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SECOND PROGRESS REPORT
ON THE MODEL
SODIUM HEATED STEAM GENERATOR

MASTER

AEC CONTRACT AT(II-1)-1280

RESEARCH REPORT NO. 5455

BY: D. W. KOCH

DECEMBER 31, 1964

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Subj. REPORT NO. 5455 - SECOND PROGRESS REPORT ON THE
MODEL SODIUM HEATED STEAM GENERATOR

Date
JANUARY 21, 1965

This letter to cover one customer and one subject only.

We are forwarding to you herewith a copy of Research Report No. 5455 entitled "Second Progress Report on the Model Sodium Heated Steam Generator" by D. W. Koch. This report covers work on this program for the period of March 1, 1964, to December 31, 1964.

This report is being distributed for the purpose of documenting construction revisions to the test equipment and the operational results through 4000 hours of testing. A separate report will be developed and distributed by the Metallurgy Section covering the material examinations for the 1000, 2000, and 4000 hour test periods.

T. M. Campbell, Jr.

TMC/ns

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SECOND PROGRESS REPORT ON THE
MODEL SODIUM HEATED STEAM GENERATOR

By D. W. Koch

ABSTRACT

PURPOSE

A model sodium-heated steam generator has been designed to simulate the full-size steam generator being developed by the Company for a 1000 Mwe nuclear reactor plant under AEC Contract AT(11-1)-1280. The model steam generator will be utilized to investigate the effects of carbon transfer on a system containing both ferritic and austenitic alloys. This test program was developed to provide confidence in the selection of materials of construction for the 1000 Mwe units.

PROJECT STATUS

The model was modified to meet the specified design conditions and has been satisfactorily operated for 4000 hours. Results of the examination of the Croloy 2-1/4 specimen exposed to 980 F sodium for 2000 hours indicate partial decarburization to a depth of approximately 5 mils. Examination of Type 316 specimens after 2000 hours exposure to 1100 F sodium revealed some precipitation of carbides at the inner surface which is attributed to sensitization of the material rather than carburization from an external source. No further change was observed in the Type 316 materials after exposure for 4000 hours. However, decarburization of the Croloy 2-1/4 specimen had progressed to a depth of approximately 10 mils after exposure for 4000 hours. Quantitative determination of the carbon contents in the decarburized specimens will be made in early 1965 by electron microprobe analysis. Test operation is continuing toward completion of the planned 8000 hour program. This report describes the progress for the period of March 1 to December 31, 1964.

Report No. 5455, 610-0067,
4004-02, BAW-1280-18,
AEC Contract AT(11-1)-1280
December 31, 1964

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INTRODUCTION

The design for the sodium-heated steam generators for a 1000 Mwe nuclear power station is being developed by the Company under AEC Contract (11-1)-1280. The plant will consist of three loops, each having a steam generator of sufficient capacity to produce one-third the steam required for 1000 Mwe. Each steam generator is a once-through type unit with the boiler bank consisting of Croloy 2-1/4 tubes and the superheater section of Type 316 stainless steel tubes. The heating surface is compactly arranged utilizing concentric helical coils for both the boiler and superheater sections.

In liquid metal systems composed of both ferritic and austenitic alloys, the migration of carbon from the ferritic to the austenitic material can adversely affect the mechanical properties of both materials. While the decarburization-carburization problem is well known, the parameters affecting this phenomenon are not clearly defined. In the absence of such fundamental data, this test program was established to provide confidence in the selection of these alloys for the steam generator units.

A single-tube model sodium-heated steam generator has been designed to simulate the full-size steam generator and will be operated for 8000 hours to investigate the effects of decarburization and carburization as a function of time.* This report

* The design and construction phases of the project were detailed previously in B&W Research Report No. 5452.

documents the modifications to the loop that were required to meet the test conditions and to assure reliable operation. The operation of the model for 4000 hours is also presented. The period covered by this report is March 1 to December 31, 1964.

DESCRIPTION OF APPARATUS

The test apparatus is illustrated schematically in Figure 1. The model steam generator consists of a separate boiler and superheater. The former is fabricated of Croloy 2-1/4 and the latter of Type 316 stainless steel. The sodium system consists of an electromagnetic pump, sodium heater, electromagnetic flowmeters, sodium preheater, sump, expansion tank, hot trap, cold trap and plugging indicator. The water-side system includes a controlled volume pump, reservoir, subcooler, economizer, feedwater heater, boiler, superheater, condenser-cooler, cooler, and back-pressure control valve. The sodium system and water-side components shown in Figure 2 were described in detail in B&W Research Report No. 5452, and only those components requiring modification will be described below.

