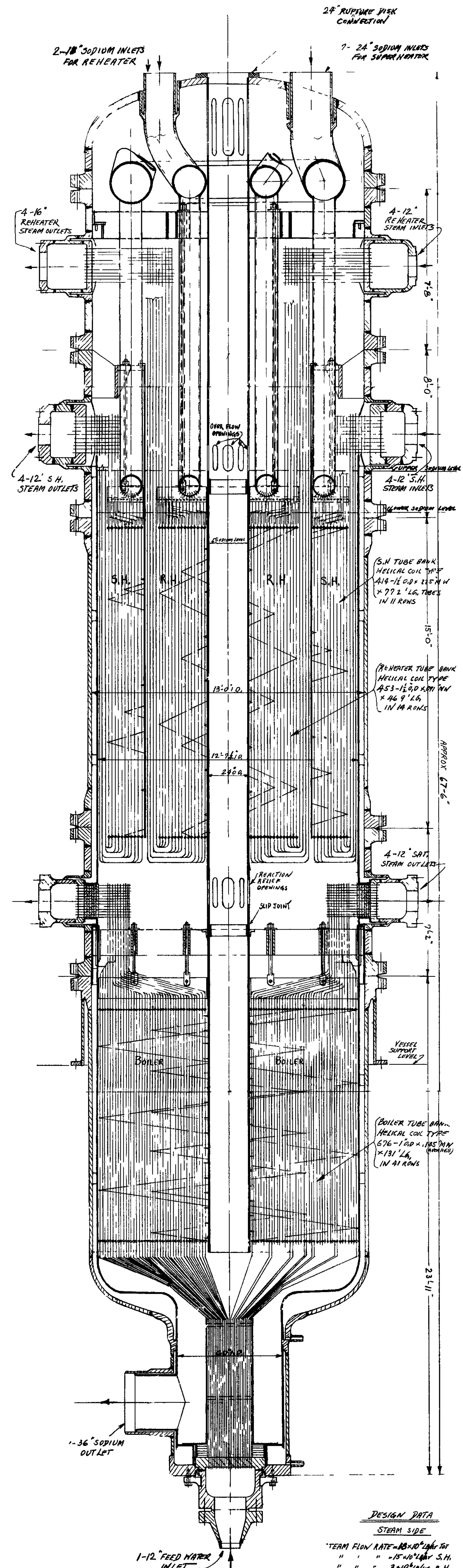
3.3 FEASIBILITY OF INTEGRAL REHEATER STEAM GENERATOR DESIGN:

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:

Layout drawings have been started to determine the optimum arrangement of superheater and reheater bundles within the shell. When a satisfactory arrangement is found a drawing will be made to obtain an approximate cost estimate of this steam generator. This approximate cost will indicate of the integral reheater steam generator design has a significant cost advantage over the steam generator with a separate reheater.



DESIGN DATA

STEAM SIDE

STEAM FLOW RATE = 18×10⁶ Lb/hr TOT
" " " = 15×10⁶ Lb/hr S.H.
" " " 3×10⁶ Lb/hr R.H.
DESIGN PRESSURE = 2500 PSI
" TEMPERATURE = 1050°F
HEATING SURFACE (EFFECTIVE):
BOILER = 34,573 Ft²
S.H. = 12,584 Ft²
R.H. = 8,338 Ft²
REHEATER DESIGN PRESS. = 500 PSI
" " TEMP. = 1000 F

SODIUM SIDE

SODIUM FLOW RATE = 18×10⁶ Lb/hr TOTAL
" " " = 15×10⁶ Lb/hr S.H.
" " " = 3×10⁶ Lb/hr R.H.
DESIGN PRESSURE = 300 PSI
" TEMP. = 1200 F

INTEGRAL SODIUM HEATED
NUCLEAR STEAM GENERATOR
(BOILER - SUPERHEATER - REHEATER)
1000 MWe

SK-1000-1

8-29-1963
REVISED 9-17-1963

3.4 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 1 and 2. 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.

Problem Areas of Full-Size Steam Generator and Modeling of These Problems in Prototype:

The primary purpose of the Prototype is to prove the structural integrity of this design under both steady-state and transient service so that the results can be extrapolated with confidence to the Full-Size Steam Generator. In addition to this, the Prototype will demonstrate any manufacturing problems that may later occur on the Full-Size Steam Generator and will provide an opportunity to solve these problems. Of secondary importance is the proving of the methods of calculating the performance used on the Full-Size and Prototype Steam Generator.

A sodium-heated steam generator will have the same problems as any steam generator, plus the problems that may result from the high heat transfer rates and very fast temperature changes that can occur when using sodium as a heat transfer fluid. The various problems studied under Phase I of this Contract, and how these problems will be modeled in the Prototype, are discussed below. Most of these problems were listed in Section 7 of the Proposal, but were not discussed in detail at that time. The problems are divided into four categories: stress problems, performance problems, material selection problems, and fabrication problems. Some of these problems can be adequately analyzed and do not require exact model testing in the Prototype Steam Generator.

