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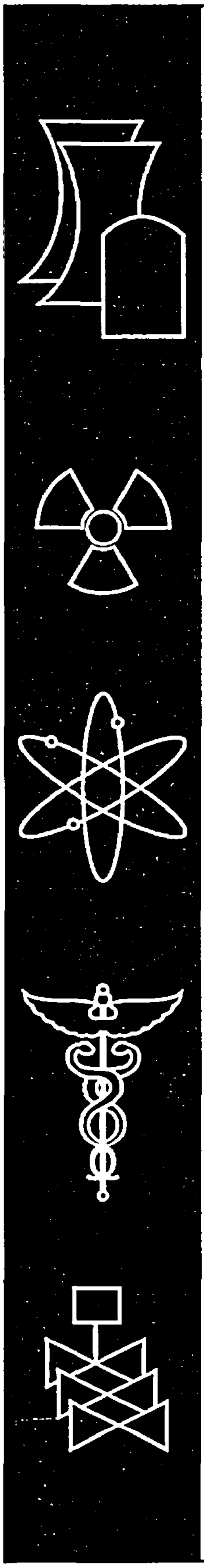

Argonne Model Boiler Facility

Topical Report

Argonne National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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Argonne Model Boiler Facility

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Abstract

A model boiler has been developed to simulate prototypical thermal hydraulics and bulk chemistry conditions on the secondary side of steam generators in pressurized water reactors. The facility produces prototypic crevice conditions by simultaneously matching both crevice heat flux and temperature. The model boiler is a simplified design involving no circulating primary or secondary loops. It is designed for unattended long-term operation. This report describes the design, operation, and shakedown testing of the model boiler. Stable operation with primary and secondary temperatures/pressures reasonably prototypical of actual steam generators and yielding prototypic across-tube heat fluxes has been demonstrated using multiple Alloy 600 tube test assemblies [0.30-m (12-in.) long, 22.2-mm (7/8-in.) diameter]. The facility secondary chamber has been fitted with steam-generator tube/instrumented crevice simulator ring test assemblies, and the first chemical hideout benchmarking tests involving 20 ppm NaOH additions to the bulk secondary water have been initiated. The model boiler will be used to better determine the physical and chemical conditions in crevices in the secondary side of steam generators as a function of bulk water chemistry and the thermal hydraulic conditions expected at different locations in steam generators. The crevice chemistry and physical conditions established from the model boiler studies will be used in other laboratory test systems to establish stress corrosion cracking (SCC) initiation times and crack growth rates of Alloy 600 and 690 specimens. This crack initiation and growth rate data will be used to develop predictive models. Once the predictive models are developed, the model boiler could be used to experimentally validate the models.

FOREWORD

During numerous field inspections of operating nuclear power reactors, representatives of the U.S. Nuclear Regulatory Commission (NRC) have observed steam generator tubes that have suffered degradation as a result of primary or secondary side stress corrosion cracking. If that degradation exceeds the applicable acceptance criteria, the affected tubes are removed from service (i.e., plugged or pulled for additional testing). Tubes that are pulled are tested to determine if they can withstand the allowable pressure differential across the tubes for both normal operation and the design-basis accident (DBA). For normal operation, the tubes must be able to withstand 3 times the normal operation pressure differential. By contrast, the DBA assumes a main steam line break that depressurizes the secondary side of the steam generator, so the tubes must be able to withstand 1.4 times the DBA operation pressure differential across the tubes with the secondary side depressurized.

To assist the NRC's Office of Nuclear Reactor Regulation (NRR) in evaluating industry assessments of steam generator tube integrity to support license amendments and other licensing tasks, the Office of Nuclear Regulatory Research (RES) contracted with Argonne National Laboratory (ANL) to conduct this study. This study also provides guidance for the NRC's regional inspectors to use in verifying proper implementation of licensees' steam generator programs.

In some previous studies, the industry conducted tests at a slow pressurization rate, as well as tests run at a faster pressurization rate, and the results of those tests suggested that the rate has a significant effect on the unstable burst pressure (ligament rupture pressure) in degraded steam generator tubes. However, in examining those test results, ANL noted that the industry conducted the slow and fast pressurization rate tests using two different test procedures, and that difference could confound the results. Consequently, ANL conducted its tests in this study using a variety of specimen geometries and more consistent test procedures, which showed a small effect of pressurization rate, with the effect increasing as the flaw size decreases.

This report also presents failure maps for complex multiple cracks. Stress corrosion cracks generally consist of multiple cracks separated by ligaments (rather that a single planar crack). Although ligament geometry can be very complex, this study idealized the ligaments as radial, axial, or circumferential. When radial (part-throughwall) ligaments rupture during pressurization, the cracks become through-wall. By contrast, the rupture of axial or circumferential ligaments results in longer cracks, which could subsequently rupture under normal or accident conditions. Consequently, ANL developed failure maps showing the range of ligament and crack sizes that would be susceptible to ligament rupture during normal or accident conditions.

In addition, this report describes tests conducted to better establish the range of flaws for which the orifice flow model predicts valid leak rates. The results of this study show that the orifice flow model remains valid roughly when the length of the orifice is less than 5 times the diameter. The diameter for this model is twice the crack opening and the length is the thickness of the tube.

Carl J. Paperiello, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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Executive Summary

This report describes design, operation, and shakedown testing of a model boiler that can achieve prototypic nuclear steam generator (SG) conditions for temperature and heat flux at crevice geometries in tube/support plates or tube/tubesheets. The model boiler is a simplified design involving no circulating primary or secondary loops. It is designed for unattended long-term operation. The model boiler will be used to better determine the physical and chemical conditions in crevices in the secondary side of steam generators as a function of varying bulk water chemistry and thermal hydraulic conditions expected at different locations in steam generators. The crevice chemistry and physical conditions established from the model boiler studies will be used in other laboratory test systems to establish stress corrosion cracking (SCC) initiation times and crack growth rates of alloy 600 and 690 specimens.

The Model Boiler pressure vessel is designed according to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section VIII, Div. 1, for a maximum allowable working pressure (MAWP) of 20.7 MPa (3000 psi) at 360°C (680°F) and has been hydrostatically tested by a qualified third-party at room temperature to 31.0 MPa (4500 psi) in accordance with ASME Section VIII. The pressure vessel consists of a lower primary reflux boiler chamber, where steam is generated, and a secondary upper chamber, where boiling occurs on the outside of multiple 0.30-m (12-in.)-long SG tubes capped on the top and open on the bottom to the steam generated in this chamber. The primary steam condenses on the inner walls of the tubes, creating a boundary condition of high heat flux. Each tube is fitted with an instrumented collar that creates a crevice where chemical concentration can occur. The reflux boiler chamber is driven by a 40-kW electrical heater that is sized to achieve prototypical heat fluxes across the tubes. The primary-side temperature and pressure are maintained by a controller setpoint on the 40-kW heater that operates on a primary bulk water thermocouple. Noncondensable gases in the primary-side deionized water are kept low to maximize the effectiveness of the condensation film heat transfer occurring inside the tubes. The secondary water simulates secondary-side water chemistries of interest to pressurized water reactors (PWRs). Closed-loop control between a thermocouple that measures the bulk temperature in the secondary water and a variable-frequency/speed drive fan controller is used to maintain the temperature and pressure on the secondary side by controlling heat rejection to the ambient air from a finned, fan-cooled steam condenser pipe. The condenser is a 4.0-m (13-ft)-long, 38.1-mm (1.5-in.)-diameter pipe with stainless steel fins brazed to the outside surface. It is divided into three equal subsections, each having its own motor/fan. Conditioning and monitoring of secondary water chemistry are achieved by a bleed/feed system.

Facility shakedown thermal testing has been successfully completed. Stable operation at primary and secondary temperatures and pressures reasonably prototypical of actual steam generators and yielding prototypic heat fluxes across the tubes has been demonstrated using multiple [0.30-m (12-in.) long, 22.2-mm (7/8-in.) diameter] Alloy 600 SG tube test assemblies, [0.30-m (12-in.) long, 22.2-mm (7/8-in.) diameter]. The secondary chamber has been fitted with SG tube/instrumented collar crevice test assemblies, and the first chemical hideout benchmarking tests involving 20 ppm NaOH additions to the bulk secondary water have been initiated.

Acknowledgments

The authors wish to thank J. Muscara and J. Davis of the NRC for their long-term interest and support in the development of the Model Boiler Facility. The authors also wish to thank C. W. Vulyak and J. W. Lucas, research technicians, for their contributions to the experimental effort. This work is sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Job Code Y6588; Program Manager: Dr. J. Davis.

Acronyms and Abbreviations

1-D	One-dimensional
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
DAS	Data acquisition system
ID	Inner diameter
MAWP	Maximum allowable working pressure
MULTEQ	Computer code for calculating equilibrium water chemistry
NI	National Instrument
NRC	U.S. Nuclear Regulatory Commission
ODSCC	Outer-diameter stress corrosion cracking
PWR	Pressurized water reactor
SCC	Stress corrosion cracking
SCFM	Standard cubic feet per minute
SG	Steam generator
SS	Stainless steel
TC	Thermocouple
YSZ	Yttria-stabilized zirconia

1 Introduction

A multiple-tube model-boiler has been built for the NRC that can produce prototypic nuclear steam generator (SG) conditions for the temperature and heat flux at crevice geometries in tube/support plates or tube/tubesheets. It will be used to better determine the physical and chemical conditions in crevices in the secondary side of steam generators as a function of bulk water chemistry and thermal hydraulic conditions. The model boiler is a simplified design involving no circulating primary or secondary loops intended for unattended long-term operation. This report describes the design, operation, and shakedown testing of the model boiler.

Boiling heat transfer in SG tube crevices can cause chemical concentration of impurities in the secondary-side bulk water in the crevices, which can result in SCC on the outside of the tubes. Experience and models show that impurities can be concentrated by a factor of many thousands or more in the crevices.

To produce prototypic conditions on the secondary side of the Model Boiler SG tubes in the crevice region formed by the tube/support plate interface, the tubes and crevice simulators are made of prototypic materials, and the crevice region is subjected to prototypic temperatures, pressures, and heat fluxes. The nominal temperatures and pressures are 338°C (640°F) and 14.2 MPa (2060 psi) on the primary side and 288°C (550°F) and 7.24 MPa (1050 psi) on the secondary side. Modeling of the heat transfer conditions in the crevice region indicates that prototypic tube temperatures and heat fluxes are achieved in the Model Boiler. Secondary-side tube crevice hideout and SCC will be studied using impurities characteristic of plant operating experience. Although some SCC may occur during model boiler operation, these studies will primarily focus on the study of the crevice chemistries. Companion autoclave studies will be used for the study of the resulting corrosion and SCC behavior. Elevated primary-side water temperatures and pressures as high as 360°C (680°F) and 18.7 MPa (2710 psi) can be used to accelerate cracking and explore the influence of heat flux and crevice superheat on hideout and SCC.

Two model boiler concepts were initially considered and evaluated before the design described in detail in Section 2 was adopted. The concepts differed mainly in the secondary-side features. The first concept evaluated, shown in Fig. 1, has a secondary-side flow loop driven by natural convection that contains a steam condenser for rejection of heat to maintain the desired secondary-side temperature. The second concept, which was the design ultimately selected, has no secondary loop, and the heat is rejected by a single finned vertical pipe steam condenser with a finned vertical pipe. Both designs underwent an extensive design review by an external review committee, and their comments have been factored into the final design.

In the boiler concept shown in Fig. 1, a primary-side reflux boiler chamber (driven by a 40-kW electrical heater) is used to create heat transfer across multiple 30-cm (12-in.)-long SG tubes using falling film condensation inside the tubes and boiling on the outside of the tubes. A secondary-side natural convection loop that contains a steam condenser maintains constant boiling conditions on the outside of the tube by rejecting heat to the ambient. Collars can be

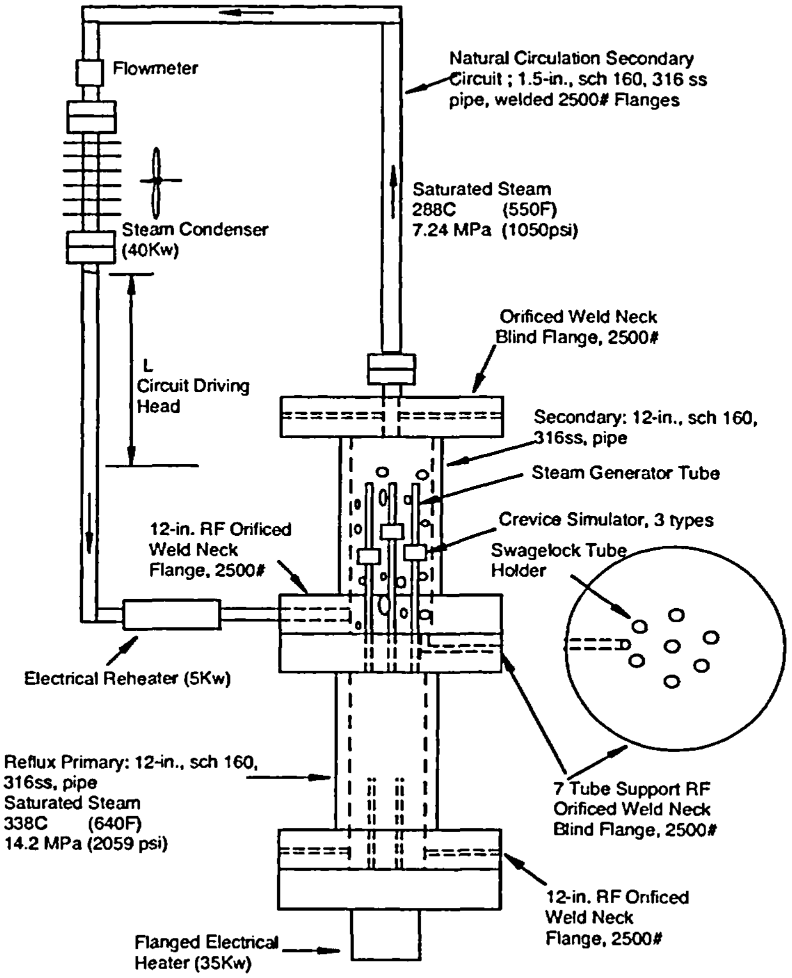


Figure 1. Argonne initial concept for Model Boiler Facility with natural-circulation secondary flow loop

placed on the tubes to simulate the tube/support plate crevices where localized chemical hideout and tube cracking can occur. This concept avoids the pumped primary and secondary loops used in earlier designs, and thus reduces costs. The temperatures and pressures can be controlled through the primary-side reflux boiler electrical heater and the secondary-side steam condenser and electrical reheater. The circuit driving head, L, is a key parameter in maintaining a natural convection flow in the secondary- side flow loop, thus ensuring proper function of the Model Boiler. A thermal-hydraulic model was developed to predict L for the various operating temperatures pertinent to achieving prototype crevice conditions, and the workability of this loop design was demonstrated.

However, in an attempt to further simplify the Model Boiler, a design involving a falling-film condenser consisting of a single vertical finned pipe mounted on top of the secondary chamber outlet flange was conceived, analyzed, and eventually selected. This design eliminates the need for the multiple-tube condenser bank, secondary-loop piping, and the electrical re-heater of the initial concept. It also simplifies facility control and reduces places where chemicals can hide out outside of the secondary chamber crevices, thus facilitating the ability to control the secondary water chemistry. The condensing-steam falling film inside the vertical condenser behaves similarly to that present inside the boiler steam generator tubes and provides a boundary condition of very high heat flux inside the tubes. In fact, the analysis used for the secondary condenser is similar to that employed for the steam generator tubes, the difference being that, for the outside of the secondary condenser, a heat transfer coefficient that represents fins under forced air cooling was employed.

Section 2 of this report describes in detail the selected model boiler design and its safety features. Section 3 describes the modeling of tube/crevice heat transfer and hideout that contributed to establishing that the Model Boiler design would produce prototypic crevice conditions. Section 4 describes Model Boiler operation and results from facility operational shakedown testing. Finally, in Section 5 the initial crevice hideout/chemistry testing is described.

2 Model Boiler Facility Design

The Model Boiler pressure vessel is designed according to the ASME Boiler and Pressure Vessel (B&PV) Code Section VIII, Div. 1, for a maximum allowable working pressure (MAWP) of 20.7 MPa (3000 psi) at 360°C (680°F) and has been hydrostatically code tested by a third-party code at room temperature to 31.0 MPa (4500 psi). The Model Boiler pressure vessel consists of a lower primary reflux boiler chamber, where steam is generated, and a secondary upper chamber, where boiling occurs on the outside of the multiple 0.30-m (12-in.)-long SG tubes. Each tube is capped on the top and open on the bottom to the steam generated in the primary reflux boiler chamber. The primary steam condensing on the inner walls of the tubes creates a boundary condition of high heat flux. Each tube can be fitted with an instrumented crevice simulator, which is where chemical hideout occurs. Figure 2 shows a schematic of the pressure vessel.