Sodium System

1. Heater

The sodium heater consists of 1-1/4-inch Sch 40 Type 316 pipe with three Type 304 lugs for electrical connections. The heater is composed of four sections that are connected with 1-1/4-inch Sch 40 tees to minimize space requirements since the overall developed length of the heater is 16 feet.

Initial operation of the heater indicated that the sodium temperature could not be raised to the design value (1140 F). Investigation of the problem revealed an extremely low power factor (0.5) for the sodium heater circuit. From the study of oscilloscope wave-forms, the cause of the low power factor was determined to be a highly inductive circuit produced by a high self-inductive reactance due to the specific geometry of the sodium heater piping. To reduce the effect of this reactance, the electrical resistance of the heater was increased by inserting 3/4-inch Sch 40 Type 316 pipes inside the existing 1-1/4-inch pipes to allow the sodium to flow in the annulus formed by the two pipes. Operation of the modified heater at full load conditions revealed a severe vibrational problem. In effect, the 3/4-inch pipe fixed at each end had a natural frequency for the first harmonic of approximately 63 cycles per second and was in resonance with the current flow. To reduce the natural frequency of the 3/4-inch pipe to allow satisfactory operation, the pipe was packed with magnesium oxide. Power measurements subsequent to these modifications showed that the power factor had been increased to 0.8, thereby providing the heat input for the required sodium temperature.

Water System

1. Subcooler

A subcooler is located between the reservoir and the suction side of the pump to eliminate the possibility of water flashing to steam in the pump. The subcooler originally consisted of a Type 304

1/2-inch O.D. x 0.040-inch wall x 35 ft long tube inside of a 3/4-inch O.D. x 0.035-inch wall soft copper tube. The tubes formed a helix having a diameter of 12 inches and a length of 32 inches.

Initial operation of the positive-displacement, duplex pump indicated that cavitation was occurring in the pump. Analysis of the problem revealed that the pressure drop in the subcooler was sufficient to cause the formation of vapor in the pump. The original subcooler was replaced with a straight, concentric, double-pipe cooler consisting of a 1/2-inch Sch 40 Type 304 x 10 ft long pipe inside a 1-1/2-inch O.D. x 0.125-inch wall Type 304 tube. Primary water passes through the 1/2-inch pipe and secondary cooling water is circulated through the annulus formed by the two pipes. This cooler was designed to provide primary water at 150 F to the suction side of the pump with an NPSH* sufficient to preclude the possibility of water flashing to steam in the pump.

2. Feedwater Heater

Water is circulated from the tube-side of the economizer to the feedwater heater where the temperature of the water is raised from 480 F to 530 F prior to entering the boiler. The feedwater heater consists of a 440 V, 10 KW immersion heater welded into one end of a 3-inch Sch 80 x 4 ft long Type 304 pipe. A pipe cap

* Net Positive Suction Head is the head available, above the vapor pressure of the liquid being pumped to force liquid into the pump suction port.

is welded on the opposite end of the pipe, and the unit is mounted vertically with water entering at the bottom and exiting at the top.

Depending upon the line voltage and small upsets in the condenser-cooler system, it was found difficult at times to maintain the feedwater outlet temperature at 530 F. Four 120 V, 1 KW strip heaters were attached to the 3-inch pipe at 90° intervals around the circumference. The strip heaters are operated manually by means of toggle switches and the immersion heater is automatically controlled to provide a fluid temperature of 530 F at the boiler inlet.

3. Boiler and Superheater

The boiler and superheater are designed to simulate the boiler and superheating sections of the full size steam generating unit. The following parameters have been duplicated as closely as possible: 1) tube wall outside surface temperature, 2) thermal gradient across the wall thickness, 3) sodium inlet and outlet temperatures, and 4) water-side inlet and outlet temperatures. A comparison of the temperature distribution in the model and the full size unit is shown in Figure 3.

The model boiler and superheater are single-tube, once-through, sodium-heated units with the former constructed entirely from Croloy 2-1/4 and the latter entirely of Type 316 stainless steel. The boiler and superheater are of similar design consisting of a 1/2-inch x 0.075-inch wall tube inside of a 1-1/4-inch

Sch 40 pipe. Spacers are welded to the tube at approximately 4-5 ft intervals to center the tube within the pipe and provide a uniform annular area. Originally, the boiler consisted of a heated surface for a 36 ft length and the superheater for a 14 ft length.