A. Stress Problems:

The areas which have presented stress problems are as follows:

1. Tubesheets and Thermal Sleeves:

By locating the tubesheets out of the sodium up in the inert gas space, it has been possible to protect them from rapid sodium temperature transients, however, tubesheets for high-pressure service are a source of concern and the most sophisticated analysis techniques still leave a great deal to be desired. For this reason it was decided to model one tubesheet and thermal sleeve full size in the Prototype Steam Generator. The feedwater inlet tubesheet was selected because it has higher stresses than the boiler outlet, superheater inlet, or superheater outlet. Obviously with a 1/30-size model there will not be enough tubes to fill even one tubesheet with a full compliment of tubes. To model the deflection of the tubesheet under pressure and temperature stresses, the feedwater inlet tubesheet will be drilled with the full pattern of holes of the Full-Size Steam Generator. Some of these holes will have tubes attached to them, and the rest of the holes will be blind drilled from each side of the tubesheet leaving sufficient metal at the midplane to prevent leaks. The thermal sleeve nozzle, attaching the tubesheet to the shell, will also be modeled full size to study the way the temperature gradients and motions of the tubesheet are carried out into the thermal sleeve nozzle. Strain gages and thermocouples will be installed and these data will be used to prove the adequacies of analytical techniques used in analyzing these thermal sleeves and nozzles.

The boiler outlet, superheater inlet, and superheater outlet tubesheets will be designed to meet the needs of the Prototype and will not necessarily model the Full-Size Steam Generator.

2. Sodium Inlet Nozzle:

Although the sodium inlet nozzle sees rapid temperature transients, the pressure in the sodium system is low, the metal thicknesses are small, and the steady-state and ransient stresses are relatively low. There is a dissimilar weld in the thermal sleeve where the stainless steel sodium piping joins the Croloy 2 1/4 vessel. The sodium inlet nozzle for the Prototype Steam Generator is being designed to have approximately the same sodium velocity through the nozzle as the Full-Size Steam Generator. The thermal sleeve is of the same shape as will be used in the Full-Size Steam Generator, but because the nozzle is smaller in diameter the wall thicknesses are less and the thermal stresses in this nozzle will, in general, be less than in the Full-Size Steam Generator. It is not felt that this is of consequence because the stresses in this nozzle of the Full-Size Steam Generator have not proved to be a problem.

3. Sodium Outlet Nozzle:

The sodium outlet nozzle of the Full-Size Steam Generator will undergo a severe thermal transient during the "loss of feedwater" accident. The bypass valve in the center of the steam generator will open and allow 1140 F sodium to come down the center pipe into this nozzle. It was found that by arranging the sodium outlet nozzle of the Full-Size Steam Generator to have a small annular space between the thermal sleeve and the nozzle through which there is a controlled leakage of 650 F sodium from the space below the boiler bundle, it is possible to keep the stresses in this sodium outlet nozzle within reasonable limits. The sodium outlet nozzle of the Prototype Steam Generator will be of the same configuration. The sodium velocity through the nozzle will approximately duplicate the Full-Size Steam Generator. A controlled leakage path will be provided. Thermocouples and strain gages will be installed to observe the performance of this nozzle under both steady-state and transient conditions.

4. Flanges:

The large vessel flanges are protected against rapid temperature changes by the annular inert gas space between the liner and the shell. The rate of temperature change of these flanges is slow enough that there are no significant transient stress problems in these flanges. The operating pressure for the steam generator is so much lower than the design pressure that the normal operating stresses in these flanges and bolts will be extremely low. The flanges for the Prototype Steam Generator are designed on the same basis as the Full-Size Steam Generator. Because of the slow rates of temperature change and the low operating pressure, it is felt that no significant steady-state or transient stress will be developed in these flanges.

5. Tube Flexibility Problems:

Experience has shown that severe thermal expansion differences resulting in high thermal stresses can occur in sodium components. Portions of a number of sodium heat exchangers have operated beyond yield and a few have experienced tube failures due to differential expansion.

The riser and downcomer tubes of the Full-Size Steam Generator were carefully analyzed for flexibility using a sophisticated computer program to insure that the stresses in the tubes are within allowable limits.

Although the riser and downcomer tube configuration of the Prototype Steam Generator will not exactly duplicate the Full-Size Steam Generator, the same method of analysis will be used on the Prototype and its operation will demonstrate the adequacy of the method of calculation.

6. Vibration Problems:

Tube failures on one Enrico Fermi steam generator because of vibration has re-emphasized the importance of this problem. The tubes and other parts of the Full-Size Steam Generator have been analyzed for vibration. The support structure has been designed to keep the natural frequency remote from any forcing function, such as Von Karman vortices or 60 cps normal plant vibration. In addition to this, the steam generator has been analyzed for vibration during shipment in a horizontal position.

The same type analysis is being applied to the Prototype Steam Generator. Operation of the Prototype will prove out the adequacy of the method of analysis rather than modeling the vibration problems directly.

B. Performance Problems:

The Prototype Steam Generator will have tubes that are full size and full length of the Full-Size Steam Generator. It will inherently provide a reasonably good model of the steady-state performance of the Full-Size Steam Generator. Because of the smaller size of the Prototype it probably will not be possible to completely model the heat storage under transient conditions. Because of the relatively short duration of Prototype operation, it will not simulate creep and extended life effects.

1. Control Stability:

One of the problems of concern in the full-size plant is stable control under all conditions with three parallel heat transfer loops consisting of IHX's, pumps, steam generators, and reheaters. This problem has not been analyzed under this Contract. The control stability of the Full-Size plant should be studied and a simulation of the full plant from reactor to turbine generator made. Since the Prototype is a single unit and will be tested in a single loop at SCTI it will not be possible to simulate the control stability of a three-loop plant. The transient performance characteristics of the Prototype Steam Generator may be of help in deriving the equations for the simulation of the full-size plant, however.

2. Sodium Distribution:

The incoming sodium to the steam generator must be distributed over the superheater tube bundle uniformly without local high velocity streams to cause vibration of the tubes. In the design of the Prototype it is planned to study the distribution system more thoroughly using an inexpensive water model to develop in detail the distributor necessary to distribute the sodium evenly in the Prototype. After it has been proven out in the Prototype this type of distributor can then be extrapolated up to the Full-Size Steam Generator with considerable confidence.