The reflux boiler chamber is driven by an electrical heater that is sized (40 kW) to achieve prototypic heat fluxes across the tubes. The primary side is maintained at desired saturation temperature/pressure by a controller set point on the 40-kW heater that operates on a bulk water thermocouple. The secondary side is maintained at the desired temperature and pressure by controlling heat rejection to the ambient air from a finned, fan-cooled steam condenser pipe through closed-loop control between a secondary bulk water thermocouple and a variable frequency/speed drive fan controller. The condenser is a [4.0-m (13-ft) long, 38.1-mm (1.5-in.)-diameter] Schedule 160 Alloy 800 pipe, with stainless steel fins brazed to the outside surface. The outside surface is divided into three equal subsections, each having its own motor/fan. Figure 3 shows the fully assembled Model Boiler, which consists of a two-chamber pressure vessel (primary/secondary), a 40-kW primary electrical heater, six zones of combined insulation blankets and trace electrical heaters, a secondary finned steam condenser pipe for heat rejection, a three-fan air blower for controlled heat rejection in the secondary condenser pipe, and a rupture disc pressure protection system with a steam discharge collection tank. All subsystems, including their controllers, are commercially manufactured, and all set points, facility status information, and crevice data are logged continuously by a dedicated data acquisition computer system. This computer system has no control function on the facility. Figure 4 shows a schematic of the floor layout of the Model Boiler Facility.

On the primary side, the noncondensable gases in the deionized water are kept low to maximize the effectiveness of the condensation film heat transfer occurring inside the steam generator tubes. The secondary water simulates secondary-side water chemistries of interest to pressurized water reactors (PWRs), and also has a low level of noncondensables to maximize heat transfer in the secondary finned heat rejection pipe. Conditioning and monitoring of the secondary water chemistry are achieved by a bleed/feed system.

Figure 5 shows the capped Alloy 600 SG tubes [0.30-m (12-in.) long], without crevice collars that were used in the initial evaluation of facility behavior and of the thermal flux from the primary to the secondary side (across the tubing walls). The tubes are mounted in the top of the primary chamber prior to the installation of the secondary chamber. The secondary chamber is bolted to the top flange of the primary chamber. The test program for the Model Boiler will use various types of tube and crevice simulator materials, including Alloy 600or Alloy 690 tubing and stainless steel or plain carbon steel collars. Steam from the primary chamber, generated by the

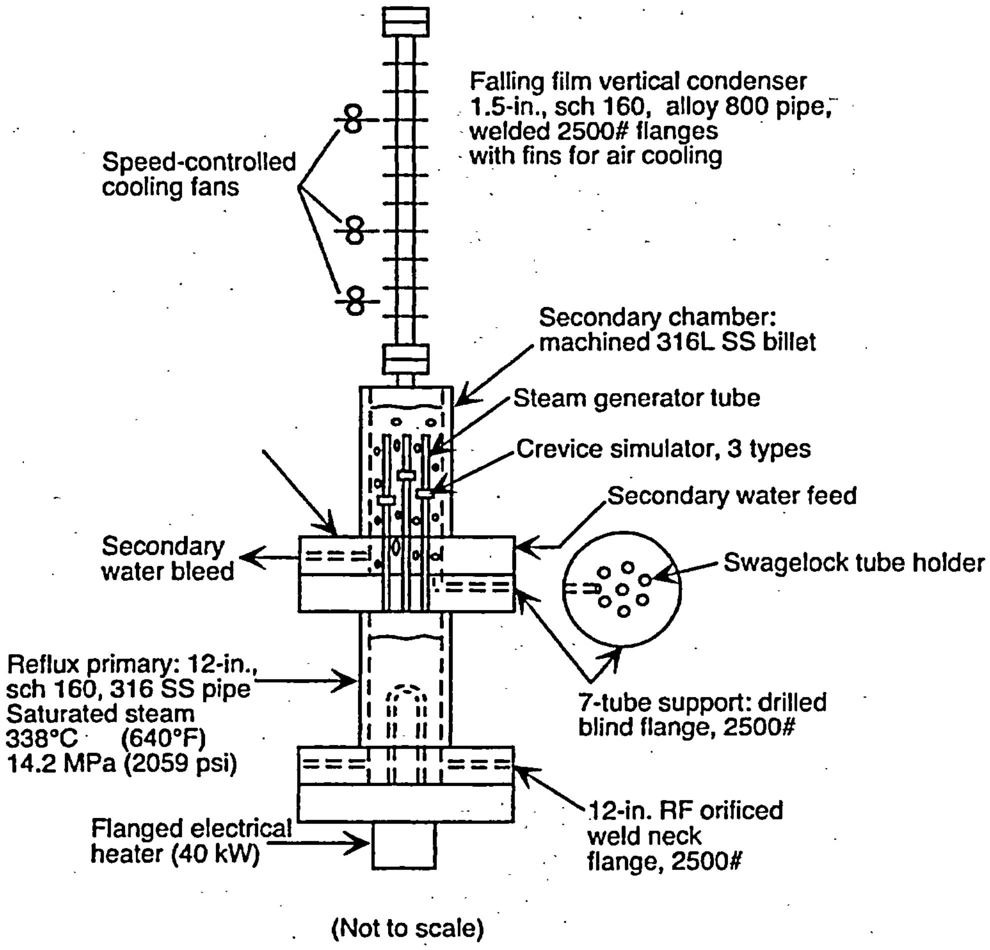


Figure 2. Schematic of the Model Boiler Facility

40-kW primary heater, rises inside the tubes and condenses on the tube walls, transferring heat across the tubes to the cooler secondary water. Boiling occurs on the outer walls of the tubes and concentrates impurities in the bulk water in the crevices. The design of the crevices and associated instrumentation is described in the following sections.

2.1 Equipment Features

The following sections describe the features of the equipment comprising the various subsystems of the Model Boiler Facility.

2.1.1 Pressure Vessel

The Model Boiler pressure vessel is built under the ASME B&PV Code, Sec VIII, Div. 1 and stamped for a MAWP of 20.7 MPa (3000 psi) at 360°C (680°F). The vessel with the 40-kW flange electric heater installed was hydrostatically tested at room temperature to 31.0 MPa

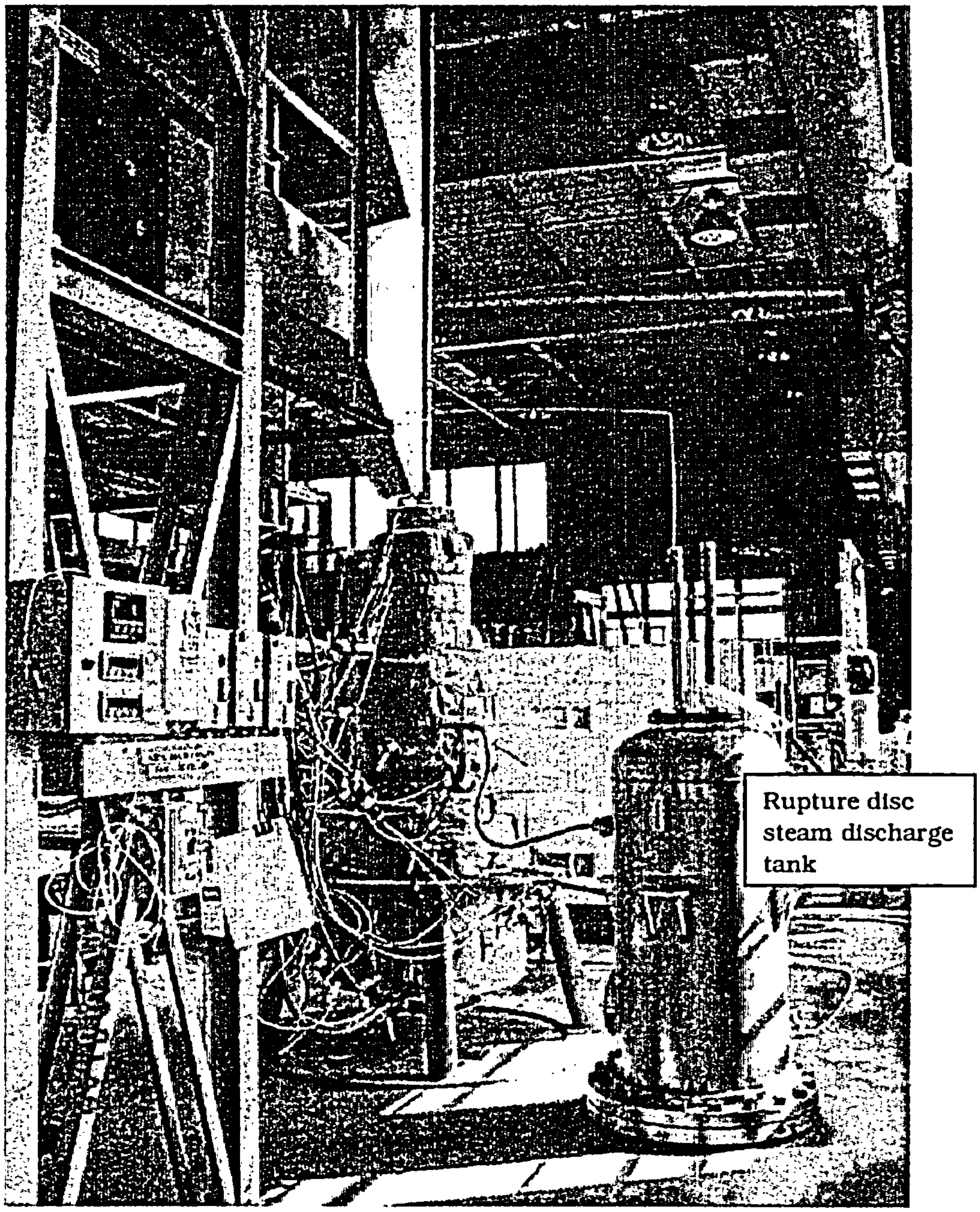


Figure 3. Photo of fully assembled Argonne Model Boiler

(4500 psi). The vessel (Fig. 6) has two pressure chambers. The lower primary reflux boiler chamber, where steam is generated, is made of Type 316 stainless steel. The secondary upper chamber, where boiling occurs on the outside of SG tube/crevice test assemblies, and trace impurity chemical(s) are concentrated in crevice simulators, is made of Type 316L stainless steel.

The two chambers are joined together by a bolted flange sealed with a crushable metal Flexitallic™ gasket. The 40-kW primary heater is likewise bolted to the bottom flange of the primary chamber and sealed with a crushable metal gasket. Figure 7 shows detailed dimensions of the pressure vessel and its support stand. The height of the pressure vessel is 2.3 m (7.5 ft).

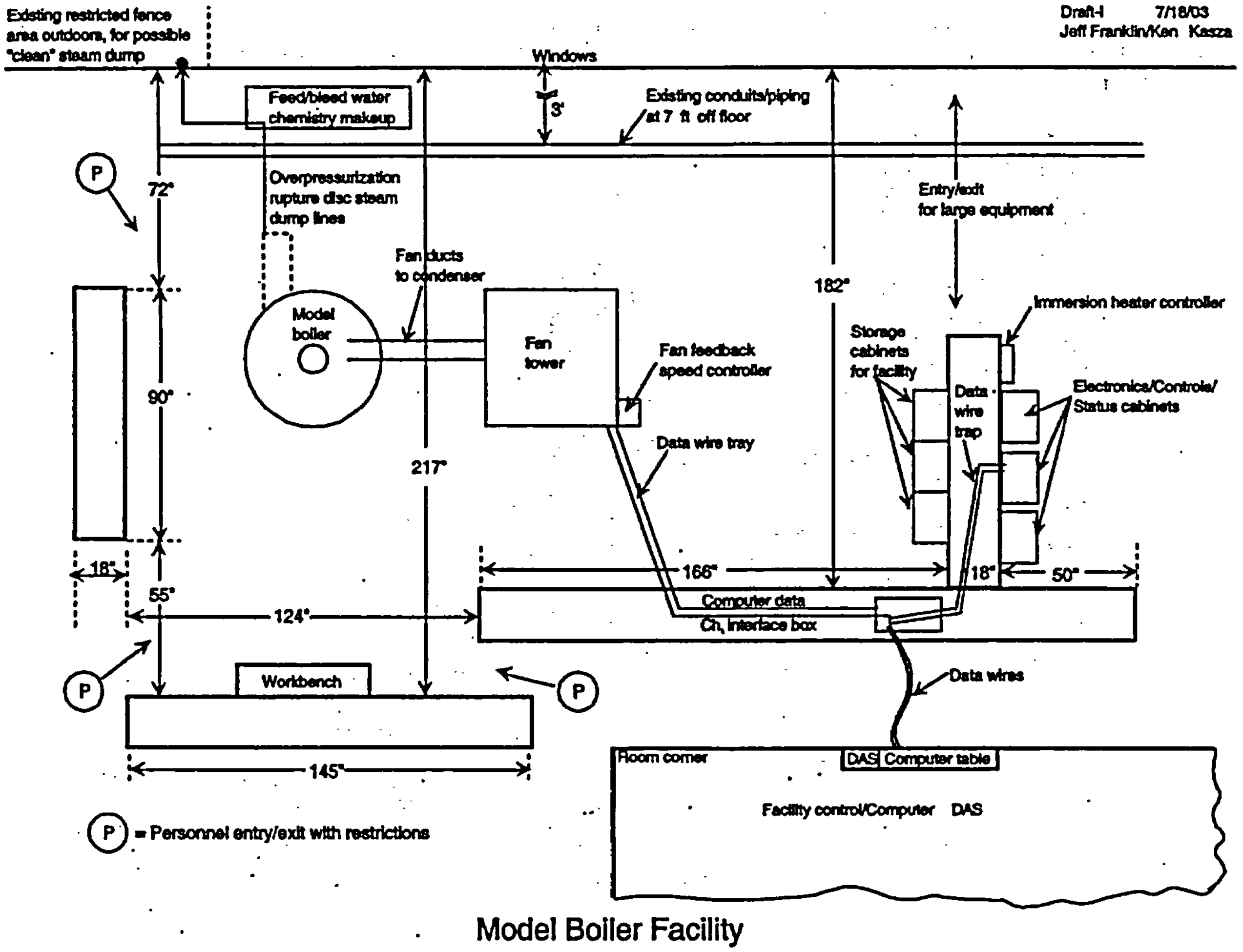


Figure 4. Floor layout of Model Boiler Facility

The SG tube layout pattern (see Figs. 5 and 7) has one tube in the center, with six tubes equally spaced on a 76.2-mm (3-in.) radius about the center tube. One of the tube positions is used to support secondary chamber instrumentation. The tubes are short to minimize the potential for interference from falling condensation-film/rising-vapor flow inside the tubes, which would reduce the attainable heat flux. Additionally, both the primary and secondary chambers are sized to minimize flow interferences at the entrances to the primary side of the tubes and on the secondary-side boiling surfaces by the crevice simulators that fit over the tubes. Both chambers have an ID of 0.26 m (10.13 in.) and a height of 0.61 m (24 in.).

The volume of each chamber is 26.4 L (6.97 gal.). Both chambers are filled with an amount of cold water such that, when heated, the chambers are nominally only 2/3 full.

Primary- and secondary-side instrumentation and water bleed/feed access is through ports in the flanges on each chamber. High-pressure Swagelok™ and Conax™ fittings located on pipe stand-offs are used to seal instrumentation leads.

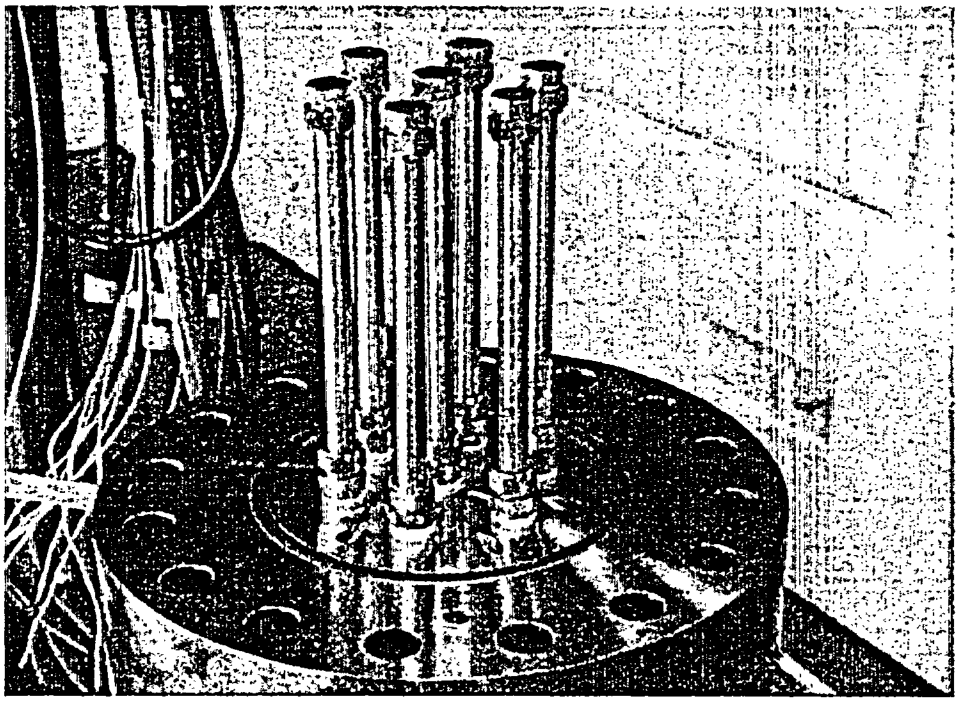


Figure 5. Photo of capped SG tubes [0.30-m (12-in.) long] mounted in the top of primary chamber (bottom floor of secondary chamber) prior to bolting on the secondary chamber

2.1.2 Primary 40-kW Heater

A one-dimensional (1-D) heat transfer model of the tube/crevice geometry was developed (see Section 3) to assist in the design of the Model Boiler. Calculations for various parameter combinations established the reflux boiler heater requirement to be 40 kW in order to generate prototypic heat fluxes across the multiple SG tubes. A commercial flanged 40-kW electric immersion heater with temperature controller, automatic safety shutdown, and power meter was procured (Figs. 8 and 9). Deionized water is used in the reflux boiler. The initial water charge into the primary chamber is such that, over the operating temperature range of the Model Boiler, the heating elements are not uncovered. At the highest operating temperature, due to significant water expansion, the water/steam interface in the primary chamber stays at least 100 mm (4 in.) below the top of the primary chamber so as to not interfere with steam rising up into the steam generator tubes mounted in the top of the primary chamber.

