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Steam Generator

Tube Denting

Simulation Testing

MASTER

Bettis Atomic Power Laboratory
West Mifflin, Pennsylvania 15122

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STEAM GENERATOR TUBE DENTING SIMULATION TESTING

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February, 1978

Contract No. EY-76-C-11-0014

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ABSTRACT

Tube denting has been reported in steam generators in a number of commercial nuclear power plants in recent years. In order to aid in understanding of the mechanism leading to tube denting in the steam generators, a Bettis laboratory test program was initiated to attempt to reproduce tube denting and to investigate the effects of chemistry, design, and temperature.

The results of the tests indicate that denting can be reproduced in the small model steam generator test apparatus devised for this testing. Denting was observed under carbon steel support plates in seawater-contaminated secondary water in a test with hydrazine-ammonia chemistry and a primary water inlet temperature of 590°F and in a test with hydrazine-morpholine chemistry and a primary water inlet temperature of 545°F. The parameters of these two tests simulate conditions in a typical commercial steam generator and the Shippingport Atomic Power Station steam generators, respectively.

INTRODUCTION

The phenomenon of steam generator tube denting has been reported to have occurred in a number of commercial nuclear power plants. Denting occurs as a local deformation of the tube wall to reduce the tube diameter at the support plate location. This is apparently caused by the rapid corrosion of carbon steel support plates in the tube support plate crevices, filling of the crevices with corrosion products, and

continued corrosion producing stresses that dent the tubes.

Nearly all the reported occurrences of denting have been in plants operating on all-volatile chemistry (typically hydrazine-ammonia or hydrazine-morpholine), in some cases following conversion from sodium phosphate chemistries. The Shippingport Atomic Power Station is currently operating with an all-volatile (hydrazine-morpholine) secondary chemistry after having converted from phosphate chemistry in 1971⁽¹⁾. No denting has been observed to date in Shippingport steam generators based on an eddy current inspection performed of a steam generator in 1975 after 4 years operation with all-volatile chemistry.

Two laboratory tests were initiated to aid in understanding the corrosion mechanism responsible for tube denting in commercial steam generators. These tests were conducted in a small model steam generator facility, designated a boiling simulator, which is capable of mocking up many steam generator operating conditions.

The test program objectives were:

- (1) To determine whether the boiling simulator provided a suitable facility for denting investigations.
- (2) To determine the parameters such as chloride concentration, secondary water chemistry control methods, temperature, support plate orientation, and support plate hole geometry which affect denting.
- (3) To determine methods for preventing or arresting denting.

This report describes the test facility, tests that were performed, and results obtained from these tests.

TEST METHOD AND DESCRIPTION OF APPARATUS

A. Boiling Simulator Test

1. Design

The boiling simulator consists of an array of vertically and horizontally oriented tube segments, illustrated in Figure 1. The tube array is enclosed in a shroud to divide the autoclave into a steam generation section flanked by a downcomer region. The riser and separator are integral parts of the shroud assembly. Provisions were made to provide crevices, using simulated support plates on the various tube sections. The shroud dimensions may be adjusted to vary the equivalent tube bundle flow area, and the secondary water inlet area can also be adjusted to provide variable inlet restriction. By varying these parameters and others (i.e, secondary flow rate) the thermal and hydraulic conditions within the boiling simulator may be controlled. The steam generator conditions which can be simulated by the test apparatus include **primary and secondary** water temperatures, secondary water velocity, heat flux, steam quality, and water chemistry.

The objective of the boiling simulator was to provide a test facility which could achieve conditions that would more closely simulate those existing in operating steam generators than in non-heat transfer tests such as capsules but would not require a large tube bundle such as in a model boiler.

Calculations were performed to provide conditions with the simulator which would closely approximate the thermal and hydraulic parameters in operating steam generators. Instrumentation was provided in the design to monitor and control downcomer water level, primary system heat input, both primary and secondary water temperatures, primary and secondary system flow rates, and system pressures. Protection systems were incorporated to prevent overpressurization, dryout in the boiling section, or overtemperature in the primary loop. The system provides close control of secondary chemistry during operation. Controlled additions of chemicals are made to the secondary makeup tank. Batch additions to the test vessel can be made through the chemical injection cylinder in the feed system. Chemicals or contaminants in the boiling simulator may be removed by blowdown to drain.