Operation at full loop test conditions indicated that the overall heat transfer surface of the boiler and superheater were adequate. However, the steam temperature at the boiler outlet was higher than the desired 750 F by approximately 260 F. Heat transfer analysis of temperatures through the boiler and superheat circuit were possible since the model boiler and superheater were instrumented with thermocouples at 3 ft intervals on the outside of the sodium pipes. Analysis of the data indicated that the superheated steam film conductance was considerably less than the calculated value. The test data obtained from the original arrangement for the model boiler and superheater are plotted on Figure 4. Also shown in the figure are the calculated sodium temperatures at the different locations in the boiler and superheater. From these data, it was determined that the boiler length should be reduced by 13 ft and that the superheater length should be increased by 14 ft. The test data obtained after the modifications were made to the boiler and superheater are plotted on Figure 5. The steam temperature at the boiler outlet after modification was about 760 F.

4. Condenser-Cooler

Steam is discharged from the sodium preheater at 680 F to the condenser-cooler where it is condensed and subcooled to 600 F. The condenser-cooler is a boiling water type heat exchanger, where water is boiled and evaporated on the shell side, thereby condensing and cooling the steam on the tube side of the exchanger. The condenser-cooler consists of a 1/2-inch O.D. x 0.075-inch wall x 28 ft long Type 316 tube that is wound into a helical coil with a diameter of 4-1/2 inches and an overall length of 4 ft. The outer shell is a 6-inch Sch 40 carbon steel pipe that is supplied with Zeolite-treated water that, when evaporated, is vented to the atmosphere. The primary outlet temperature is controlled by the water level maintained on the shell side.

After operation for about one week, difficulty was experienced such that the outlet temperature could not be maintained at the proper value. The shell-side vent was found to be plugged with sodium carbonate. The solids in the Zeolite treated water (about 1000 ppm Na) were being concentrated as the water was being boiled off, carried over with the steam and deposited in the cold vent line.

This problem was solved by placing a cone-shaped deflector inside the shell just below the vent and an overflow line in the shell approximately 6 inches from the bottom. A continuous blow-down of 400-600 cc/min is maintained in order to prevent concentration of solids.

TEST PROGRAM

The test conditions for the model steam generator are as follows:

Sodium System

Superheater Inlet Temperature	1100 F
Boiler Outlet Temperature	650 F
Mass Flow	3280 lb/hr
O ₂ Content	<30 ppm

Water System

Boiler Inlet Temperature	530 F
Superheater Outlet Temperature	1050 F
Superheater Outlet Pressure	2400 psig
Mass Flow	514 lb/hr
pH (adjusted with hydrazine)	8.5 - 9.2
O ₂ Content	0.005 ppm
Copper Content	0.002 ppm
Chloride Content (as Cl ⁻)	0.1 ppm
Iron Content	0.01 ppm
Silica Content	0.02 ppm
Total Dissolved Solids	0.05 ppm
Suspended Solids	0.01 ppm

To investigate the effects of decarburization and carburization as a function of time, short sections of loop piping of each alloy are removed after 1000, 2000, 4000, and 8000 hours exposure to sodium. Metallographic examinations will be performed on the

removed sections of piping to observe changes in the microstructure of both materials. After completion of 4000 hours of exposure, all specimens collected to that point will be analyzed with the microprobe for evidence of transport of chromium and nickel. By February 1965 the necessary accessories for the microprobe will be available to allow examination of these specimens for minute changes in the carbon content.

At the conclusion of 8000 hours of operation, the model boiler and superheater components will be destructively examined to determine the extent of carburization and decarburization of Type 316 material and Croloy 2-1/4 material, respectively, at several temperature levels. Microprobe analyses will also be made at several locations to determine the extent of the transport of carbon, chromium and nickel. Chemical analysis of water-side deposits and microscopic examination of the components exposed to the water-steam environment will be made, with particular emphasis on the boiling or transition zone phenomena.

PRESENT STATUS

After completion of the modifications detailed above, operation at the specified full-load conditions began on May 20, 1964. The test was interrupted upon completion of 1006.5 hours of operation to remove piping specimens for metallographic examination. These specimens were removed from two locations in the sodium loop. Two Type 316 specimens were removed from an expansion bend

located between the sodium heater and the superheater as shown in Figure 1. One Type 316 and one Croloy 2-1/4 specimen was removed from an expansion bend located between the superheater and the boiler. One leg of the expansion bend is Type 316 pipe and the other leg, Croloy 2-1/4 pipe as indicated in Figure 1. The test was resumed on July 20, 1964, and interrupted for pipe specimen removal after completion of 2000 hours. Test operation was resumed on September 10, 1964. Piping specimens were also removed as described above after completion of 4000 hours of operation.

No difficulties have been encountered in maintaining the waterside chemistry listed in the Test Program section. Typical results of the water analyses are shown in Table 1. It is anticipated that this water treatment will be effective in minimizing waterside corrosion and the deposit of solids in the boiling or transition zone.