The heater depicted in the drawing of Fig. 8 has the following features:

Conforms to ASME B&PV Code and is stamped for MAWP of 20.7 MPa (3000 psi) at 360°C (680°F).

Contains Watlow™ 480 V, 3-phase immersion heater with 2500 class, Type 316 stainless steel flange bolted to the bottom of the primary chamber and sealed by a crushable metal gasket.

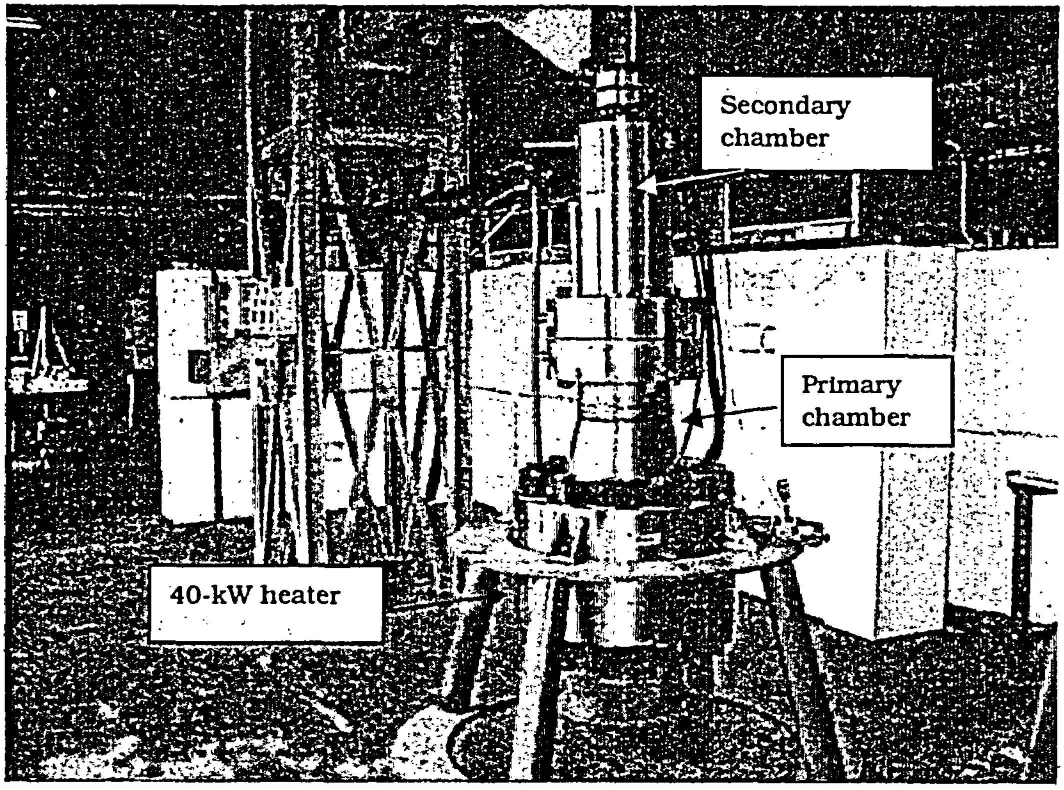


Figure 6. Photo of uninsulated Model Boiler pressure vessel showing upper secondary chamber, middle primary chamber, and lower flanged 40-kW primary heater

Contains twenty-seven Alloy 800 sheathed heater elements, 0.30 m (12 in.) in length.

Operates by feedback control with a process temperature thermocouple and a programmed controller set point.

Furthermore,

Accidental heater burnout due to partial uncovering of a heater element or over-pressurization due to over-heating are prevented by means of automatic shutdown of the electric power by the controller operating on a maximum temperature limit point and a heater element thermocouple.

Ultimate pressure safety from overheating is provided by a primary-chamber overpressurization rupture disc set to operate at a pressure of 18.6 MPa (2700 psi).

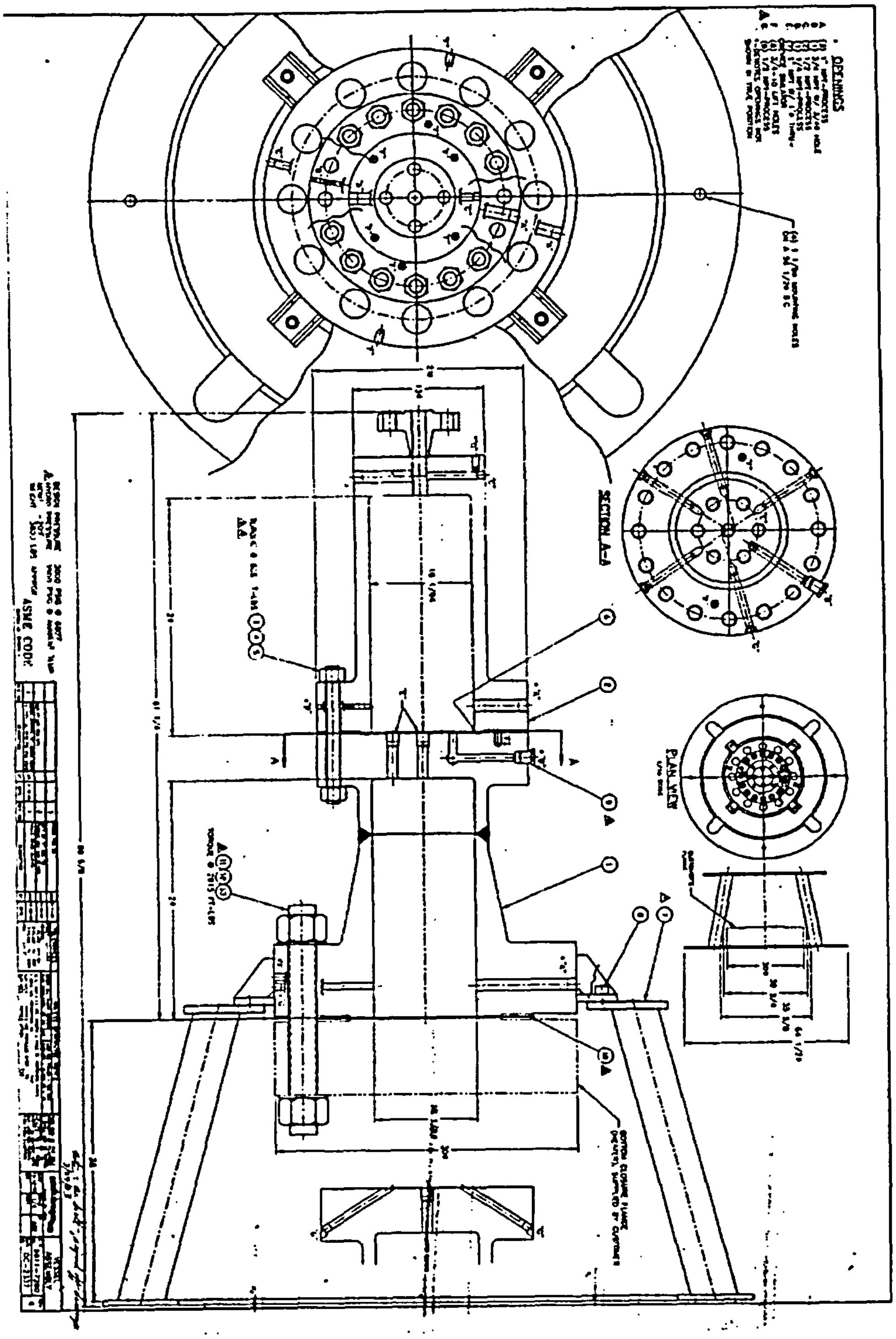


Figure 7. Detailed drawing of Model Boiler pressure vessel

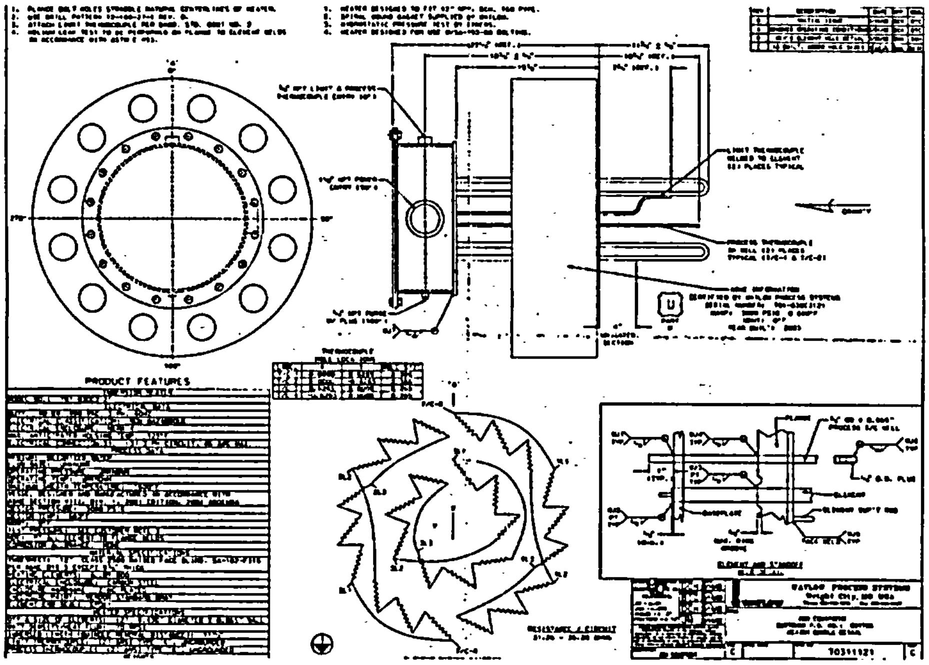


Figure 8. Drawing of 40-kW electric heater for primary chamber

2.1.3 Trace Heaters and Insulation for Pressure Vessel

The pressure vessel is covered with custom-made dual heating/insulation jackets (see Fig. 10) for mitigating heat loss to ambient. This insulation also maintains the primary and secondary chamber outer walls at the inside process temperatures to reduce temperature gradients through the thick pressure vessel walls and flanges. Thermocouples located in each of the separate heater zones read outer wall temperature and are input to individual heater electrical controllers that maintain temperature at the desired set point. Additional thermocouples sense heating element temperature and activate limit-temperature shutdown of electrical power. The programmable controllers for the multiple heater zones are shown in Fig. 11. Additional features of the trace heating/insulation are as follows:

> Top four insulation zones have built in heaters. The bottom flanges (zones 5, 6) are heated by band heaters. The power for each zone is:
>
> - Zone 1, 360 W.
> - Zone 2, 3757 W.
> - Zone 3, 2640 W.
> - Zone 4, 1920 W.
> - Zones 5 and 6, 6000 W. (3000 W per flange)

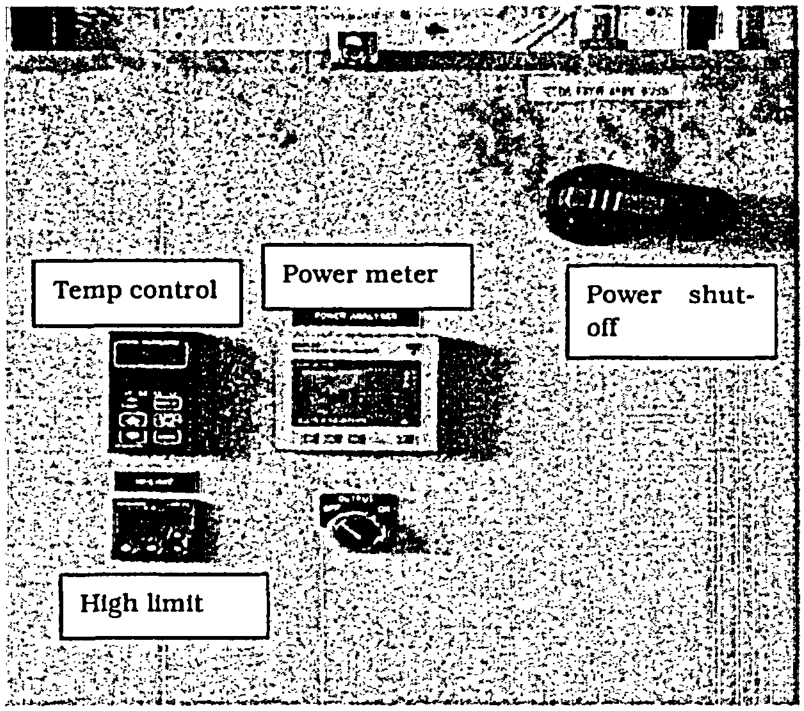


Figure 9. 40-kW heater control panel showing power shut-off, temperature set-point control, temperature high-limit set-point control, and power meter

Trace heaters are 208 V, single phase.

Insulation consists of 50 mm (2 in.) of fiberglass.

Insulation inner liner is a high-temperature fabric with strips of heating tape knitted into the liner.

2.1.4 Secondary Steam Condenser Pipe/Fan Cooling System for Heat Rejection

The secondary chamber of the Model Boiler is maintained at the desired temperature and pressure (water/steam saturation conditions) by controlling heat rejection to the ambient from a finned, air-cooled steam condenser pipe. Steam rising inside the pipe from the secondary chamber condenses on the inner wall, forming a falling condensation film. This process is identical to the primary-side condensation occurring inside the steam generator tubes. In both cases, the condensation constitutes a boundary condition of high heat flux. Figure 3 shows a photograph of the condenser pipe and fan cooling system as part of the overall facility.

The condenser is a Schedule 160, Alloy 800 pipe with stainless steel fins brazed to the outside surface to enhance heat rejection to the ambient air blown over the pipe. It is 4.0-m (13 ft) long, 38.1-mm (1.5-in.) in diameter, and has been ASME B&PV Code stamped for a MAWP of 21.0 MPa (3000 psi) at 360°C (680°F). The condenser pipe is capped on top and bolted to the top flange of the secondary chamber. The condenser pipe is divided into three equal-length subsections, each having its own motor, fan, and air delivery ductwork located on a vertical tower