2. Principles of Operation

The boiling simulator is a small natural recirculation steam generator adapted to the confines of an autoclave. A water level is maintained in the downcomer region, and the sub-cooled water flows down to enter the boiling region through holes in the bottom of the shroud. The velocity of the liquid is controlled by the sizing of the inlet holes.

Secondary water flow is sufficiently low (about one lb/min.) that relatively large amounts of vapor are generated by the time the fluid reaches the exit of the tube bundle region. At the exit, the quality is approximately 20%. Essentially all of the vapor is removed through the steam exit, while nearly all of the liquid is recirculated to the downcomer region where it mixes with the injected feedwater. The amount of liquid carryover is held to a minimum by a separator baffle. Thermocouples are installed to monitor primary hot leg (T_H), primary cold leg (T_C), and secondary water temperatures. The simulator-tube assembly is shown in Figure 2, and a schematic of the boiling simulator test loop is shown in Figure 3.

3. Normal Operation of a BST Loop

The boiling simulator facility incorporates the function of the steam generating, steam, condensate and feedwater systems of an operating steam plant. Automated operation provides the degree of control required to adhere to the specified operating conditions. The boiling simulator loop thermal data are recorded daily. This includes primary and secondary loop temperatures and flow rate to insure that the primary average temperature is held constant and that the required heat is generated.

Daily chemistry samples are obtained from the test vessel secondary water and makeup tank. The samples are analyzed, and adjustments are made as necessary to correct out-of-specification conditions. Blowdowns to control chemistry of the loop are accomplished by removing liquid through the sampling line to drain.

Volatile chemicals (such as hydrazine, ammonia and morpholine) are added to the test vessel via the makeup water tank. Solid chemicals, contaminants, and sludge are normally added through a pressurized chemical addition cylinder directly to the test vessel by lining up the feedwater system to carry the addition to the simulator. The simulator can be placed into hot standby by securing the secondary steam flow or into wet layup by stopping both secondary and primary flow.

B. Tube Array and Support Plate Material

The support plate material tested was AISI Grade 1020 carbon steel, which has a composition similar to material used for steam generator support plates in commercial nuclear power plants and the Shippingport Atomic Power Station. Composition of the support plate material used is listed below.

AISI 1020 Steel

C - 0.22%

Mn - 0.45%

P - 0.03%

Si - 0.11%

Cu - 0.06%

Ni - 0.06%

Fe - Remainder

Figure 4 shows the location and type of support rings on the denting test simulators. The tests contained 1 in. cylindrical rings, 1 in. hourglass rings with a 5/32 in. land, and 3/4 in. cylindrical support rings. The support ring inside diameter was $0.515 \pm .002$ in. The gap between tube and support plate in the tests is typical of that for many operating commercial steam generators.

The tubing used was Alloy 600 having a composition (shown below) and dimensions representative of tubing used in the Shippingport steam generators.

	Ladle Analysis	Check Analysis
	wt. %	wt. %
C	0.04	0.04
Mn	0.29	0.18
S	0.007	0.006
Si	0.26	0.34
Cr	15.13	15.02
Ni	76.24	75.20
Ti	0.25	0.24
Co	0.04	0.08
Cu	0.23	0.11
Fe	7.78	8.56

The Alloy 600 tubing used was 0.5 in. outside diameter with 0.047 to 0.051 in. wall thickness and was in the mill annealed condition (1675°F min. in dry hydrogen). The tubing and carbon steel received no further heat treatment.

PRE-TEST MEASUREMENT AND INSPECTION

Provision was made to obtain tube inside diameter measurements through installed access fittings. Pre-service inspection included inside diameter measurements of all tubes prior to welding the assembly. After welding, micrometer measurements were again obtained from the inside diameter of the vertically oriented tubes. The vertical tubes also were eddy current inspected prior to testing, using a standard dual coil bobbin probe at three different frequencies, 200 kHz, 400 kHz, and 775 kHz.

Base line signals recorded in the pre-service inspection were subsequently used for comparison with interim inspection results.

To obtain "dent" eddy current signals, a 0.5 in. inside diameter Alloy 600 tube was dented in the laboratory by squeezing between nylon rollers and rotating to distort the full circumference. The two characteristics of the signals from the laboratory "dents" using conventional dual-coil techniques were:

- 1) The signal is horizontal and starts to the left.
- 2) With an equipment calibration to give a 6.5 volt signal from a 0.040 inch diameter x 100% through wall hole, the signal amplitude from a "dent" is greater at higher frequencies.