3. Corrosion on the Water-Steam Side of the Steam Generator Tubes:

Under some circumstances severe internal corrosion of once-through steam generators can occur. There have been concern about stress accelerated corrosion at the location of Departure from Nucleate Boiling. The R&D Program conducted as part of this Contract on the Effect of Coiling a Tube on Heat Transfer and Two-Phase Flow has shown that these problems apparently are not nearly as severe as anticipated. The temperature cycling of the inner surface of the tube at the location of DNB is much less than had been predicted and should not cause any problem. In addition to this, the one-tube Model Steam Generator being operated in a sodium test loop as a part of this Contract will give additional information on corrosion within the tube. This Model Steam Generator is being operated with heat fluxes and thermal gradients equal to or higher than the Full-Size Steam Generator. At the end of the test program this steam generator tube will be cut up and examined for signs of corrosion. Although no problems are expected, the Prototype Steam Generator will model exactly the flow conditions and heat transfer of the inner rows of tubes of the Full-Size Steam Generator and, therefore, will model exactly any corrosion conditions that may occur.

C. Materials Selection Problems:

To meet the objective of designing economical steam generators, the designer must use inexpensive materials to as close to their use limits as possible. In this steam generator it is planned to use Croloy 2 1/4 material for the boiler bundle because it is relatively inexpensive and has superior strength up to a temperature of approximately 1000 F. For the superheater bundle, where the metal temperature may be as high as 1140 F in some locations, Type 316 stainless steel was chosen because based on presently available data, Type 316 has superior strength and, therefore, will cost less as applied to this superheater than any of the other materials. A study was made of mass transfer in sodium as it affects Croloy 2 1/4 and Type 316 stainless steel. Modified design allowable stress curves were developed for Croloy 2 1/4 and Type 316 stainless steel taking into account the change in properties due to mass transfer and the 30-year life specified for the steam generator under this Contract. This study is reported in topical report No. BW 67-3, to be issued soon. The one-tube model steam generator operating in the sodium test loop at B&W Alliance Research Center will simulate the actual carbon and mass transfer problems of the Full-Size Steam Generator and will add confidence to the design allowable stress curves mentioned above that were plotted on the best available knowledge to date. Since the Prototype Steam Generator will have identical tube diameters and identical materials to the Full-Size Steam Generator, it will model the mass transfer that a Full-Size Steam Generator will experience. Examination of sections taken from the Prototype Steam Generator after the test program will be helpful in understanding the manner in which mass transfer occurs in an actual steam generator and what effect mass transfer has on the properties of the materials of construction.

D. Fabrication Problems:

1. Access for Welding:

Because the Full-Size Steam Generator is a very compact arrangement, having a great deal of heating surface contained in a small volume, access for making the welds connecting the riser and downcomer tubes to the tube bundles is difficult. To prove the ability to make these welds the Prototype Steam Generator is being designed to have, as nearly as possible, welds in the same locations as the Full-Size Steam Generator. A great deal of information will be obtained during the fabrication of the Prototype on the detailed procedures that are required to make these welds and do the non-destructive testing on them.

2. Dissimilar Welds:

The Full-Size Steam Generator is designed so that the location where the ferretic Croloy 2 1/4 material joins the austenitic Type 316 stainless steel is outside the steam generator. These dissimilar welds will be in a location where they can be inspected from time to time if desired and where the consequences of a leak in this weld are not severe. There are no dissimilar welds in the barrier separating the water from the sodium in the steam generator. This same design philosophy has been applied to the Prototype Steam Generator. Examination of the dissimilar welds after completion of the test program will demonstrate the adequacy at these welds.

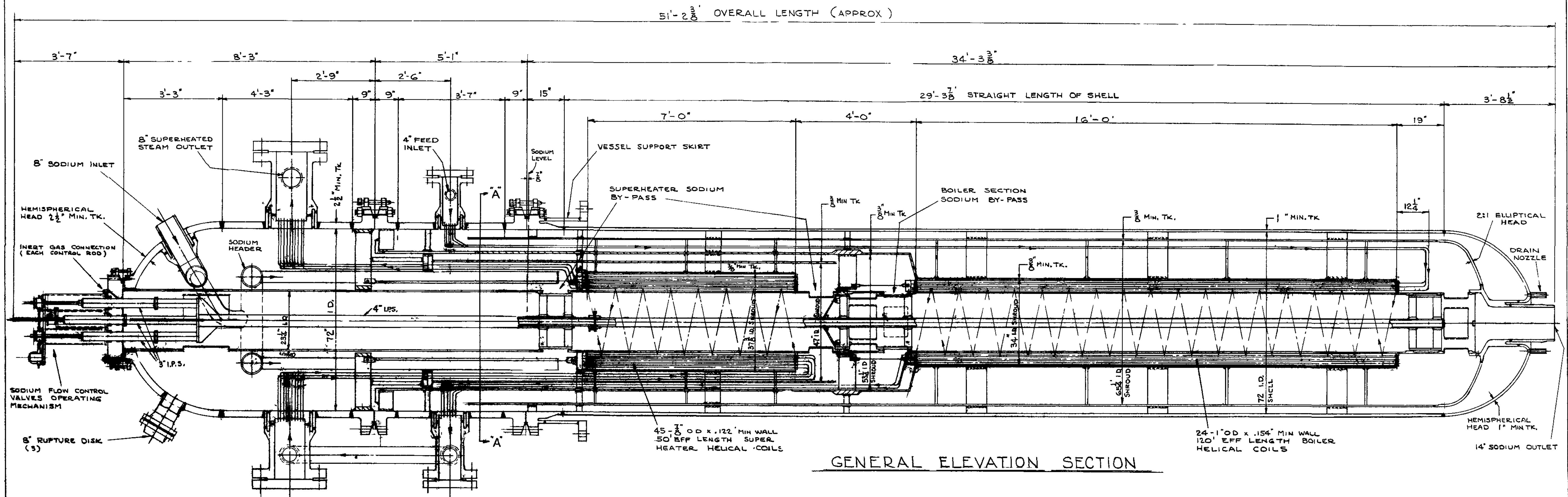
3. Crevice-Free Tube-To-Tubesheet Welds:

One of the R&D projects under this Contract is to develop a procedure for welding the tubes to the sodium face of the tube-sheet, thereby eliminating the crevice between the tube and tube hole. This procedure will be demonstrated on the tubes of the Prototype Steam Generator, which are full size. Testing of the Prototype Steam Generator will demonstrate the integrity of these welds under service conditions at least as severe as the Full-Size Steam Generator will encounter.

3.4 PRESENT STATUS:

Layout drawings have been completed and the first general arrangement drawing of the Prototype Steam Generator is being made.

Stress analysis is proceeding to check the structural adequacy of the Prototype, and also to model as closely as possible the important problem areas of the Full-Size Steam Generator.



GENERAL ELEVATION SECTION

DESIGN PRESSURES

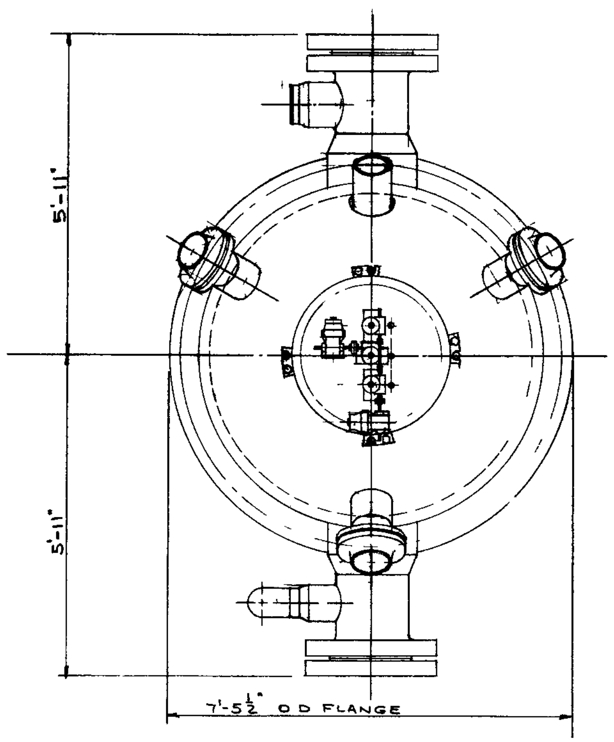
SHELL SIDE (SODIUM SIDE) = 300 PSIG
FEEDWATER INLET (WATER SIDE) = 2825 PSIG
BOILER OUTLET (") = 2725 PSIG
SUPERHEATER INLET (" ") = 2700 PSIG
" OUTLET (" ") = 2675 PSIG

MATERIAL

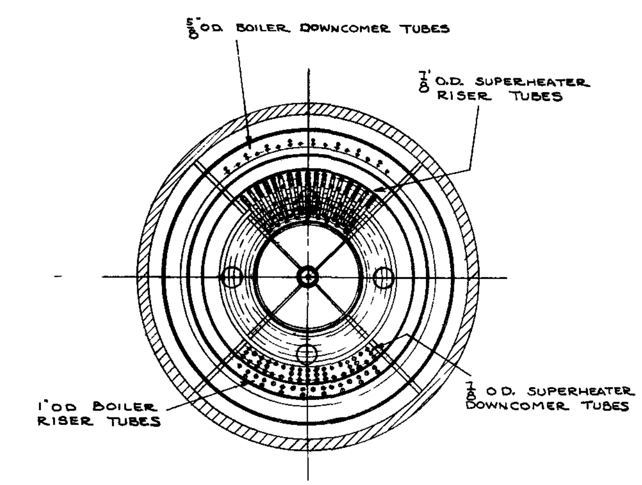
SHELL & HEADS – CROLOY 2 1/4
BOILER BANK & TUBE SHEETS – CROLOY 2 1/4
SUPERHEATER BANK & TUBE SHEETS – TYPE 316 ST ST
SODIUM INLET & BY-PASS SYSTEM – TYPE 316 ST ST

CODE

ASME SECTION VIII WITH NUCLEAR CASE RULINGS



PLAN VIEW



SECTION "A-A"

PROPOSITION DRAWING OF PROTOTYE

25 MWT SODIUM STEAM GENERATOR

ALE 5-15-63

ORDER No 610-0067-45

THE BABCOCK - WILCOX CO
BARBERTON OHIO

SK- 051568

TABLE 1

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 – Nucleate Boiling	618 B/hr/ft^2 /F
Boiler – Film Boiling	455 B/hr/ft^2 /F
Superheater	459 B/hr/ft^2 /F
Fouling Factor	3333 B/hr/ft^2 /F
Corrosion Allowance	0.009 inches

BOILER SECTION
TABLE 1 (CONT'D)

<u>Heat Transfer Surface</u>

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

<u>Boiler Inlet Tubes</u>

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

<u>Boiler Outlet Legs</u>

Size	1" O.D. x 0.165" MW

<u>Pressure Drop</u> (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 2

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 x 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

30 MWT PROTOTYPE SUPERHEATER
SECTION
TABLE 2 (CONT'D)

<u>Outlet Tubes</u>	
Size	7/8" O.D. x .120" MW
Material	TP 316 SS
<u>Pressure Drop</u> (Steam Side)	
Tube Bundles	68.9 psi
Transverse Tube Spacing ST	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.
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 Materials Simulating Full-Size Plant:

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 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 dissembled and the materials examined by appropriate techniques such as metallographic, electron microprobe, electron microscope, and spectrographic means.