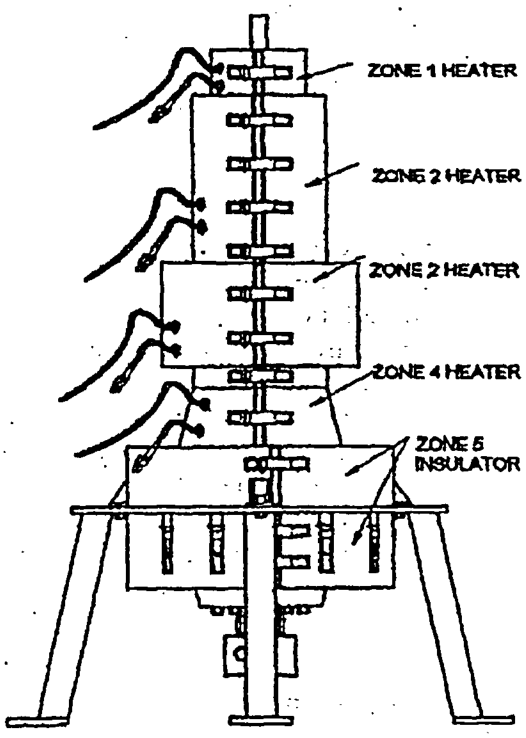


Figure 10. Pressure vessel trace heater zones/insulation

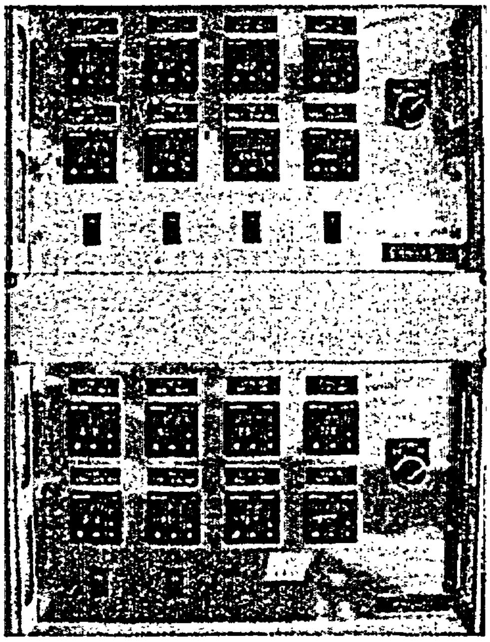


Figure 11 . Programmable controllers for the six trace heater zones

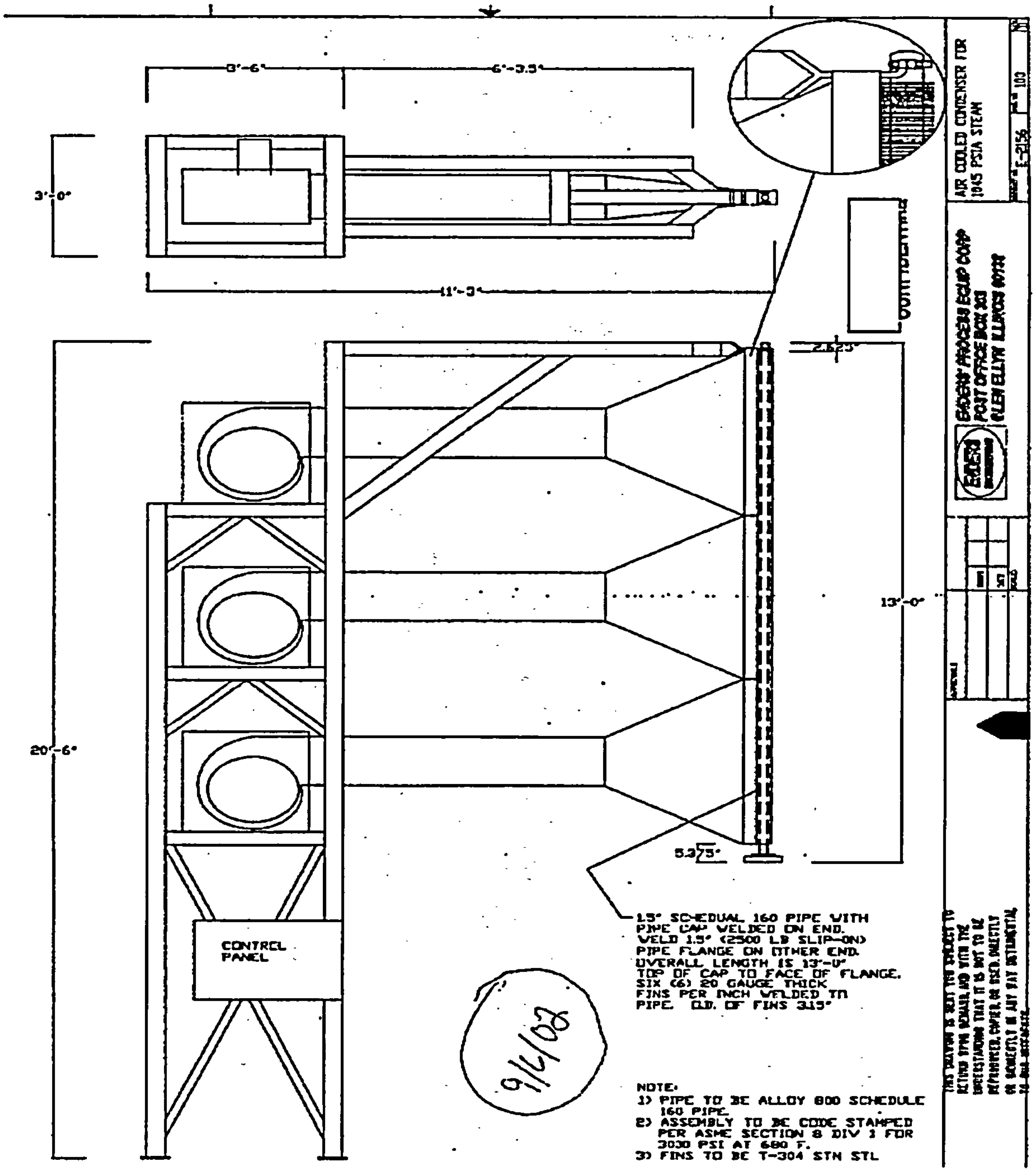
support structure that is 6.2-m (20.5-ft) high. Three 1.5-hp, three-phase induction motors (1760 rpm) directly drive squirrel-cage fans and deliver 60 m^3/min(2100 SCFM) at a 50-mm (2-in.) static pressure. The condenser is sized to reject up to 40 kW using three fans and down to 3 kW using only one fan. Figure 12 shows a detailed drawing of the fan tower. Figures 13 and 14 show, respectively, a photograph of the bottom portion of the condenser pipe/ductwork, where it bolts to the top flange of the secondary chamber, and a view of one of the fan inlets and the associated ductwork.

Closed-loop feedback control between a bulk water thermocouple in the secondary chamber, and the variable frequency/speed drive fan controller adjusts heat rejection to maintain the desired secondary set-point temperature. If the secondary chamber rises above the desired temperature, the fan speed is increased to cool it down. Figure 15 shows a photograph of the fan system control panel consisting of temperature set-point module, programmable fan speed controller, three fan on/off switches, and a master electrical power shut-off. Thermocouples on the inlets and outlets to the air blower ducts allow monitoring of condenser pipe cooling at the three duct elevations. One thermocouple is located in the air stream of each duct upstream of the condenser pipe, and three thermocouples are placed on each duct flap in the air downstream of the condenser pipe. These thermocouples allow monitoring of heat rejection from the condenser over three sectors of the finned pipe, and the data are recorded on the facility computer.

2.1.5 Crevice and Tube Assembly

This section describes design of the Model Boiler Alloy 600 capped SG tubes and crevice simulator collars that fit over the tubes mounted in the secondary chamber. Figure 16 shows the crevice simulator collar assembly, which consists of, from left to right, a crevice collar, a cone wedge, a tube-fastening/crevice-sealing ring, and a four-screw fastening ring. Figure 17 shows a crevice simulator mounted at mid-span on a capped steam generator tube. The bottom of the steam generator tube is welded into a Swagelok™ threaded fitting that screws into the floor of the secondary chamber, which is the top of the primary chamber.

The crevice simulator collars for the initial studies will have crevice radial gaps of 0.51, 0.38, and 0.35 mm (0.020, 0.015, and 0.010 in.) with the SG tube so that the effect of the gap on crevice heat transfer and hideout can be studied. The initial crevices are closed at the bottom and open to bulk secondary water at the top. For these gaps, the OD of the crevice simulator is 48.8 mm (1.92 in.), and the wall thickness is nominally 12.7 mm (0.5 in.), with the inner hole diameter varied to achieve the desired range in crevice radial gaps. The thickness of the collar is based on thermal modeling of the Model Boiler crevice heat transfer (see Section 3), which showed that a collar of this thickness would produce crevice heat fluxes and temperatures (superheat) that are prototypic. The dimensions can be adjusted after the initial tests if the desired conditions are not achieved. The height of the simulator is 25.4 mm (1.00 in.) The two middle rings shown in Fig. 16 comprise the wedging system that holds and centers the crevice simulator on the tube. The cone-shaped ring has a 15° wedging angle, which interfaces with a 12° bevel angle on the bottom edge of the crevice simulator hole to form a seal. The beveling and cone ring, when fitted together, reduce the height of the crevice gap by 3.2 mm (1/8 in.). The wedging action has proven to be very effective in holding and centering the crevice simulator on the tube, without great force. To further ensure centering of the ring on the tube, three gauge pins are inserted in the crevice gap when tightening the four screws and are removed after tightening.



1.5" SCHEDUAL 160 PIPE WITH PIPE CAP WELDED ON END. WELD 1.5" (2500 LB SLIP-ON) PIPE FLANGE ON OTHER END. OVERALL LENGTH IS 13'-0" TOP OF CAP TO FACE OF FLANGE. SIX (6) 20 GAUGE THICK FINS PER INCH WELDED TO PIPE. O.D. OF FINS 3.15"

NOTE:
1) PIPE TO BE ALLOY 800 SCHEDULE 160 PIPE
2) ASSEMBLY TO BE CODE STAMPED PER ASME SECTION 8 DIV 1 FOR 3030 PSI AT 680 F.
3) FINS TO BE T-304 STN STL

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Figure 12. Drawing of the fan tower associated with the secondary air-cooled steam condenser pipe

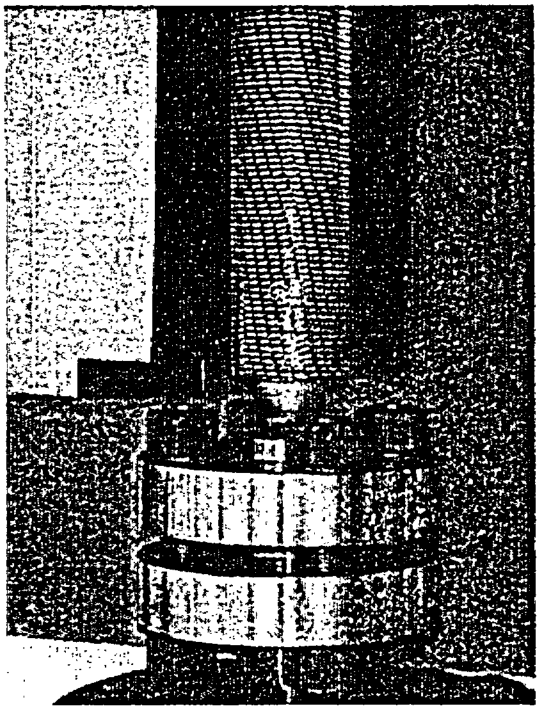


Figure 13. Photo of the bottom portion of condenser pipe/ductwork where it bolts to the top flange of the secondary chamber

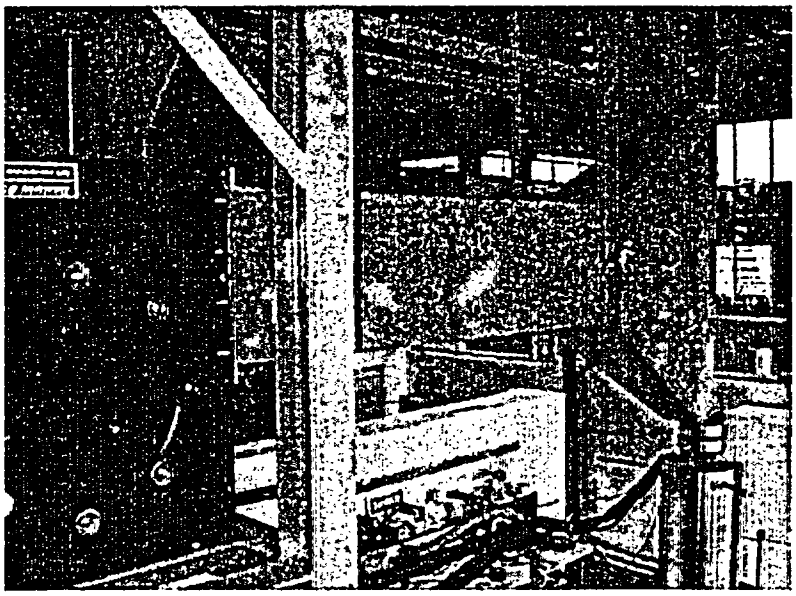


Figure 14. Photo of one fan inlet and the associated air duct

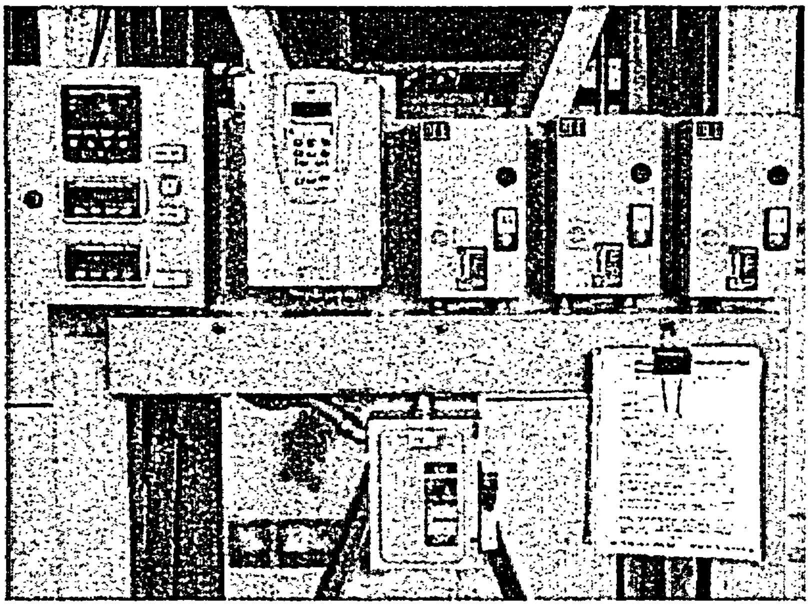


Figure 15. Fan system control panel showing (left to right) temperature set-point module, programmable fan speed controller, three fan on/off switches, and a master electrical power shut-off

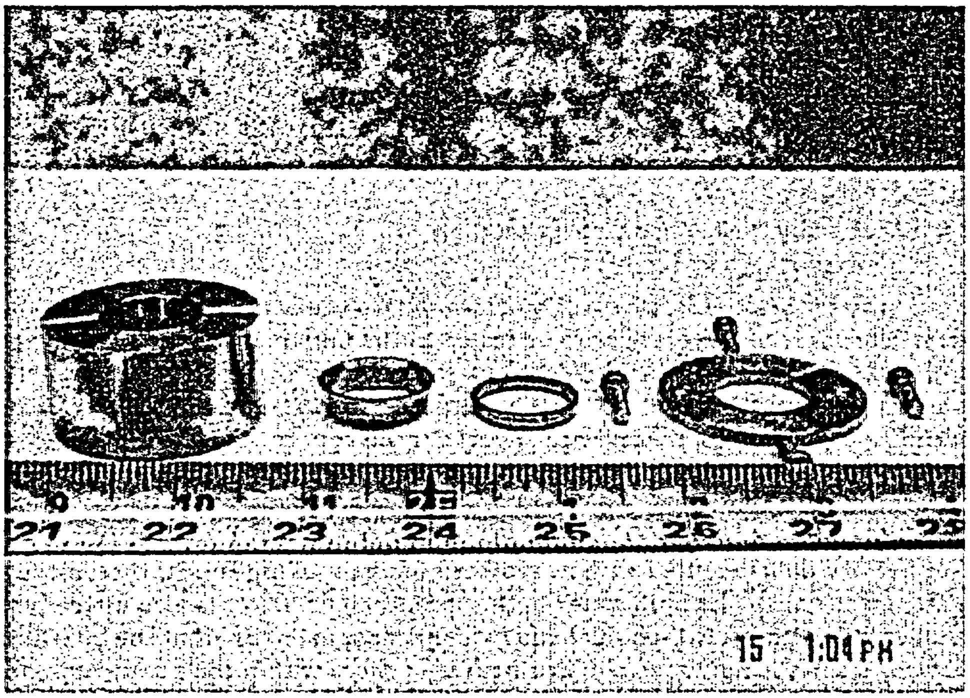


Figure 16. Crevice simulator ring assembly

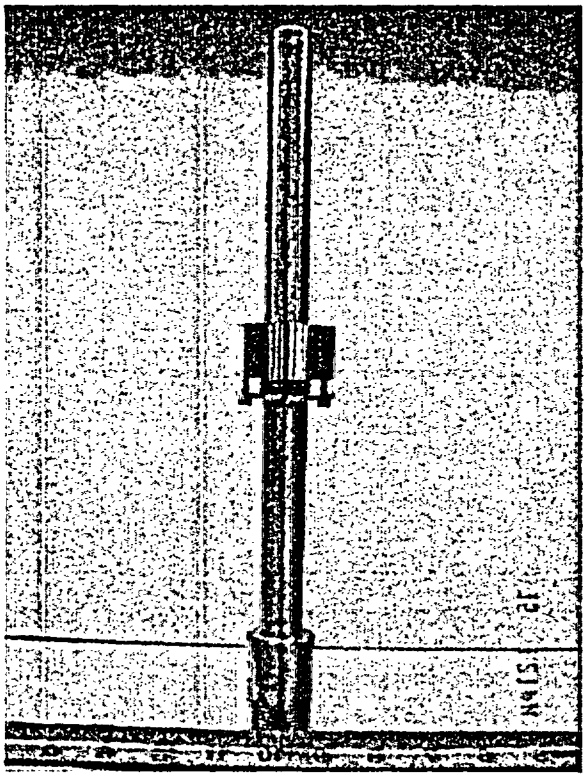


Figure 17. Crevice assembly mounted on capped 0.30-m (12-in.)-long SG tube

2.1.6 Crevice/Secondary Bulk Water Instrumentation

This section describes the crevice and bulk secondary water instrumentation to be used in the initial crevice tests. The two crevices to be tested in the initial chemical hideout experiments have 0.38- and 0.51-mm (0.015- and 0.020-in.) radial gaps and will involve NaOH at bulk secondary water concentration of 20 ppm. It is anticipated, based on crevice heat transfer and hideout modeling (see Section 3), that crevice superheat will concentrate NaOH by a factor of 20-30 thousand over that in the bulk water if the thermodynamic concentration limit, which is a function of crevice superheat, is achieved.

The crevices are instrumented with micro-bore fluid sampling tubes, thermocouples, and water chemistry electrodes. The bulk water in the secondary chamber is also instrumented with similar instrumentation plus a two-point steam/water sensor to ensure that the interface stays at the desired level. The layout of the two instrumented crevices within the secondary chamber for the initial tests and the associated crevice and secondary instrumentation are shown schematically in Fig. 18 and by the photograph in Fig. 19.

Figure 20 shows a schematic of the location of the instrumentation on a crevice simulator ring. To sample the crevice fluid periodically and determine the concentration of the hideout species, two micro-bore stainless steel tubes routed radially through the crevice simulator ring are used to draw small samples of crevice fluid outside the pressure boundary, where they are cooled prior to entering a micro-metering valve. The samples are then collected for analysis. For the sampling process to be effective, a volume of sufficient size for measurement must be withdrawn, and it must be a small fraction of the entire crevice volume so as to not upset the crevice hideout process. The volume of crevice sample needed for characterization is nominally 0.1 ml (0.061 in.^{3}). The volume of the smallest crevice, which has a 0.25-mm (0.010-in.) radial gap, is 0.39 ml (0.024 in.^{3}). The volume of the fluid residing in the 1.2-m (4-ft) length of the 0.23-mm (0.005-in.) ID micro-bore tubing being used to route the sample out of the secondary chamber is 0.015 ml (9.43 x 10^{-4} in.^{3}). Hence, several tube volumes can be drawn out of the crevice and still constitute a small fraction of the crevice volume, thus minimizing upset of the crevice and yielding a fluid sample of size adequate for characterization.