Eddy current inspection was used to identify the presence (or absence) of a dent. Tube inside diameter measurements were also used to determine the presence and magnitude of the dent.

As the testing progressed, provision was also incorporated into the simulator for inspection of two horizontal legs. Tube inside diameter measurements were obtained at the #2 position (hourglass support ring) and the #9 position (1-inch cylindrical support ring). Figure 5 shows the inspection access hole drilled (which was subsequently rewelded) at the #9 horizontal support ring position from Test No. 1.

OPERATING TEST CONDITIONS

Two tests have been conducted to investigate tube denting.

For these tests an attempt was made to accelerate denting by maintaining high concentrations of chloride (150-200 ppm) in the test vessel during all test periods except as noted. Other test conditions were selected as

described below to be within typical operating ranges for operating commercial steam generators or the Shippingport Atomic Power Station. In Test No. 1 the objective was to establish that denting could be produced under conditions approximating those for which denting occurred in severely dented nuclear steam generators (e.g., Turkey Point 4 and Surry 2). This test has a primary water inlet temperature of 590°F, a primary water outlet temperature of 560°F, a maximum heat flux of about 70,000 Btu/hr-ft², test vessel water velocity of 1 to 2 ft/sec (in the two-phase region), and a secondary bulk water temperature of 500 ± 20°F. Secondary water chemistry was hydrazine (5 to 50 ppb) and ammonia (0.5 to 1 ppm). Chloride was added as seawater to maintain 150 to 200 ppm in the test vessel. Periodic blowdowns were made to control chloride in the desired range. Makeup water pH was controlled in the range of pH 8.5 to 9.2. Test vessel pH was monitored, but not controlled, and was usually in the range of pH 6.0 to 7.5. Carbon steel (AISI Grade 1020) was used to fabricate the simulated support plate rings. The test was operated for 3 months with an inspection performed every month.

Test No. 2 was performed to determine whether denting would occur at the lower operating temperatures and with the secondary water chemistry used in the Shippingport steam generators. The primary water inlet temperature for this test was 545°F, outlet temperature was 530°F, the maximum heat flux was about 70,000 Btu/hr-ft², test vessel water velocity (in the two-phase region) was 1 to 2 ft/sec, and the secondary bulk water temperature was 450°F ± 20°F. Secondary water chemistry was controlled with hydrazine (5 to 50 ppb) and morpholine (1 to 4 ppm). Chloride was added also as seawater, to maintain 150 to 200 ppm in the test vessel. Seawater was used so the test results would be on the same basis as Test No. 1. The makeup water pH was controlled in Test No. 2 in the range of pH 8.5 to 9.2, and test vessel pH was monitored

in the range of pH 6.0 to 7.5. Simulated support plate rings were fabricated from AISI Grade 1020 carbon steel. The test was operated for one month at the high chloride level, inspected, and then operated for an additional 2 months without seawater addition. The test was examined every month to determine whether denting would continue without any further chloride addition.

For all tests about 100 grams of an artificial sludge was placed in the test vessel at the start of testing and was injected at the rate of about 2.5 grams per week. In addition, two support plate crevice regions (Nos. 6 and 9) were pre-packed with sludge at the start of test (see Figure 4). The artificial sludge used was a mixture principally of oxides of iron, nickel and copper, plus copper metal.

TEST RESULTS

Interim inspections were performed on each test at about 1 month intervals. In test No. 1, denting was observed during the first month of operation and continued during subsequent steaming periods. Denting to a maximum 5 mils was found at the vertical positions. The horizontal hourglass and cylindrical support plate (Position Nos. 2 and 9 in Figure 4) positions had more severe denting, measuring 11.8 mils and 7.4 mils respectively. The reason for this behavior could be that the vertical positions receive more flushing action than do the horizontal positions. Test No. 1 results are listed in Table I.

Test No. 2 also had three interim inspections. However, unlike Test No. 1 which operated for the entire three month period with high chloride, Test No. 2 operated with high chloride for only one month, and denting occurred. Following the initial month of steaming operation, seawater addition was suspended to determine if denting could be arrested. Although seawater was

not added, chloride return was observed during the second month of Test No. 2 operation with a maximum level of about 43 ppm chloride and an average concentration of about 8 ppm. During the third month of Test No. 2 operation, chloride return was minimal, with a maximum level of 0.4 ppm and an average concentration of $\leq$ 0.2 ppm. Despite suspension of seawater additions, however, the magnitude of the dents increased by up to 1.9 mils during the second month and up to 0.5 mils during the third month. Test No. 2 denting results are in Table I. Figures 6 and 7 show graphically the Test Nos. 1 and 2 denting data.