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

Present Status:

The test loop shut down on July 13 after 1000 hours of full temperature operation for removal of small samples from the pipe walls. These samples were removed from locations labeled "examination section" on Figure 1. The loop was re-welded without adding any new surface exposed to sodium.

Examination of the samples microscopically showed no significant decarburization or carburization in 1000 hours at these temperatures. Chemical analysis of these samples is proceeding.

The test loop was placed back in full temperature operation on July 20. The next shut-down is scheduled for mid-September after completion of 2000 hours operation.

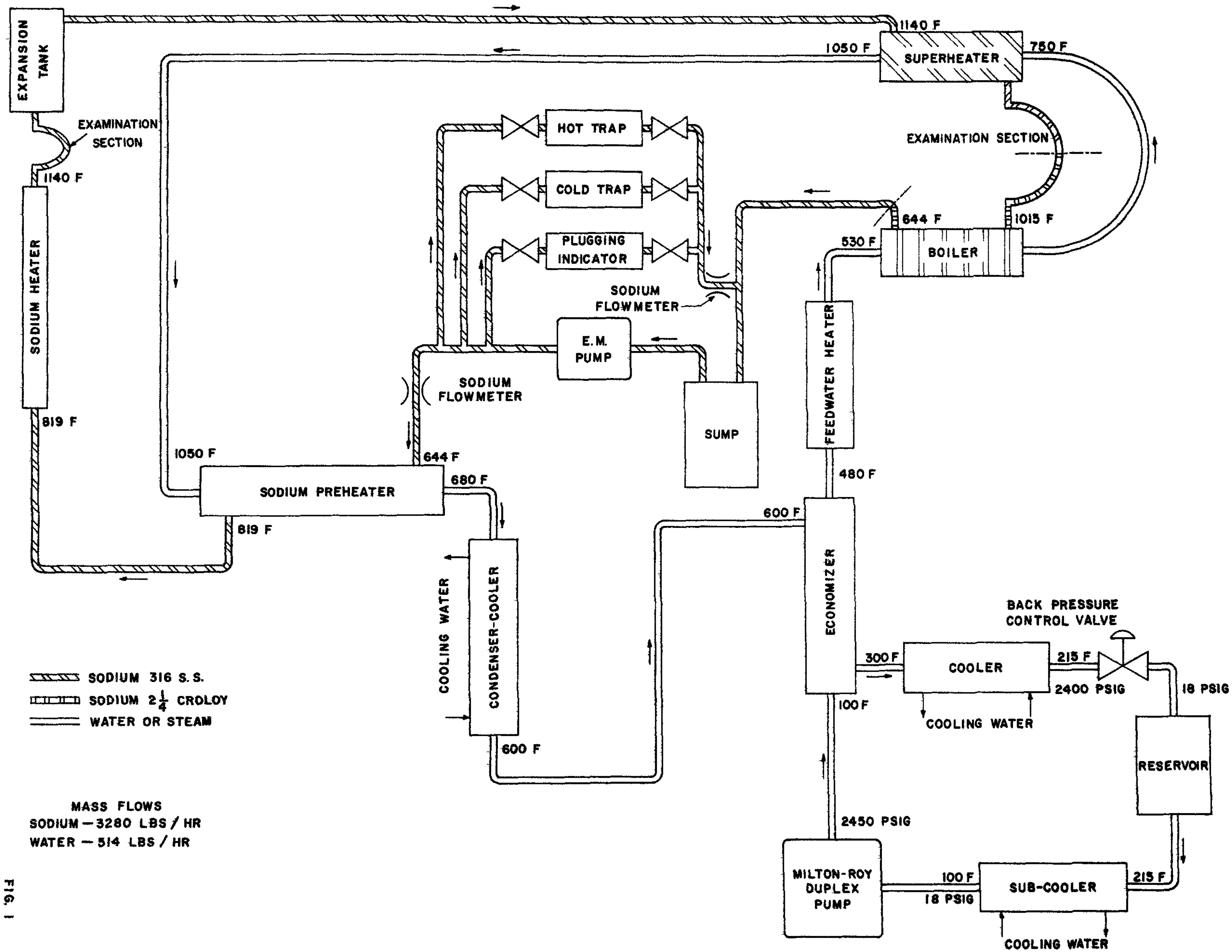
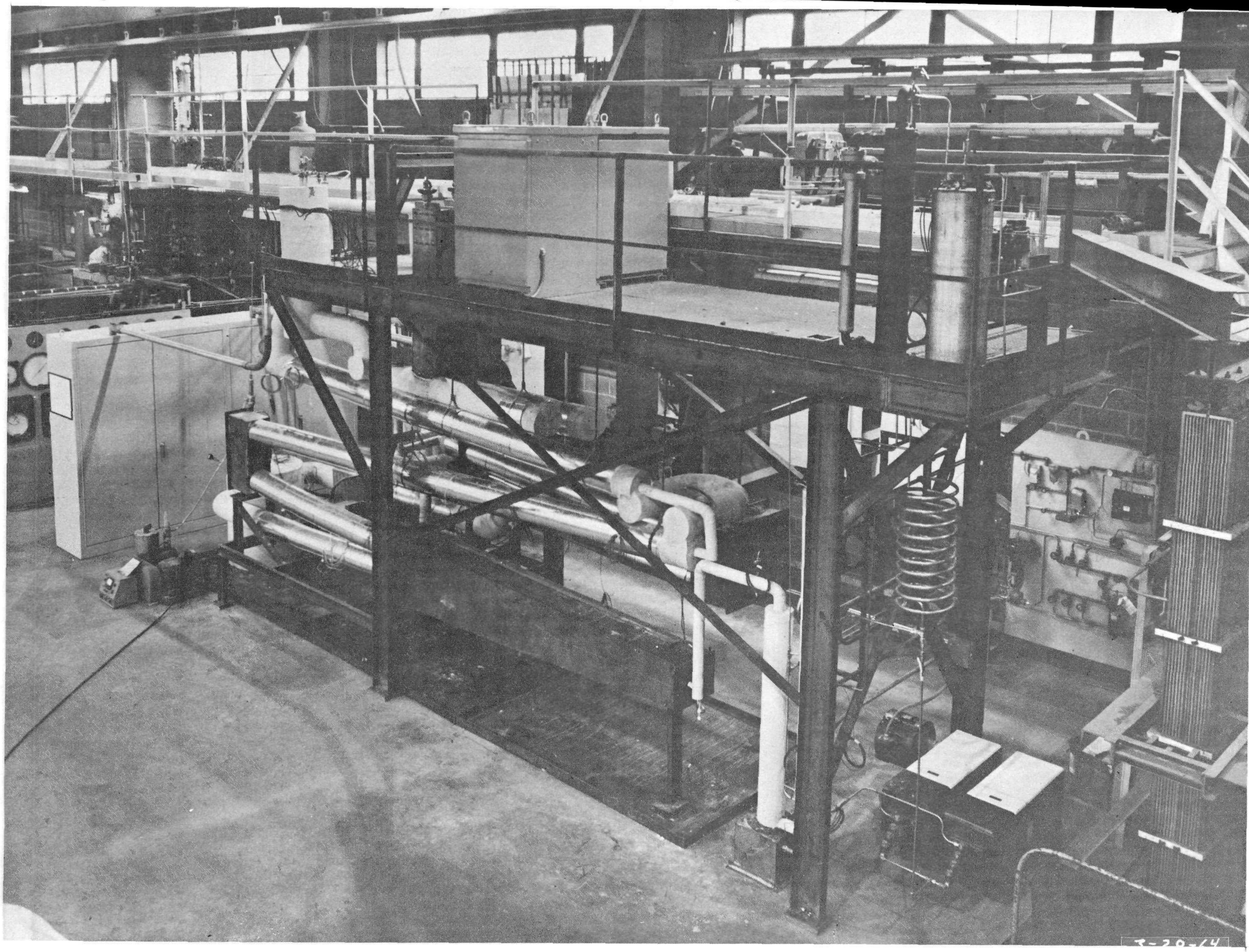