For each crevice, four thermocouples (TCs) are placed in the collar, and two thermocouples are placed in the crevice fluid close to the inner wall of the collar (see Fig. 20). The Incoloy 800 sheathed thermocouples are fine gauge (0.25 mm or 0.010 in.) and have a fast response time to allow tracking of temperature oscillations generated by boiling in the crevice. The thermocouples for measuring the crevice fluid/wall interface temperature oscillations are located at mid-crevice depth at two circumferential locations on each crevice, with the junction beads slightly recessed from the inner wall surface. The temperature oscillations will diminish as the chemical hideout progresses towards the thermodynamic limit with time. The oscillations will be used to study progression of hideout and to detect possible dryout in the crevice due to steam blanketing.

The four thermocouples in the wall of the collar yield data used in the 1-D heat transfer model to calculate the heat flux through the ring wall as well as the temperature at the inner wall of the ring. This information is important in evaluating what is happening in the crevice fluid. The thermocouples are located at two circumferential locations around the crevice at mid-crevice depth, with the lead wires routed parallel to the axis of the ring (see Fig. 20). Each circumferential location consists of two paired TCs with beads located 3.2 mm (1/8 in.) from the inner and outer walls of the crevice simulator ring.

Finally, as depicted in Figs. 20 and 21, there are two crevice chemistry instrumentation ports, allowing electrodes to be inserted radially and located in the crevice gap fluid. The electrodes are located at different crevice elevations, and electrochemical potential is monitored at each location. Each crevice chemistry probe contains three metal electrodes consisting of Ni, Alloy 600, and Pt wires. Each wire is sheathed in insulating Teflon™ and has a small exposed tip wetted by the crevice fluid. In addition, each probe has an associated thermocouple for measuring local temperature. Located in the bulk secondary water is a sensor similar to those on the crevices, which measures electrochemical potential (see Fig. 22). The bulk secondary water also has a reference electrode adjacent to the three-electrode assembly (Fig. 22). Yttria-stabilized zirconia (YSZ) membrane-type pH electrodes are being considered for the direct measurement of pH in the bulk and in the crevice. However, there is a concern that the membrane may be hydrolyzed in the range of operating temperatures, particularly in basic solutions. This instrumentation is undergoing further development.

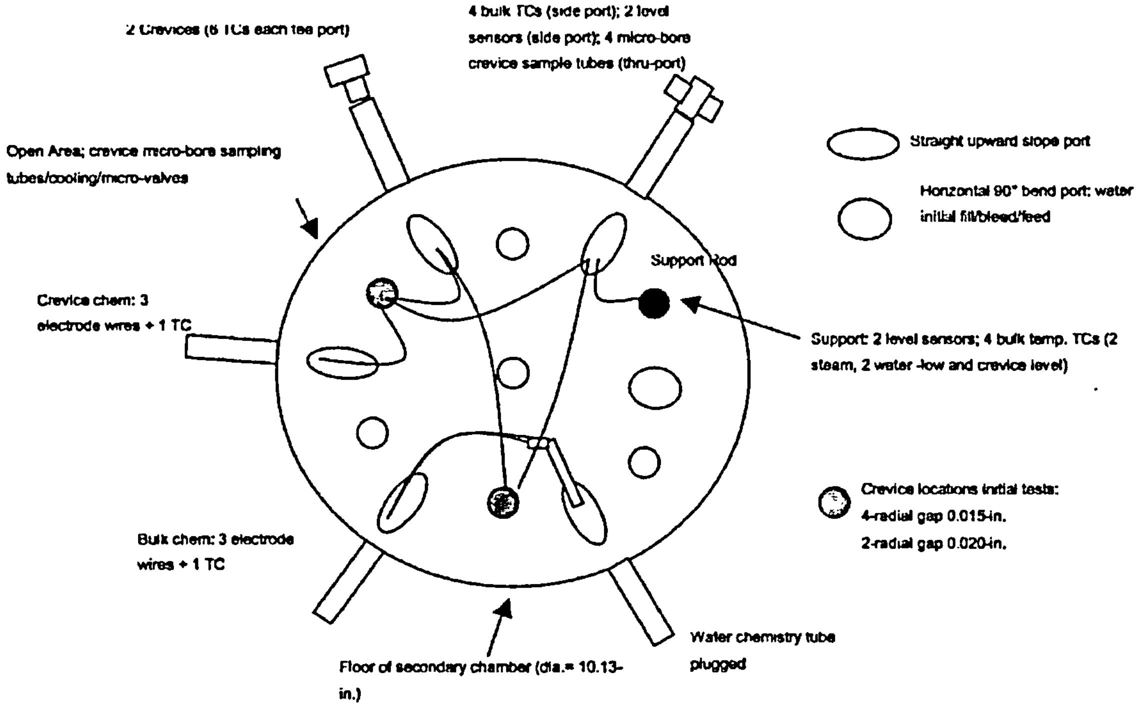


Figure 18. Schematic of tube/crevice and instrumentation locations in Model Boiler secondary chamber

It is very important to the successful operation of the Model Boiler to maintain the secondary chamber water level so that it is not so low as to uncover SG tubes and not so high as to interfere with the rise of secondary steam into the vertical finned steam condenser pipe. Too high a water level also makes it difficult to maintain the secondary chamber at the desired operating temperature. Upsets of the water level could arise from removing or adding too much makeup water as part of water chemistry control or a leak in the secondary pressure boundary. To monitor the water/steam interface location, a two-point (max and min) interface sensor based on the measurement of the differences in resistivity in water and steam has been developed, and a prototype has been fabricated and mounted in the secondary chamber. The signals from the two resistivity sensors monitor whether the water/steam interface is between the desired levels and, if not, whether it is too high or too low.

Figures 23 and 24 show photographs of the resistivity sensors mounted on a 0.51-m (20-in.)-long vertical support rod that fastens to the bottom of the secondary chamber at the location shown in the schematic of Fig. 18. The sensors are each held on the support rod by a set screw. They are vertically separated by 100 mm (4 in.), with the bottom sensor located at the minimum level of the steam/water interface, which is 0.36 m (14 in.) above the floor of the secondary chamber, and the top sensor located at the highest desired level for the interface. Figure 24 is a close-up view of a level sensor showing the paired stainless steel wires exposed over a 6.35-mm (0.25-in.) length to the water or steam separated by a 6.35-mm (0.25-in.) measurement gap across which the resistivity is measured. The two wires, each set in a shallow groove, each held in position by two screws and a retaining plate. The wires are covered beyond their exposed tips with electrical insulating Teflon™ coating. The leads for each probe exit the pressure vessel through a high-pressure Conax™ fitting.

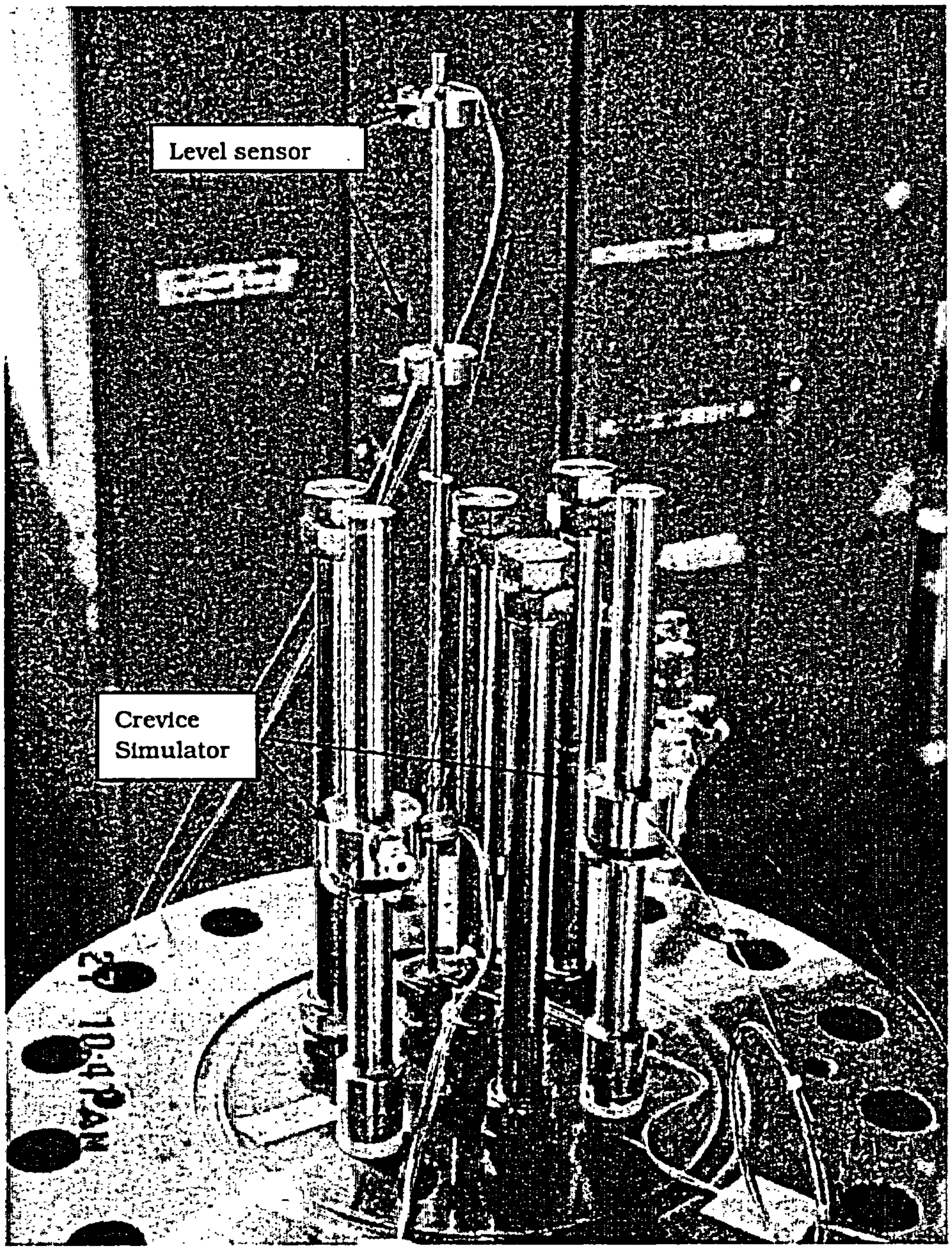


Figure 19. Photo of tube/crevice and instrumentation locations in Model Boiler secondary chamber

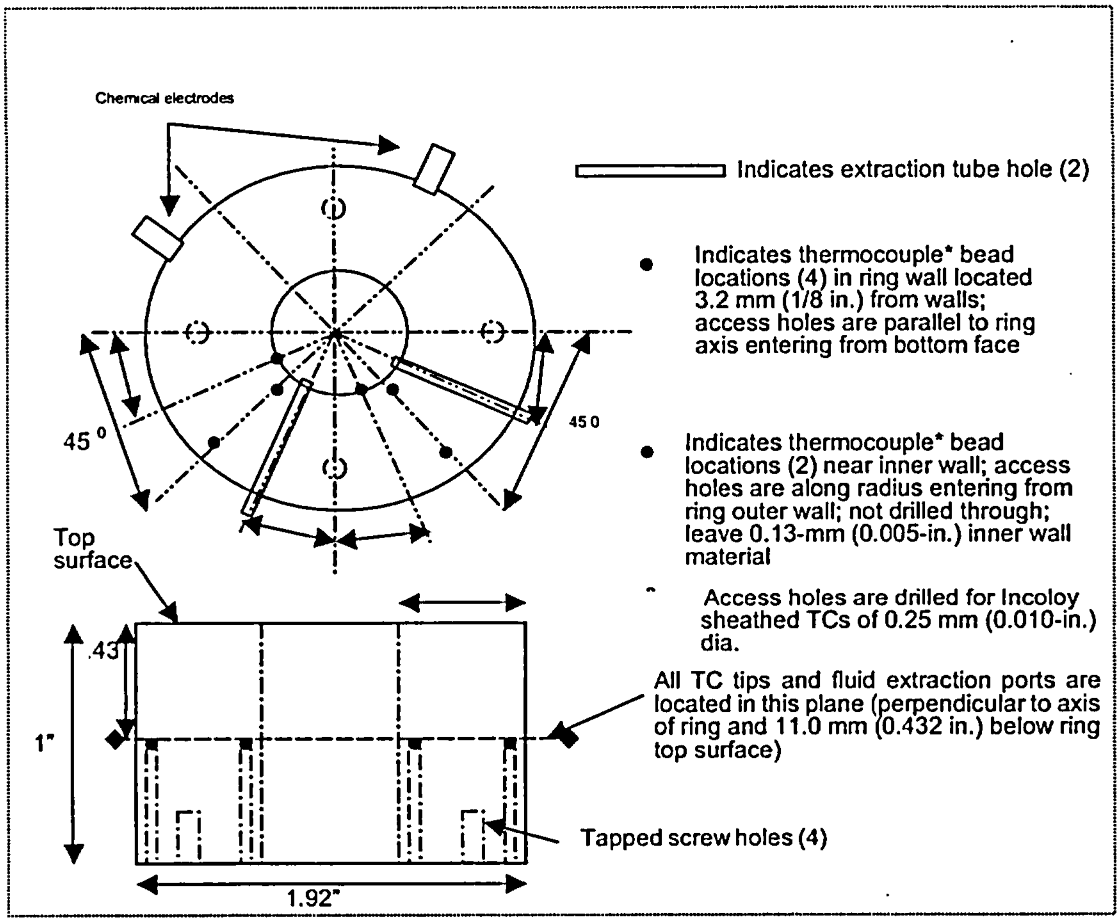


Figure 20. Crevice simulator ring instrumentation: location of thermocouples, micro-bore fluid-extraction tubes, and electrodes

During shakedown testing at elevated temperature (>316°C or >600°F), the Teflon™ coating proved to be satisfactory, and the signals from the paired resistivity elements were confirmed to differ by three orders of magnitude between steam and water immersion. The same approach is used to insulate the leads associated with the crevice and bulk secondary water electrodes. The generated high- and low-level signals are recorded on the facility computer acquisition system (DAS). An audible alarm indicates when the steam/water interface is either too high or too low.

2.1.7 Water Chemistry Control

The secondary-side bulk solution in the boiler will simulate secondary-side water chemistries of interest to PWRs, as revealed by autoclave studies on crack initiation and by plant experience. The feed solutions will be prepared from high-purity deaerated and deionized water. The first benchmarking tests of chemical hideout will involve NaOH as a trace contaminant at 20 ppm. This species was chosen as a starting point because of the existing data on crevice hideout

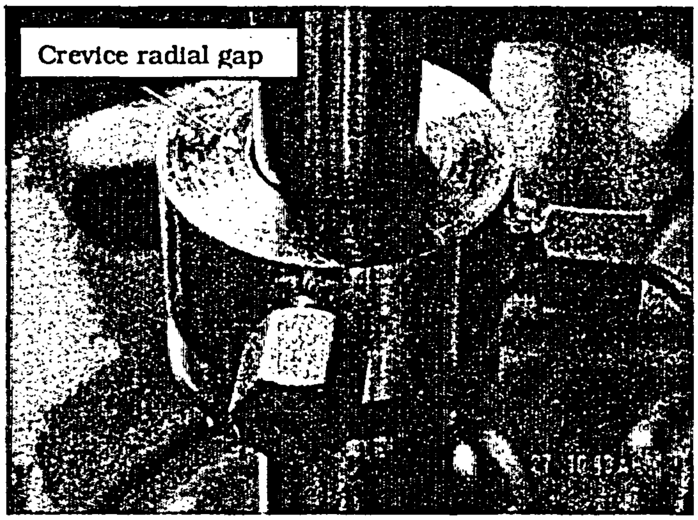


Figure 21. Photo of crevice simulator ring mounted on tube, showing concentric radial gap and two electrochemical potential electrode ports

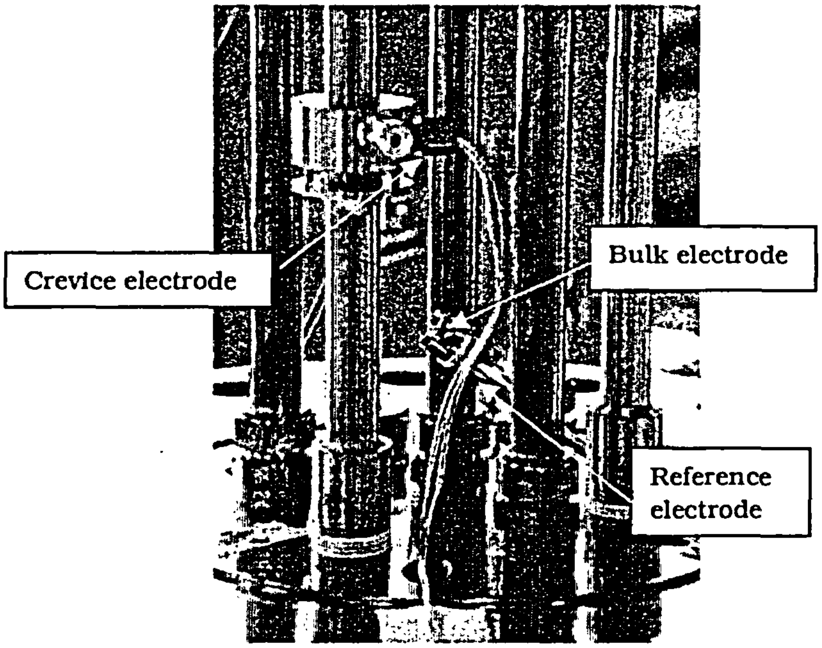


Figure 22. Photo of crevice simulator ring showing water chemistry electrode, secondary bulk water electrode (located below and to right of crevice), and reference electrode