Table III presents some typical inside diameter measurement data from each denting test after the first interim examination.

CONCLUSIONS

Based on the above results from the boiling simulator tests with high levels of seawater contamination, the following conclusions are made:

- 1) The boiling simulator tests can produce tube denting under conditions approximating those in operating commercial steam generators with seawater contamination.
- 2) There does not appear to be a large temperature effect in the range of temperatures tested since denting occurs about equally for secondary temperatures of 450°F and 500°F.
- 3) There was no apparent difference in severity of denting between hydrazine-ammonia and hydrazine-morpholine chemistry in these tests (with 150-200 ppm chloride).
- 4) Denting severity in these tests for horizontally oriented tubes is equal to or greater than for vertically oriented tubes.

REFERENCES

- (1) Singley, W.J., "Shippingport Atomic Power Station Steam Generator
Tube Damage and Water Chemistry Control", WAPD-TM-1309, **January, 1978.**

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TABLE I

MAXIMUM DENTING MEASURED IN
TESTS 1 AND 2 AFTER THREE
MONTHS OF OPERATION

Test No. 1

<u>Support *</u> <u>Ring</u>	<u>1st</u> <u>Inspection</u> <u>28 Days</u>	<u>2nd</u> <u>Inspection</u> <u>50 Days</u>	<u>3rd</u> <u>Inspection</u> <u>80 Days</u>
4 (3/4" cylinder)	2.0 mils	3.7 mils	4.8 mils
5 (1" cylinder)	2.5 mils	3.0 mils	4.4 mils
7 (3/4" cylinder)	2.6 mils	3.6 mils	3.9 mils
8 (1" cylinder)	2.2 mils	3.4 mils	5.0 mils
2 (1" hourglass)**	not measured	not measured	11.8 mils
9 (1" cylinder)**	not measured	not measured	7.4 mils

Test No. 2

<u>Support*</u> <u>Ring</u>	<u>(27 Days)</u>	<u>(56 Days)</u>	<u>(80 Days)</u>
4 (3/4" cylinder)	3.3 mils	4.2 mils	4.4 mils
5 (1" cylinder)	2.1 mils	4.0 mils	4.5 mils
7 (3/4" cylinder)	4.0 mils	4.7 mils	5.0 mils
8 (1" cylinder)	2.8 mils	4.1 mils	4.5 mils
2 (1" hourglass)**	not measured	not measured	4.5 mils
9 (1" cylinder)**	not measured	not measured	5.6 mils

Notes:

* See Figure 4 for location.

** Horizontally oriented tubes - all others are vertically oriented.

TABLE II

Typical Tube Inside Diameter Measurements Obtained During the Denting Tests

<u>Tube Position*</u>	<u>Average ID Measurement Post Weld (inches)</u>	<u>Average ID Measurement 1st Interim Exam. (inches)</u>	<u>Average Δ M (mils)</u>
<u>Test No. 1</u>			
Outside of Crevice	0.4101	0.4106	+ 0.5
Under #5 Support Ring	0.4103	0.4082	- 2.1
Under #5 Support Ring	0.4102	0.4087	- 1.5
Under #5 Support Ring	0.4104	0.4079	- 2.5
Outside of Crevice	0.4104	0.4104	0
 <u>Test No. 2</u>			
Outside of Crevice	0.4114	0.4116	+ 0.2
Under #7 Support Ring	0.4115	0.4077	- 3.8
Under #7 Support Ring	0.4116	0.4077	- 3.9
Under #7 Support Ring	0.4115	0.4075	- 4.0
Outside of Crevice	0.4116	0.4117	+ 0.1

* Note #5 is a one-inch cylinder support

#7 is a one inch cylinder support

Figure 1 - Boiling Simulator

Figure 2 - Simulator Tube Assembly

STEAMING LOOP SYSTEM

Figure 3 - Boiling Simulator Test Loop

Figure 4 - Location and Type of Support Rings

Figure 5 - Drilled Hole at Test No. 1 #9 Horizontal Support Ring Position

Figure 6 - Denting Vs. Time - Test No. 1

Figure 7 - Denting Vs. Time - Test No. 2