FIG. 1

SCHEMATIC OF MODEL SODIUM-HEATED STEAM GENERATOR



4.2 EFFECT ON HEAT TRANSFER AND TWO-PHASE FLOW OF COILING TUBES:

This project has been completed. The Topical Report on the work, B&W Research Report 4438 has been distributed. Additional copies are available on request. The total cost of this project was approximately 90% of the estimate.

The results of this research work have been used in the design of the Prototype Steam Generator. The design of the Full Size Steam Generator will be corrected during the review of the Full Size design following the testing of the Prototype Steam Generator. Preliminary estimates indicate a saving of $50,000 to $75,000 in the cost of the steam generators for a 1000 MWe plant because of the improvement in heat transfer demonstrated by this R&D project.

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.

PRESENT STATUS OF WORK:

The present status of the various phases of this investigation are listed below as well as a brief preliminary evaluation of the results.

RATE OF CORROSION OF CROLOY 2-1/4 STEEL IN AQUEOUS SODIUM HYDROXIDE:

Tests to date have been conducted on the corrosiveness of aqueous sodium hydroxide solutions at concentration levels of 24.2, 48.8, and 98.6 weight per cent sodium hydroxide. These tests indicate that temperature plays the dominant role in the corrosion rate of Croloy 2-1/4 in this alkaline medium. Tests conducted at the lower sodium hydroxide concentrations (24.2 and 48.8 per cent) with overlapping temperature ranges showed little effect of alkali concentration itself on the rate of corrosion. A linear relationship between exposure time and rate of corrosion was indicated at the low hydroxide concentrations. Some reduction in corrosion rate with time was noted at the higher concentrations.

A corrosion rate of approximately 1" per year was obtained at the maximum temperature tested, 700F, (atmospheric boiling point of 98.6 per cent in NaOH). This corrosion rate would not be catastrophic in a steam generator when compared to the short time required for venting the water from the steam generator, but it must be pointed out, however, that the corrosion rate appears to be increasing rapidly with temperature, and much higher temperatures, (1500F or higher), were reported at the time of the Enrico Fermi tube failures.