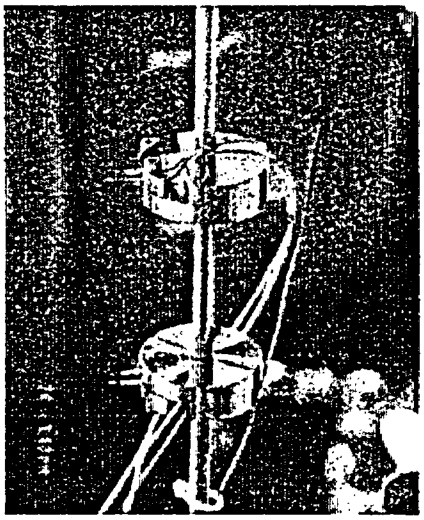


Fig. 23. Photo of two water/steam interface level sensors mounted on 0.51-m-long vertical support rod fastened to the bottom of the secondary chamber

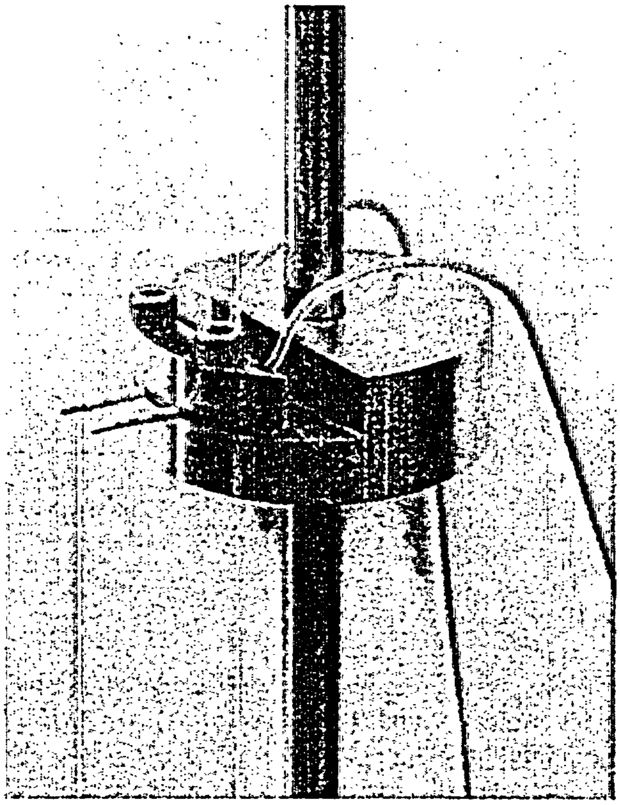


Fig. 24. Close-up photo of a level sensor showing the Teflon™ coated resistivity probe wires with exposed tips located 6.35 mm apart

for its chemistry. Investigations will progress to include other species, such as Na^+, K^+, Ca^{2+}, NH_4^+, PO_4^{3-}, SO_4^{2-}, OH^-, Cl^-, and N_2H_4.

Figure 25 shows the design of the conditioning and monitoring system for bulk secondary-water chemistry, which is capable of batch or continuous bleed/feed conditioning to ensure water-chemistry control and stability. The appropriate water chemistry is charged, by using a metering pump from a 190-L (50-gal) supply tank, into the secondary chamber under the continuous mode at a rate of 5 to 15 ml/min, and this same amount of solution is simultaneously bled from the chamber. The bleed-off of solution is controlled by a micro-metering valve. Under the batch mode, ≈2.3 l (5 lb) of water will be withdrawn over a period of 1 h, and an equal amount of chemistry-enriched solution will be charged by the metering pump into the chamber. The total water residing in the secondary chamber is nominally 17.3l (35 lbs), which is monitored by the two level sensors described earlier and serves as a control on removing or adding too much solution.

The chemical monitoring will be used to track the movement of trace chemicals from the bulk water to the crevices over time. Changes in the concentration of the trace chemicals in the bulk secondary water under conditions of an intentional cessation of the continuous water chemistry bleed/feed system or with batch changes will be correlated in time with changes in the temperature and chemistry data from the instrumented crevices.

2.1.8 Dedicated Computer Data Acquisition System

The Model Boiler Facility has a dedicated computer data acquisition system based on National Instrument (NI) data acquisition hardware and NI LabView 6.1 software. The following lists the primary features of the DAS, and Figs. 26 and 27 show photographs of the hardware:

The stand-alone computer for the DAS continuously logs all subsystems, including their controllers; all setpoints; and all thermal-hydraulic parameters, including temperatures, pressures, and water chemistry in the crevice regions.

The DAS is not a safety-mandated or a safety-related system, but is a passive data-taking system.

The DAS is located in the control room of the Steam Generator Tube Test Facility, which is a clean/stable environment.

The DAS consists of a PC as an embedded processor as part of the NI data acquisition hardware and NI LabView 6.1 software (similar to a computer system with many specialized card slots) (see Fig. 27).

A second Dell PC stores data received at selectable intervals from the NI computer for redundancy of data storage and facilitates data analysis off-line without interrupting data acquisition (see Fig. 26). If the analysis computer crashes, the event has no effect on the data collection by the NI computer.

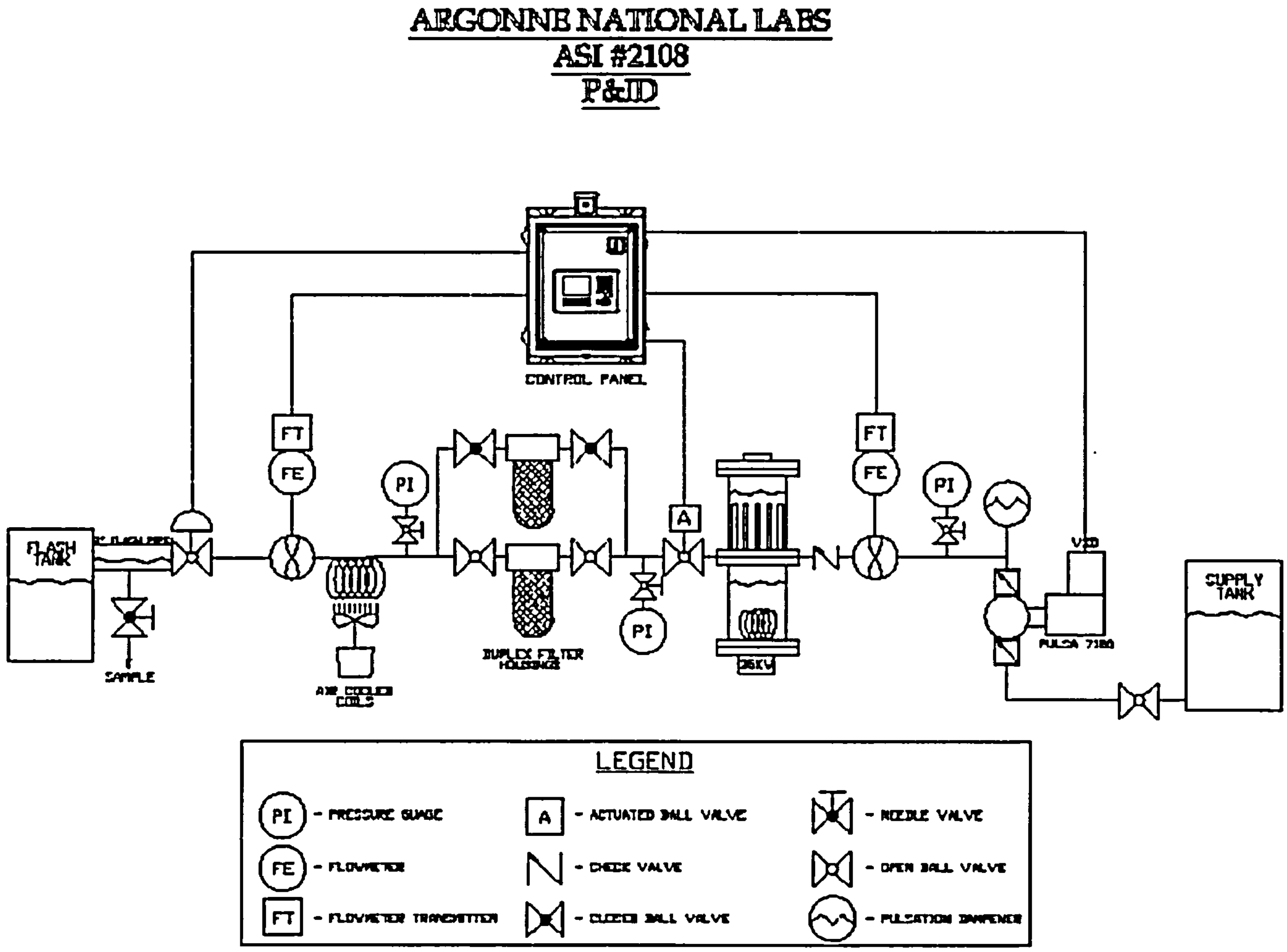


Figure 25. System for treatment, monitoring, and control of secondary-side bulk water chemistry

There are two monitors, one for the embedded computer and one for the data archiving and data analysis. Figure 28 shows the computer monitor window associated with the embedded computer, displaying a facility schematic in which current facility state variables are displayed during data recording. Other windows display plots of Model Boiler state variables and control parameters versus time.

Data are normally recorded at a nominal rate of every 30 s to 5 min (selectable by the operator). At the operator's discretion, data can be taken at a higher sampling rate for a prescribed time interval, i.e., in burst mode (sampling rate 10 to 100 samples/sec). For example, crevice temperature oscillations resulting from boiling and crevice outflow/inflow can be recorded at the high sampling rate initiated by the operator periodically to evaluate the influence of chemical hideout on the boiling.

Figure 26. Computer data acquisition system for Model Boiler: Monitor on left displays data recorded by an NI embedded PC, and the Dell computer and monitor on right display and store data received at selectable intervals from the NI computer for data storage redundancy and off-line data analysis.

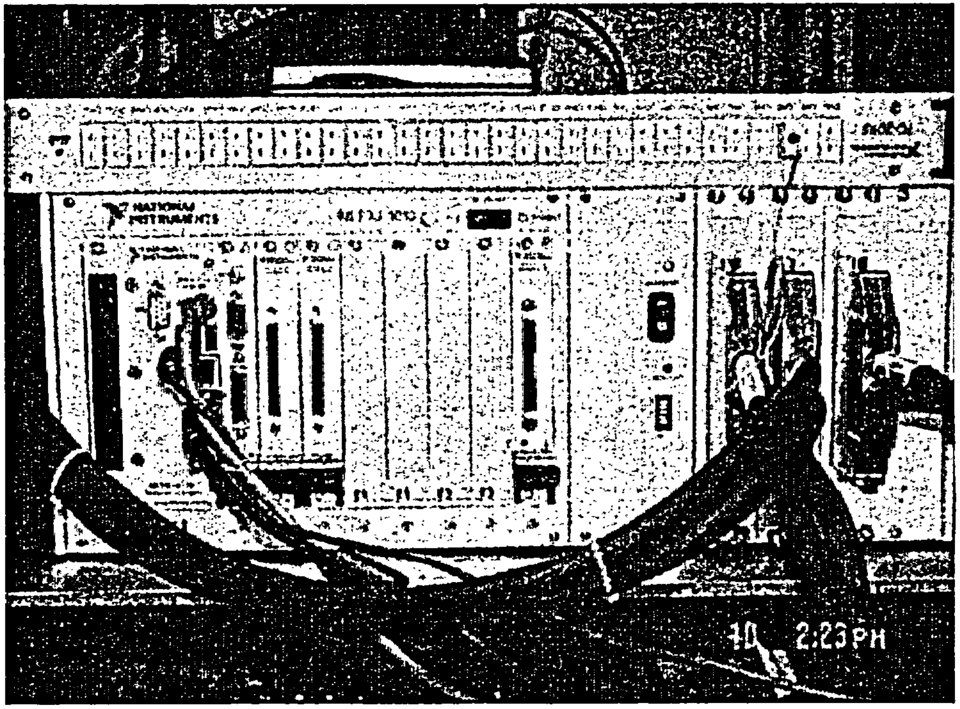


Figure 27. National Instrument (NI) data acquisition embedded PC hardware

2.2 Safety Features

The Model Boiler Facility has engineered safety features designed to protect against potential hazards from high-pressure, high-temperature steam, burn, and electrical shock. During its design, the Facility underwent formal NRC-sponsored design reviews by a third party, as well as an extensive formal Argonne safety review. The equipment associated with the various safety features is described in Section 2.1. The safety features associated with the facility are listed below:

Model Boiler pressure vessel, 40-kW electric heater, and finned condenser pipe are designed and built according to ASME B&PV Code Section VIII, Div. 1, and are stamped for an MAWP of 20.7 MPa (3000 psi) at 360°C (680°F).

All pressure-boundary fittings are commercial-grade high-pressure fittings with pedigrees certifying pressure integrity at 20.7 MPa (3000 psi). No fittings are shop modified or used in non-recommended ways.

The pressure vessel with the 40-kW flange electric heater as an assembled unit has been hydrostatically tested at room temperature to 31.0 MPa (4500 psi) by a third party.

Over-pressurization protection rupture discs, as mandated by the ASME B&PV Code, are located on both the primary and secondary chambers. There are no valves located upstream or downstream of the rupture discs, and the lines are sized to relieve pressure at a steam rate based on the full 40-kW primary heater input, which is the primary facility energizer. If venting is needed, the steam is dumped to a 380-L (100-gal) indoor tank, which condenses the steam. Any possible steam not condensed is released outside to a controlled fenced-in area already approved for dumping of steam from the adjacent High-Temperature Blowdown Facility at pressures to 20.7 MPa (3000 psi) and 360°C (680°F) and at steam rates of 640 kg/min (1400 lb/min). There is sufficient margin between needed test conditions for the Model Boiler studies, rupture-disk-to-open pressures, and pressure vessel specifications to ensure safe and reliable operation, as follows:

- The maximum vessel temperature of 360°C (680°F) corresponds to a 18.7 MPa (2708 psi) saturation pressure.
- The 20.7 MPa (3000 psi) MAWP corresponds to saturation at 369°C (697°F).
- The 338°C (640°F) primary temperature is the highest temperature needed in the experiments, which corresponds to a saturation pressure of 14.2 MPa (2060 psi).
- The primary temperature is always greater than the secondary temperature.
- The over-pressurization relief device in the primary chamber is set to open at 18.6 MPa (2700 psi).
- The over-pressurization relief device in the secondary chamber is also set to open at 18.6 MPa (2700 psi).

A concrete block protective barrier surrounds all high-pressure equipment.

Entrances to the enclosed area have flashing red lights that operate when the system is pressurized. Under these conditions, only cognizant personnel can enter the area.

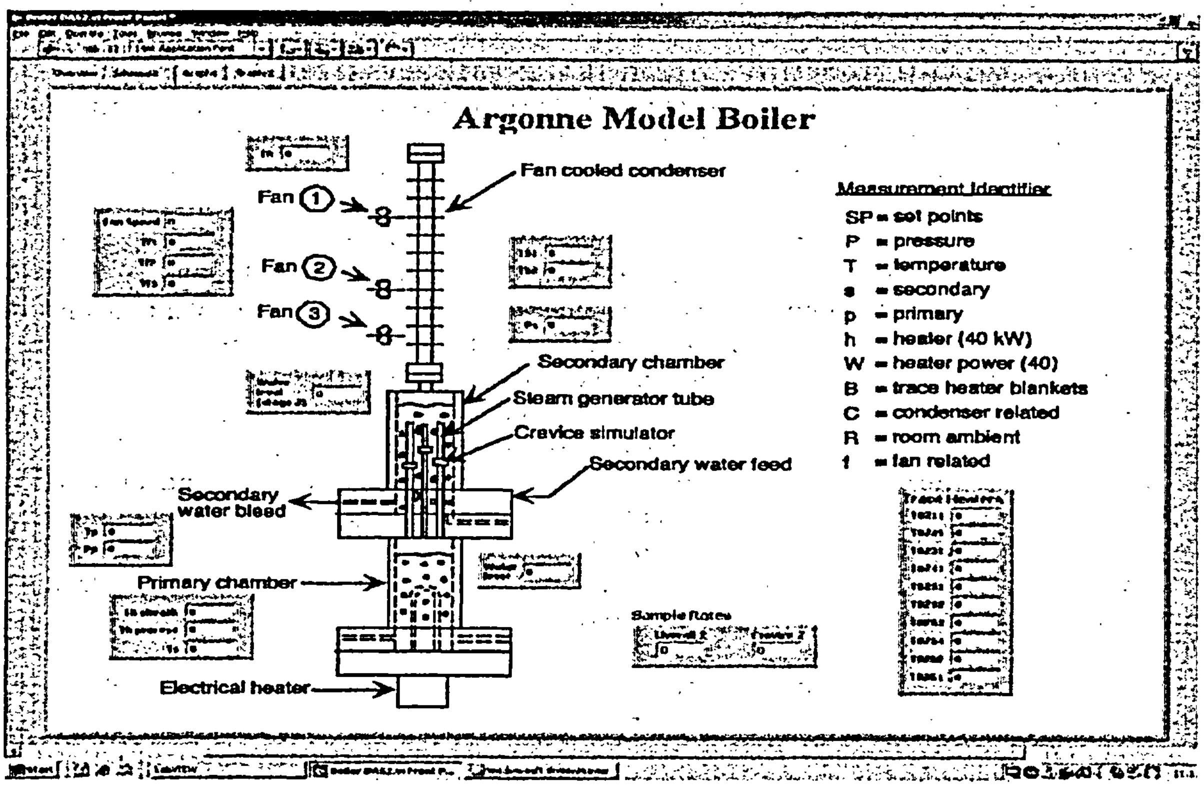


Figure 28. Computer-recorded data display showing state variables of the Model Boiler Facility. The display is updated periodically for easy visual assessment of facility status, and other windows show state variable plots versus time.