The cold trap and hot trap have been effective in maintaining the oxygen content of the sodium at less than 30 ppm. The plugging indicator runs have generally shown the oxygen level to range between 10-20 ppm. It has not been necessary to continuously hot trap or cold trap the sodium system. General practice has been to cold trap for about 12 hours after removal of specimen material thereby reducing the oxygen level to about 25-35 ppm. This has been followed by hot trapping for 6-8 hours at 1200 F to further reduce the oxygen level to about 10 ppm. Further trapping has not been done unless the plugging run indicated an oxygen level greater than 25 ppm.

Examination of the piping specimens from the 4000 hour exposure period is being completed. The detailed materials examination of the 1000, 2000, and 4000 hour specimens will be described in a separate report. In general, analysis of the Croloy 2-1/4 specimens indicated that partial decarburization to a depth of approximately 0.005 inches had occurred after 2000 hours exposure to 980 F sodium. Examination of the Type 316 specimens after 2000 hours exposure to 1100 F sodium revealed some precipitation of carbides near the inner surface along certain crystallographic planes. Carburization or sensitization could produce the same changes in microstructure. Examination of sensitized specimens of the "as-received" Type 316 pipe revealed essentially a duplication of the 2000 hour specimens. Analysis of these examinations indicate that the observed changes in the Type 316 microstructure of the 2000 hour specimens are due to precipitation of carbides rather than to carburization from an external source. Preliminary examination of specimens removed after exposure for 4000 hours revealed essentially no change in the Type 316 material from the 2000 hour inspection period. However, significant decarburization of the Croloy 2-1/4 is clearly evident to a depth of about 10 mils from the surface; slight decarburization is detectable about 5 mils further within the specimen.

The test operation was continued after the interruption for the removal of the 4000 hour specimens on December 3, 1964.

Submitted by: D. W. Koch
D. W. Koch

Approved by: T. M. Campbell, Jr.
T. M. Campbell, Jr.

TABLE 1

WATER ANALYSES

Date	pH	Dissolved Oxygen as ppm O ₂	Chloride as ppm Cl ⁻	Iron as ppm Fe	Copper as ppm Cu	Silica as ppm SiO ₂	Resistivity megohms	Suspended Solids	Total Solids @ 600°C ppm
9-11-64	9.5	0.001	0.26*	0.006			0.072	Nil	
9-14-64	8.8	<0.001	<0.05				0.050	"	
9-15-64	8.3	<0.001	<0.05	<0.001	<0.002		0.046	"	0.28
9-16-64	8.8	<0.001	<0.05			0.023	0.065	"	
9-17-64	8.3	<0.001	<0.05				0.087	"	
9-18-64	8.5	<0.001	<0.05				0.078	"	
9-21-64	8.8	0.004	<0.05			0.012	0.190	"	
9-22-64	7.8	0.004	<0.05				0.650	"	
9-23-64	9.5	0.015	<0.05			0.012	0.050	"	
9-24-64	9.4	0.001	<0.05	<0.001	<0.002		0.040	"	
9-25-64	9.3	0.001	<0.05				0.046	"	
9-28-64	9.1	0.001	<0.05			0.012	0.092	"	
9-29-64	8.8	0.006	<0.05				0.088	"	
9-30-64	9.2	0.006	<0.05				0.100	"	
10-1-64	8.9	0.006	<0.05	<0.001	0.002		0.182	"	
10-2-64	9.2	0.006	<0.05				0.146	"	
10-5-64	8.8	0.006	<0.05				0.286	"	
10-6-64	9.1	0.006	<0.05				0.242	"	
10-7-64	8.0	0.006	<0.05	<0.001	<0.002		1.420	"	
10-8-64	8.0	0.006	0.15				0.120	"	
10-9-64	8.6	0.003	0.05				0.127	"	
10-12-64	8.4	0.010	<0.05			0.017	0.240	"	

* Start-up

SCHEMATIC OF MODEL SODIUM-HEATED STEAM GENERATOR

ARRANGEMENT OF SODIUM HEATED MODEL STEAM GENERATOR

COMPARISON OF TEMPERATURE DISTRIBUTION
FOR MODEL & FULL SIZE GENERATOR

COMPARISON OF DESIGN & ACTUAL SODIUM TEMPERATURES
 OF ORIGINAL ARRANGEMENT FOR MODEL BOILER & SUPERHEATER

FIGURE 4

SODIUM TEMPERATURES FOR
THE MODIFIED MODEL BOILER & SUPERHEATER

FIGURE 5