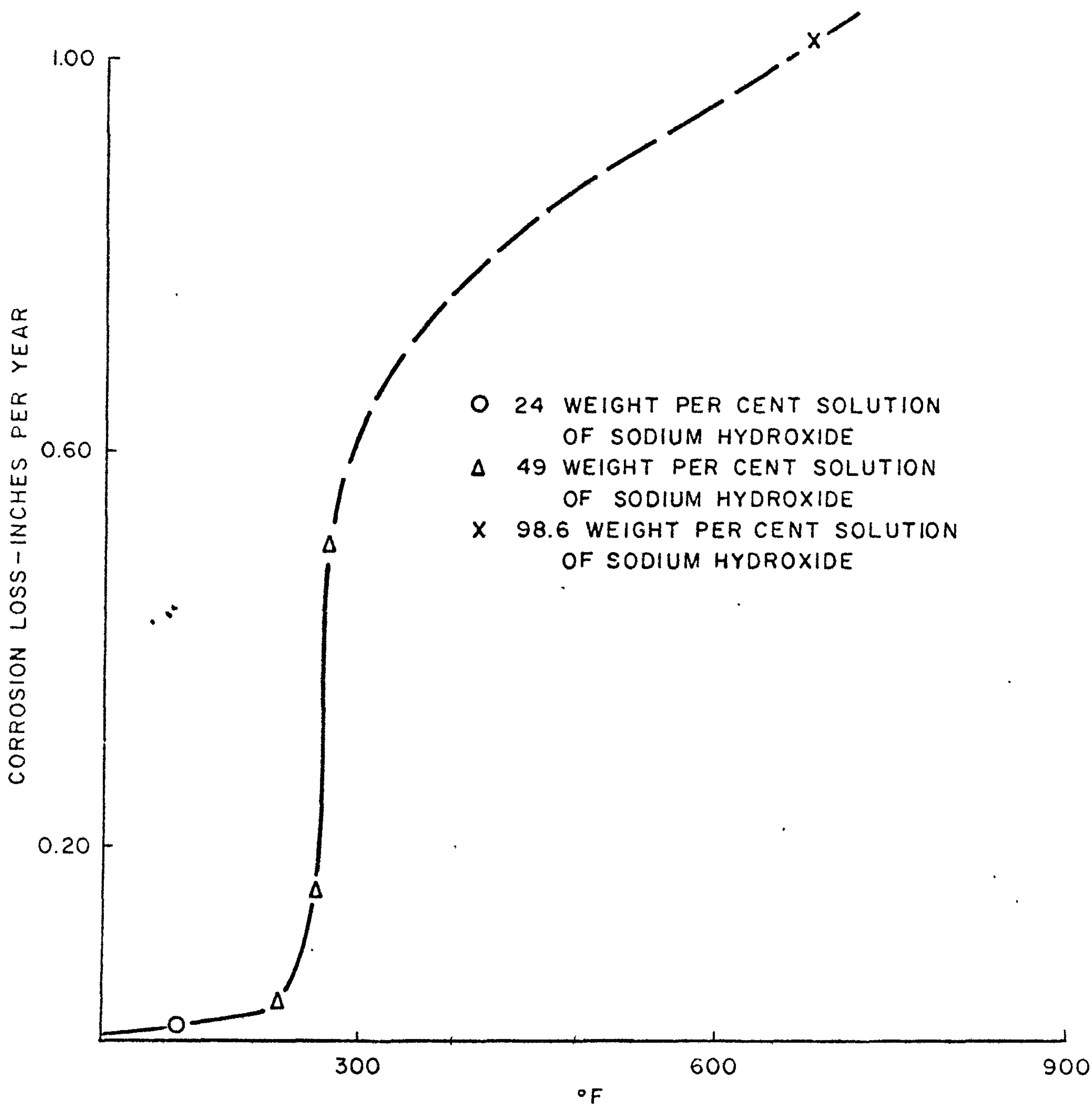
The preliminary data from corrosion of Croloy 2-1/4 in aqueous sodium hydroxide is plotted on Figure 1. This curve shows the rapid increase in corrosion rate as the temperature is increased.

CORROSION OF CROLOY 2-1/4 IN SODIUM HYDROXIDE IN SODIUM:

The initial tests on this phase of the project included base corrosion rates of Croloy 2-1/4 in sodium alone at temperatures of 400, 900, and 1200F. Corrosion rates, as expected, were relatively low. The weight loss measurements indicate corrosion rates less than 0.01 inches per year. The corrosion testing of Croloy 2-1/4 in sodium at calculated saturation levels of NaOH at temperatures of 900, and 1200F showed a strong dependency on temperature. This is the same general trend as was observed in the aqueous solution. Additional tests of the above mentioned temperatures using excess amounts of NaOH above saturation levels are planned to assure saturation during the entire duration of the tests. Tests at temperatures approaching 1500 F will also be carried out. A comparison of corrosion rates between aqueous sodium hydroxide and sodium hydroxide in sodium at equivalent temperatures clearly indicates that the aqueous NaOH is much more corrosive to the Croloy 2-1/4 material. Figure 2 is a plot of corrosion rate for Croloy 2-1/4 steel in sodium containing sodium hydroxide. It will be noted that at temperatures below a 800F the corrosion rate in aqueous solutions is approximately 1000 times greater than in sodium hydroxide in sodium.