Signs by entrances say "Do not enter" and warn of high-pressure, high-temperature steam.

The 40-kW and trace electrical heaters have automatic over-temperature protection that shuts off electrical power. The power does not automatically come back on when temperature drops below the over-temperature point.

All personnel are trained in facility operation and were part of the facility design, development, and shakedown testing team, making them very knowledgeable about the overall system and subsystems and their interactions.

Emergency safety power cutoffs are located outside the barrier to allow emergency shutdown of all electrical drivers, which consist of the 40-kW heater, trace heaters, and fan-tower air blowers. These systems can be put under administrative lockout by cognizant personnel during work on the facility. In the absence of electrical power, the facility will slowly cool down from heat loss through the vessel insulation and natural convection from the secondary steam condenser pipe, with a corresponding decrease in saturation pressure.

In a worst-case scenario, during unattended operation, the facility will shut down automatically either by opening of a rupture disc and/or by loss of heater power due to limit temperatures being exceeded.

3 Modeling of Tube/Crevice Heat Transfer and Hideout

The crevice analysis is based on a 1-D cylindrical geometry model of thermal and chemical hideout behavior in the crevice region. The thermal distributions and the heat flux occurring in the tube/support-plate crevice region strongly influence crevice hideout and, hence, the rate of accumulation of the low-volatility chemical impurities and their ultimate concentration.

Because of the complexity of the tube/tube support-plate crevice geometry, only an approximate evaluation can be performed with the 1-D assumption. The flow through the crevice before it becomes packed with porous debris is, in general, multiphase, with transient regions of dryout or vapor formation occurring during the evolution of the hideout process. Under some conditions, the crevice can become completely blanketed with steam. Under other conditions, if the thermodynamic chemical hideout limit is reached, boiling in the crevice can stop and the crevice become filled with liquid. The hideout process depends strongly on the detailed local nature of the temperature distributions, heat flux, and flow in the crevice and also, very importantly, on the crevice geometry. Different support-plate designs and resulting different crevice geometries have an important influence on the behavior of the water and steam chemistry in the crevice and are as important to what happens in the crevice as the thermal-hydraulic conditions of the primary and secondary bulk water.

The situation is made more complex by the fact that the flow patterns are strongly influenced by the behavior of nucleating vapor bubbles generated in the confinement of the crevice walls. This influence on the flow patterns is the result of the intense fluid-induced motions caused by the rapidly growing or collapsing vapor bubbles nucleating in the crevice.

3.1 Geometry and Boundary Conditions in the Crevice Region

Figure 29 shows crevice region geometry for a prototypic drilled-hole tube/tube support plate. This geometry was modeled by Argonne in designing the Model Boiler. Figure 30, which is a simplification of Fig. 29, was analyzed using a 1-D approximation to assess prototypic crevice conditions relative to what could be achieved in the Model Boiler crevices. Figure 31 shows the same simplified geometry for a falling condensation film boundary replacing the forced convection of the prototype shown in Fig. 30. In Fig. 31 the Model Boiler crevice outer wall is not insulated (crevice wall thickness = L), since no clear choice of insulating material can withstand the high temperatures and pressures of the Model Boiler and not leach undesirable impurities to the solution. To obtain prototypic crevice temperatures, heat fluxes, and superheat, all of which are important to chemical hideout behavior, we used the wall thickness L, primary/secondary temperatures, and the crevice gap as variables. The thermal hydraulic conditions shown in Figs. 29-31 are those in the hot leg at the first tube support plate, since the thermal conditions for hideout are believed to be greatest at this location.

For the prototype and Model Boiler crevice analysis, the tubes and support plates were specified as made of the Alloy 600 and stainless steel, respectively. Parametric calculations for other support plate and tube materials show that the variation in the thermal properties of these materials has little influence on crevice superheat and heat flux, for reasons discussed shortly. All calculations presented are for a radial gap of 0.38 mm (0.015 in.), a crevice depth

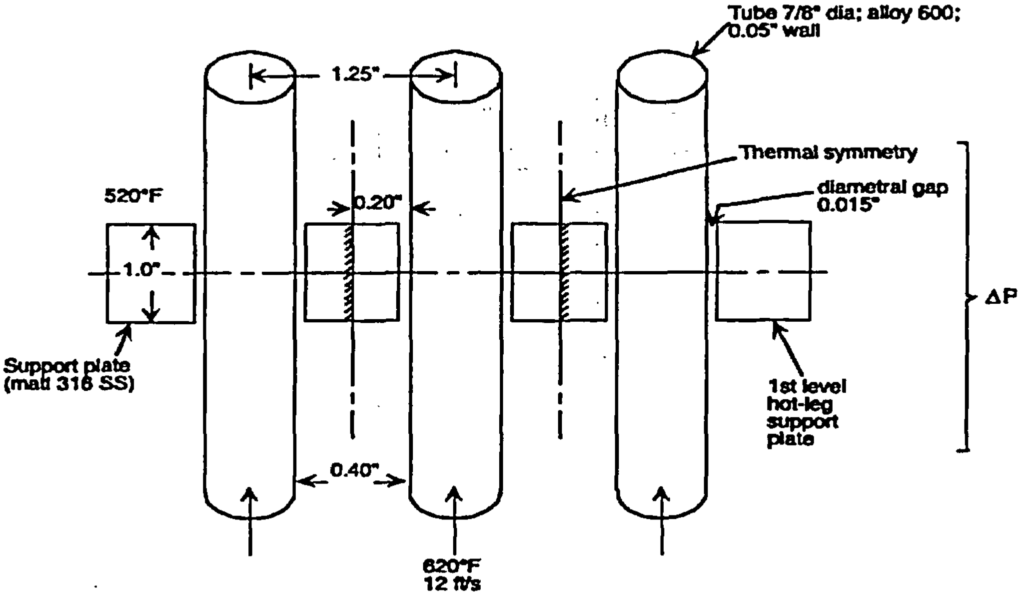


Figure 29. Crevice geometry in prototype drilled-hole support plate tube

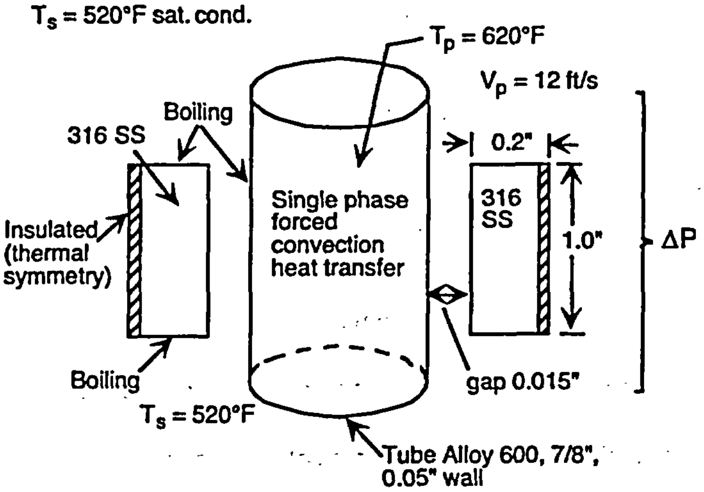


Figure 30. Simplified prototype crevice geometry

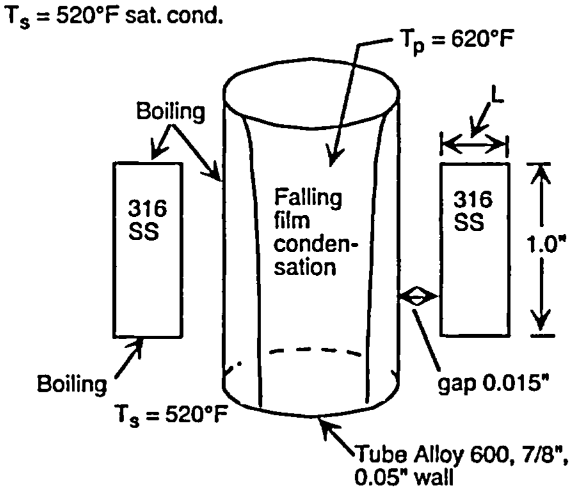


Figure 31. Model Boiler crevice geometry

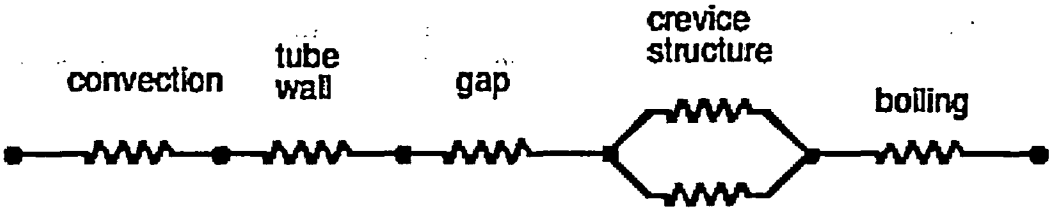
of 25 mm (1.0 in.), and primary and secondary saturation temperatures of 327 and 271°C (620 and 520°F), respectively. As shown in Fig. 30, the simplified prototype crevice has single-phase heat transfer occurring by forced convection in the tube, whereas heat transfer occurs by falling film condensation in the Model Boiler tube (Fig. 31).

3.2 Governing Equations for 1-D Model

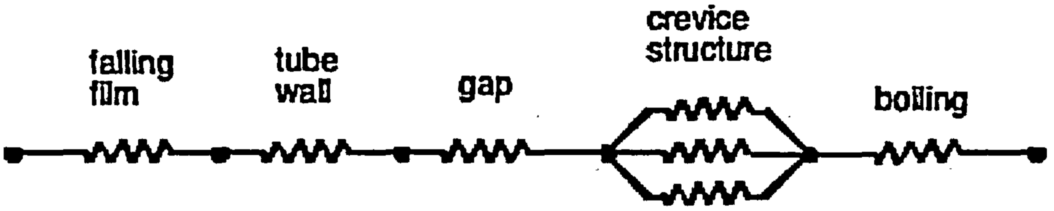
The heat transfer across the tube/crevice region is analyzed as a function of the primary and secondary thermal-hydraulic conditions and the crevice geometry. The heat transfer phenomena modeled and analyzed in comparing prototype crevice behavior with that of the Model Boiler are as follows:

1. Heat transfer by forced convection inside tube (prototype).
2. Heat transfer by falling film condensation inside tube (Model Boiler).
3. Heat conduction through the SG tube (prototype and Model Boiler).
4. Heat conduction through the support plate wall (prototype and Model Boiler).
5. Heat transfer through the crevice gap fluid (prototype and Model Boiler).
6. Boiling at the tube secondary outer diameter (prototype and Model Boiler).

Figures 32 (a) and (b) show the electrical circuit analogies used in the 1-D heat transfer modeling of the simplified prototype crevice (Fig. 30) and ANL Model Boiler crevice (Fig. 31), respectively. The crevice-wall thermal resistances shown in Fig. 32 are different for the prototype and the Model Boiler. As shown in Fig. 30 for the prototype, there are two conduction paths through the crevice wall to the boiling environment, because one surface of the crevice structure is insulated due to a thermal symmetry plane. However, this wall is not insulated in the Model Boiler, which has three conduction paths to the boiling environment.



a. Simplified Prototype



b. ANL Model Boiler

Figure 32. Electrical circuit analogy used for 1-D heat transfer modeling of the simplified prototype and Model Boiler crevices

The equations for each thermal phenomenon and their relationship to the overall heat transfer across the crevice region are discussed next. For both the prototype and Model Boiler crevices, the heat flux across the crevice region is given by $q = h_a(T_p - T_s)$, where T_p and T_s are the primary and secondary bulk temperatures, and h_a is the overall heat transfer coefficient.

The parameter h_a represents the thermal resistance series for the problem and is defined as follows:

$$h_a = \frac{1}{\frac{d_{c_{out}}}{d_{in}}\frac{1}{h_v} + \frac{d_{c_{out}} \ln\frac{d_{out}}{d_{in}}}{2k_w} + \frac{d_{c_{out}} \ln\frac{d_{c_{in}}}{d_{out}}}{2k_c} + R + \frac{1}{h_b}}$$

$$R_P = \frac{R_1}{2}$$

$$R_B = \frac{R_1 R_2}{2R_2 + R_1}$$

where

h_b = the heat transfer coefficient inside the tube, which, for this prototype, is given by the Colburn equation and, for the Model Boiler, by the Roshenow correlation (see ensuing discussion), W/m^2 °C

$d_{c_{out}}$ = external diameter of crevice, m

d_{in} = internal diameter of tube, m

$d_{c_{out}}$ = external diameter of crevice, m

d_{out} = external diameter of tube, m

$d_{c_{in}}$ = internal diameter of crevice, m

k_c = thermal conductivity of fluid in gap between crevice and outer tube wall, W/m^2 °C

k_w = thermal conductivity of tube wall, W/m^2 °C

The term R in the preceding equation represents the thermal resistances associated with the crevice wall structure, where R_p and R_B refer to the prototype and boiler, respectively:

$$R_1 = \frac{d_{c_{out}} \ln\left(\frac{L_2}{d_{c_{in}}}\right)}{2k_s}$$

$$R_2 = \frac{d_{c_{out}} \ln\left(\frac{d_{c_{out}}}{d_{c_{in}}}\right)}{2k_s}$$

where L_2 is a crevice simulator length (see Figs. 30 and 31), m; and k_s = thermal conductivity of crevice simulator, W/m °C. The five thermal resistances are shown in Fig. 32, and are determined as described below.

The Model Boiler heat-transfer coefficient for the falling-film condensation, h_v, is given by the Roshenow correlation:

$$h_v = 3.093\left[\frac{\rho_\ell(\rho_\ell - \rho_v)g\,h'_{fg}k_\ell^3}{\mu_\ell L(T_{sv} - T_{sw})}\right]^{1/4}$$

where

ρ_ℓ= density of saturated liquid, kg/m^3

$_v$ = density of saturated vapor, kg/m^3

g = gravitational acceleration, 9.807 m/s^2

μ_ℓ = liquid viscosity, kg/ms

k_ℓ = thermal conductivity of liquid, W/m^2 °C

L = length of tube, m

T_{sv} = primary saturation temperature, °C

T_{sw} = secondary tube wall temperature, °C

and

h'_{fg} = modified enthalpy of vaporization, J/kg,

$$= h_{fg_v} + 3/8\ C_{p_{\ell v}} \times (T_{sv} - T_{sw})$$

This last variable is derived from h'_{fg} where C_{plv} = specific heat of liquid in J/kg °C, and h'_{fg} = enthalpy of vaporization in J/kg.

For the prototype, the heat transfer coefficient h for forced-convection, single-phase flow inside a SG tube is given by the Colburn equation from Ref. 1:

$$\left(\frac{h}{\rho V C_P}\right)_m \left(\frac{C_P \mu}{k}\right)_f^{2/3} = 0.023\left(\frac{DV}{\nu_f}\right)^{-0.2}$$

where

C_p = specific heat of liquid, J/kg °C

= liquid viscosity, kg/ms

k = thermal conductivity of liquid, W/m^2 °C

= density of liquid, kg/m^3

V = velocity of liquid, m/s

D = inner diameter of tube, m

and

$_f$ = kinematic viscosity, m^2/s

In the above equation, the subscript m indicates properties calculated at average fluid temperature, and f indicates properties evaluated at "film" temperature defined as average of fluid temperature and the tube wall temperature.

The heat-transfer coefficient for the tube wall is given by

$$2\ k_w/d_{c_{out}}$$

The heat transfer coefficient for the crevice gap fluid, *assuming all boiling is suppressed by the chemical hideout (or the crevice is completely steam filled)*, is given by

$$2\ k_c/d_{c_{out}}$$

The nucleate-pool-boiling model of Rohsenow (Ref. 2) is used to represent the heat transfer coefficient on the crevice/tube outer surfaces:

$$\frac{c_{pl}\left(T_{bw}-T_{sb}\right)}{h_{fg}P_{rl}^{1.7}} = C_{sf}\left[\frac{q}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g\left(\rho_l-\rho_v\right)}}\right]^{0.33}$$

where

C_{sf} = constant determined by experimental data, 0.013

ρ_ℓ = density of saturated liquid, kg/m^3

$_v$ = density of saturated vapor, kg/m^3

= surface tension of liquid-vapor interface, N/m

g = gravitational acceleration, 9.807 m/s^2

h_{fg} = enthalpy of vaporization, J/kg

μ_ℓ = liquid viscosity, kg/ms

C_{p_ℓ} = specific heat of saturated liquid, J/kg °C

Pr_ℓ = Prandtl number of saturated liquid

q = heat flux, W/m^2

T_{bw} = outer wall temperature of crevice simulator, °C

and

T_{sb} = secondary saturation temperature, °C

The prediction of crevice temperature and the resulting elevation of the crevice temperature above the saturation temperature of the secondary bulk water (superheat) allows estimation, using simplifying assumptions, of the amount of crevice chemical hideout that is possible. Typical hideout locations are the crevices formed between a tube and a tube support plate, crevices within tube sheets, sludge piles, and porous scale deposits. Crevice boiling draws bulk water into the crevice and expels steam or a mixture of steam and water. Some of the low-volatility impurities drawn in with the bulk water remain behind to concentrate.