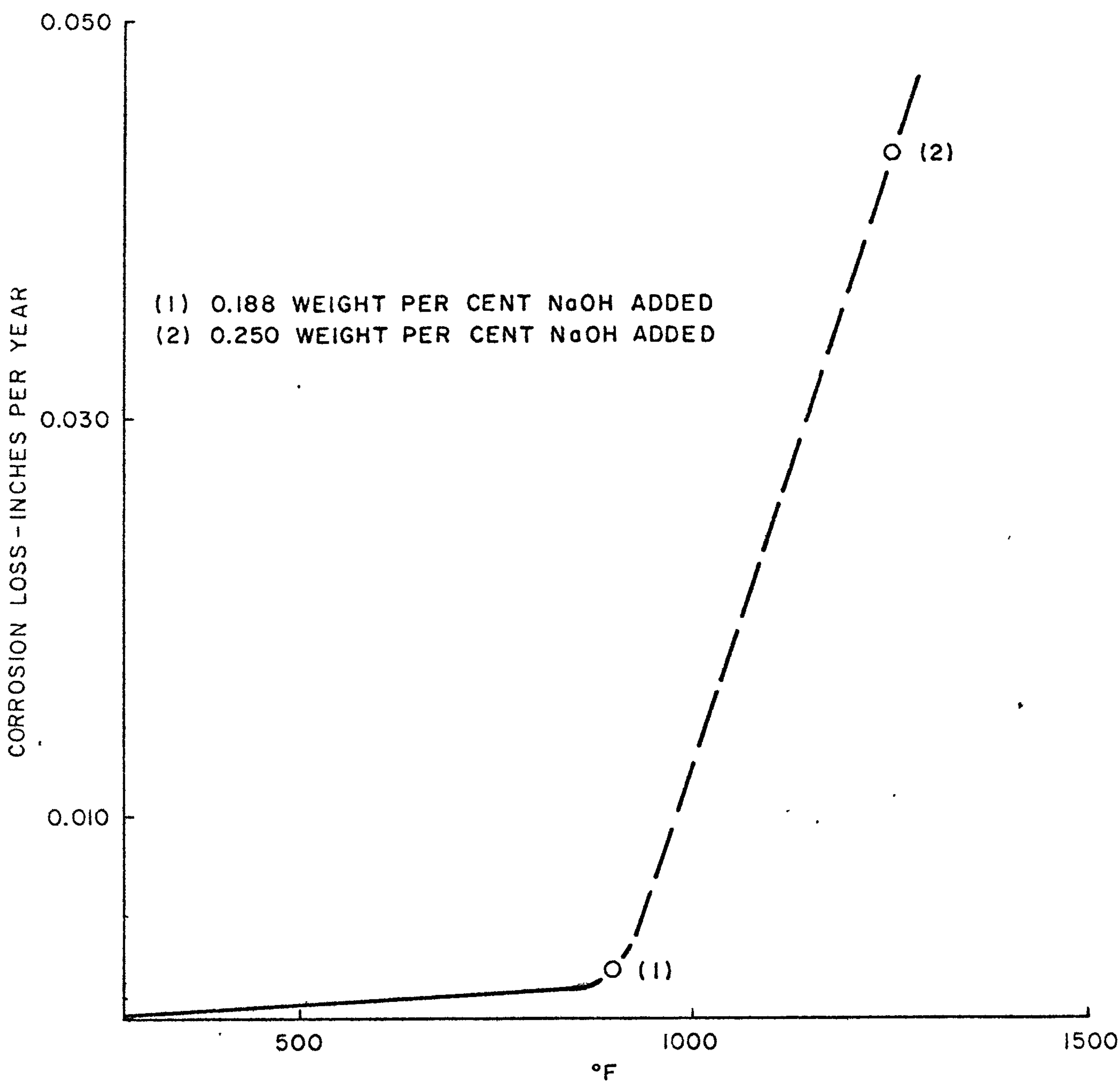
CORROSION OF CROLOY 2-1/4 STEEL IN SOLUTIONS CONTAINING SODIUM, SODIUM HYDRIDE, SODIUM OXIDE, AND SODIUM HYDROXIDE:

Although this phase of the work has not been completed, the corrosion of Croloy 2-1/4 steel and suitably equilibrated solutions of Na, NaOH, and Na_2O will be determined. A partial pressure of hydrogen will be maintained over the solution to effect desired NaH level ($Na + \frac{1}{2} H_2 \rightarrow NaH$) Temperatures employed will be relatively low due to the dissociation of NaH at elevated temperatures.



CORROSION OF CROLOY 2 1/4 STEEL IN AQUEOUS SODIUM HYDROXIDE SOLUTIONS AT ATMOSPHERIC PRESSURE

FIGURE 1



CORROSION OF CROLOY 2 1/4 STEEL IN SODIUM
AFTER SODIUM HYDROXIDE ADDITIONS

FIGURE 2

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.

A summary of the work done under this project has been prepared. The welds that were made by the electric resistance "flash" method were metallurgically sound, but the inner surface was such that the welds could not be proven by non-destructive techniques.

This summary suggests a change in work scope to discontinue work on the flash type weld and proceed on a tungsten-inert-gas process with feed-in of a filler wire. Filler wire will be required for tubes of the thickness required for the Full Size and Prototype Steam Generator.

A TIG process welder with cold wire feed-in has not previously been developed for welding inside a tube. B&W has built automatic TIG welding machines, (with cold wire feed), for tube-to-tube welds working from the outside, and for cladding the inside of nozzles. This experience will form the basis for extrapolation for this tube-to-tube sheet welder.

4.5 RADIOGRAPHIC INSPECTION OF TUBE-TO-TUBE SHEET WELD

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

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

1. Small leaks and corrosion
2. Large leaks and relieving reaction products safely. Work on the problem of corrosion in the products of a sodium-water reaction is underway and is described in Section 4.3 of this report.

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

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

If it were possible to know these things the effect on the steam generator could be predicted by thermodynamic and hydrodynamic techniques. Neither of the two basic relations is known with any certainty at this time.

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

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

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:

The computer program that was used to analyze sodium-water reaction problems in the Fermi Steam Generators is being revised to get a check on the problems of the B&W Full Size Steam Generator as soon as possible.