The concentration process can increase to the solubility limit of the impurities, leading to the precipitation of impurities that can block or alter access and escape paths for fluid or vapor. The concentration process can also increase to the extent that the boiling point of the crevice fluid is significantly increased over the boiling point of the bulk water. Crevice boiling will stop when the concentration increases sufficiently that the boiling point elevation equals the local crevice superheat, in which case the impurity concentration has reached the thermodynamic limit. The concentration buildup may also stop before the thermodynamic limit is reached, in which case the concentration is kinetically limited. Which of these two situations occurs depends on many factors, including the geometric configuration of the crevice, pathways that connect it to the bulk water, the local temperature and heat flux, the constituent boiling point, and other characteristics of the fluid. *Our initial modeling of hideout is based on the thermodynamic limit.*

The equation used to predict the hideout, as a first approximation, relates the boiling point of a solution that contains impurities to the mole fraction of the impurities present and is given by

$$\mathrm{Ln}\, X_A = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)$$

where

X_A = mole fraction of water

H_{vap} = molar heat of vaporization of H_2O

R = universal gas constant (1.987 cal/mole-K)

T_o = boiling point of pure H_2O in K

T = boiling point of solution (K)

Setting $T_o - T$ equal to the crevice superheat temperature allows calculation of the concentration of the hideout chemical corresponding to the thermodynamic limit. This was done for NaOH as a low volatility impurity in the bulk secondary water. Significant crevice superheat temperatures were found to occur, resulting in potentially high levels of chemical hideout and crevice concentration factors of 20,000-80,000 for NaOH.

3.3 Model Predictions (Prototype Versus Model Boiler)

A computer code has been developed that utilizes an iterative scheme to solve the heat transfer equations in the crevice region for a 1-D cylindrical geometry. The code calculates the temperatures of the various zones, the heat flux across the tube/crevice region from the primary to the secondary side, crevice superheat, and crevice hideout for low levels of impurity in the secondary water.

Results are presented in Tables 1 and 2 for crevice temperatures and heat fluxes for the prototype and Model Boiler geometries of the crevice region shown in Figs. 30 and 31, respectively. The conditions are as follows:

1. Two sets of bulk primary/secondary temperatures: 327°C/271°C (620°F/520°F) and 327°C/262°C (620°F/504°F).
2. The crevice gap of 0.38 mm (0.015 in.) filled with single-phase water associated with the chemical hideout having achieved the thermodynamic limit (Table 1).
3. The crevice gap completely filled with steam (note the thermal conductivity of steam is about 1/15 that of water under these temperatures) (Table 2).
4. Three values of boiler crevice wall structure thickness [L = 5.1, 12.7, and 25.4 mm (0.2, 0.5, and 1.0 in.)] (see Fig. 31).
5. Crevice wall and tube materials fabricated of stainless steel and Alloy 600, respectively.

The data in Tables 1 and 2 are for crevice superheat based on the temperature of the tube outer wall minus the bulk secondary temperature and for the heat flux rate referenced at the tube outer wall into the crevice gap. The far right column of Tables 1 and 2 lists estimates for the prototype crevice with two gap fluid states and for the same primary-to-secondary driving temperature difference of 56°C (100°F). For the liquid-filled gap (Table 1), the superheat is 49°C (88°F), and the heat flux is 57,985 W/m^2 (18,381 Btu/hr ft^2). Similarly, for the steam-filled gap (Table 2) the superheat is 55°C (99°F), and the heat flux is 6,088 W/m^2 (1,930 Btu/hr ft^2). Thus, the difference in the state of the fluid in the gap in changing from liquid to steam caused almost a 90% reduction in gap heat flux and a corresponding 6°C (11°F) increase in crevice superheat.

For the liquid-filled gap (Table 1), the prototype and Model Boiler predictions for the same diametrical gap of 0.38 mm (or 0.015-in.) and the same crevice-wall simulator thickness of 5.1 mm (0.2in.) indicate that the gap heat flux of 54,407 W/m^2 (17,247 Btu/hr ft^2) agrees well with the prototype value of 57,985 W/m^2 (18,381 Btu/hr ft^2). The corresponding superheat values are 42°C (76°F) for the boiler and 49°C (88°F) for the prototype. Hence, the boiler exhibits a superheat about 7°C (12°F) lower than that of the prototype.

Additional calculations show that crevice wall thickness L has only a slight influence on the crevice gap superheat and heat flux. With increasing crevice wall thickness beyond the prototypic value of 5.1 mm (0.2 in.), the heat flux diminished only slightly, and the superheat rose only 0.6°C (1°F). This behavior is explained by the finding that with increasing L (5.1, 12.7,

Table 1 Model Boiler and prototype crevice predictions for diametral gap of 0.38 mm (0.015 in.), crevice depth of 25 mm (1.0-in.), and various crevice wall simulator thicknesses. The calculations assume that the crevice hideout thermodynamic limit has been reached, and *the crevice gap is filled with liquid.*

	Model Boiler: Crevice Wall Thickness, mm (in.)			Prototype: Crevice Wall Thickness, mm (in.)
	5.1 (0.2)	12.7 (0.5)	25.4 (1.0)	5.1 (0.2)
T_p = 327°C (620°F); T_s = 271°C (520°F)				
Superheat, °C (°F)	42 (76)	43 (77)	43 (77)	49 (88)
Heat Flux, W/m^2 (Btu/hr ft^2)	54,407 (17,247)	53,575 (16,983)	52,717 (16,711)	57,985 (18,381)
T_p = 327°C (620°F); T_s = 262°C (504°F)				
Superheat, °C (°F)	48 (87)	-	-	-
Heat Flux, W/m^2 (Btu/hr ft^2)	63,395 (20,096)	-	-	-

Table 2 Model Boiler and prototype crevice predictions for the same conditions as in Table 1 except crevice wall thickness of 5.1 mm (0.2 in.). The calculations now assume that *the crevice is filled with steam.*

	Model Boiler: Crevice Wall Thickness = 5.1 mm (0.2 in.)	Prototype: Crevice Wall Thickness = 5.1 mm (0.2 in.)
T_p = 327°C (620°F); T_s = 271°C (520°F)		
Superheat, °C (°F)	54 (98)	55 (99)
Heat Flux, W/m^2 (Btu/hr ft^2)	6,120 (1,940)	6088 (1,930)

and 25.4 mm [0.2, 0.5, and 1.0 in.]), the crevice-gap thermal resistance as a percent of the overall thermal resistance varies as 65%, 65%, and 65%, respectively. Hence, the crevice-gap thermal resistance dominates, and varying the crevice wall thickness beyond the prototype value of L = 5.1

mm (0.2 in.) exerts little influence on the conditions in the crevice gap. This fact was used in designing the crevice wall simulators for the boiler (see Sections 2.1.5 and 2.1.6), where the walls of the simulators are made thicker to facilitate instrumentation of the crevices. The preceding also shows that the state of the fluid in the crevice gap and the dimensions of the gap will have a strong influence on the gap superheat and heat flux.

Also presented in Table 1 are results for lowering the secondary temperature from 271 to 262°C (520 to 504°F) for the same primary temperatures of 327°C (620°F) to illustrate the influence of this parameter on the gap conditions. As seen, lowering the secondary temperature, which increases the driving temperature difference to 64°C (116°F) from 56°C (100°F), causes the wall superheat to increase to 48°C (87°F) and thus become nearly equal to that present in the prototype. The corresponding boiler heat flux increases to 63,395 W/m^2 (20,096 Btu/hr ft^2), which is slightly above the prototype value. This illustrates that the boiler parameters can be varied to produce quite good simulation of prototype crevice conditions.

3.4 Electric-Heated Crevice Experiments Versus Prototype Conditions

The results for the crevice gaps filled with liquid or steam indicate a significant difference in crevice heat flux and associated superheat temperatures for the two cases. The preceding results highlight that, to obtain prototypic data from a heated crevice experiment for chemical hideout, both the temperature at the tube outer wall and the heat flux at this location must be simultaneously matched with the values present in the prototype. This critical level of matching between the experimental model and the prototype cannot be achieved in an experimental apparatus that uses an electrical heater cartridge at the tube internal boundary.

To illustrate this point, 1-D model predictions were made of the behavior of an electric heated crevice for comparison with that of the prototype crevice for L = 5 mm (0.2 in.) and for the prototype crevice operating with T_p = 327°C (620°F) and T_s = 271°C (520°F). The results are presented in Table 3 for a liquid- and steam-filled crevice.

From Table 3, it is clear that prototype similitude cannot be achieved in an experimental apparatus that uses an electrical heater cartridge at the tube internal boundary. In an electrically heated tube experiment, a change in state of the fluid in the crevice gap causes a large change in the crevice thermal resistance. However, the electrical heater flux remains constant, and the tube outer wall temperature soars to non-prototypic values, prohibiting correct pairing of tube outer-wall temperature and gap heat flux that occurs prototypically. With the Model Boiler or the type of apparatus with forced flow inside the tube, the temperature of the tube outer wall can never exceed that of the fluid inside. The heat flux across the crevice gap simply decreases as the thermal resistance in the gap increases because of changing heat transfer and flow conditions, or from the accumulation of crevice debris. Increased heat transfer resistance in the crevice causes the tube outer wall temperature to rise and approach the primary-side fluid temperature.

Table 3. Inability of an electrically heated crevice experiment to achieve simultaneously prototype crevice temperature and heat flux

	Liquid-Filled Gap	Steam-Filled Gap
Electric Heated Crevice Behavior; T_s = 271°C (520°F)		
Superheat, °C (°F)	49 (88)	898 (1648)
Heat Flux, W/m^2 ($Btu/hr\ ft^2$)	57,985 (18,381)	57,985 (18,381)
Prototype Crevice Behavior; T_p = 327°C (620°F); T_s = 271°C (520°F)		
Superheat, °C (°F)	54 (88)	55 (99)
Heat Flux, W/m^2 ($Btu/hr\ ft^2$)	57,985 (18,381)	19,206 (6,088)

3.5 Summary

The following summarizes the results on Model Boiler crevice behavior obtained from the 1-D model. These results were used to establish that the Model Boiler could produce prototype crevice conditions and to establish detailed design features of the Model Boiler, including sizing of the crevices, length of the steam generator tube, and temperatures of the primary heater and the secondary heat-rejection condenser.

> The Model Boiler simulates very well the needed prototype crevice conditions over a wide range of crevice states, and even permits exploring hideout behavior at off-normal conditions.
>
> To obtain prototypic data from a heated-crevice chemical-hideout experiment, both the temperature at the tube outer wall and the heat flux at this location must be simultaneously matched with the values present in the prototype to achieve prototypic hideout limits and rates of impurity concentration.
>
> Crevice-gap thermal resistance dominates the overall thermal resistance associated with heat transfer from inside the tube to the boiling region on the outside of the crevice. Varying the boiler crevice wall thickness beyond the prototype value of L = 5 mm (0.2 in.) exerts little influence on the conditions in the crevice gap. This fact is used in designing the crevice wall simulators for the boiler, where the walls of the simulators are made thicker to facilitate instrumentation of the crevices.
>
> What happens to the fluid in the crevice gap and the dimensions of the gap have a strong influence on the gap superheat and heat flux. Going from a liquid-filled to a steam-filled

crevice gap causes almost a 90% reduction in gap heat flux and a corresponding 6°C (11°F) increase in crevice superheat.

Prototypical crevice thermal conditions (i.e., simultaneously matching both the tube outer wall temperature and heat flux at this location) are achieved in the Model Boiler for the two important reference states of all steam or all liquid in the crevice gap.

The heat transfer resistance associated with the state of the fluid in the crevice gap exerts a strong influence on the crevice temperature and heat flux, and both of these, in turn, strongly influence the hideout limit and the rate of impurity concentration.

Crevice conditions can be varied by adjusting the crevice geometry and/or the primary and secondary temperatures.

Prototypic similitude cannot be achieved in an experimental apparatus that uses an electrical heater cartridge at the tube internal boundary. In an electrically heated tube experiment, a change in state of the fluid in the crevice gap causes a large change in the crevice thermal resistance. However, the electrical heater flux remains constant, and the tube outer-wall temperature soars to non-prototypic values, thus not allowing correct pairing of tube outer wall temperature and gap heat flux that occurs prototypically. With the Model Boiler, the heat flux across the crevice gap simply decreases as the thermal resistance in the gap increases, for example, because of steam blanketing in the crevice or from the accumulation of crevice debris, with the tube outer wall temperature rising to approach the primary-side fluid temperature.

It is anticipated that if the thermodynamic limit is achieved in the Model Boiler crevices, prototypic crevice superheats will occur, with high levels of chemical hideout approaching concentration factors of 50,000 to 80,000 for NaOH.

In conclusion, analysis of the thermal behavior of the crevices in the Model Boiler Facility has established that it can simulate prototypic conditions of the tube/tube support plate crevice. The analysis has also shown that both the crevice superheat and the heat flux must be matched simultaneously to produce a prototypic experimental environment with respect to chemical hideout and conditions causing stress corrosion cracking. The Model Boiler performance data obtained from shakedown testing, described in Section 4, confirms the general correctness of the 1-D results and the ability of the Model Boiler to achieve prototypical heat transfer conditions.

4 Facility Shakedown Thermal Testing

Data on Model Boiler thermal duty were obtained during facility shakedown testing. These data enabled us to quantify primary-to-secondary chamber heat transfer through the SG tubes. The tests also allowed us to develop and confirm operating procedures and test protocols for the facility.

Six tests were conducted to explore the performance of the Model Boiler Facility. Experimental parameters for the six tests are presented in Table 4. These tests encompass a range of primary and secondary chamber temperatures and across-tube temperature differences relevant to the crevice experiments. Some tests are similar and served as a check on experimental reproducibility.

For these tests, the following test protocol, developed during shakedown testing, was used:

1. Both the primary and secondary chambers, which are each 0.61-m (24-in.) tall, starting first with the primary chamber, are charged cold with water to the correct fill levels, nominally 16 kg (35 lb) of water. This is done to make sure that the 40-kW heating elements and the steam generator tubes are covered with about 25 mm (1 in.) of water at cold startup. The filling also ensures that at elevated operating temperatures the water levels due to thermal expansion are nominally 75 or 100 mm (3 or 4 in.) above these elements, leaving 150-200 mm (6-8 in.) of steam space in the top of each chamber. If the water levels are too high at elevated temperature, the steam cannot rise as effectively from the primary chamber into the inside of the tubes or from the secondary chamber into the finned steam condenser pipe; that condition would prevent achieving design thermal duty.

2. After filling, each chamber is heated by turning on the 40-kW primary electrical immersion heater to about 149°C (300°F). Non-condensable gases are then purged first from the primary chamber then from the secondary chamber for a period of 15 min by opening a small steam vent on each chamber. These steps result in maximum steam condensation heat flux inside the steam generator tubes of the primary chamber and the finned steam condenser pipe of the secondary chamber, thereby achieving the intended design thermal duty. This purging operation need only be performed once, unless the boiler is opened for some reason or develops a leak to ambient. After initial purging, the chambers have remained free of non-condensable gases for more than six weeks of shakedown testing, indicating that a high level of leak tightness was achieved on the pressure vessel and fittings.

3. After step 2, Model Boiler heat-up to the desired primary and secondary temperatures can be started. To minimize differential thermal expansion and pressure vessel stressing, the Model Boiler is slowly heated in 28°C (50°F) increments every 30 min by means of the immersion heater. During the heat-up, the controllers of the electrically heated trace heater are increased in temperature in unison with the temperature increases of the heater to minimize thermal gradients through the thick walls and flanges of the pressure vessel. Because the thermal driver of the primary and secondary chambers is the 40-kW heater,

Table 4. Test parameters for six Model Boiler shakedown tests.

Test	T_p °C (°F)	T_s °C (°F)	T_p-T_s °C (°F)	Test Duration, h	Heater Power, %
1	301.5 (574.7)	242.1 (467.8)	59.4 (106.9)	7.658	65
2	314.8 (598.7)	242.1 (467.8)	72.7 (130.9)	31.96	81
3	313.9 (597.1)	239.4 (463.0)	74.5 (134.1)	30.04	79
4	312.6 (594.7)	245.6 (474.0)	67.0 (120.7)	31.09	81
5	311.9 (593.5)	254.5 (490.1)	57.4 (103.4)	32.88	63
6	280.8 (537.4)	223.8 (434.8)	57.0 (102.6)	30.14	64

the heating of the secondary chamber always lags behind the primary. Ultimately, at final steady state, the secondary would be 28-83°C (50-150°F) lower than the primary chamber. During the heat-up, the fan-cooled finned condenser pipe is not turned on until the secondary bulk water temperature reaches the desired value. Once the fans are turned on, the speed controller to the automatic feedback fan controls the rejection of heat from the finned steam condenser pipe in the secondary chamber to maintain the desired temperature.

4. The shakedown testing has shown that when the primary and secondary chambers are heated up and the overall system is thermally adjusted, the controllers on the primary heater, the fan-cooled finned steam condenser pipe, and the trace heaters are capable of maintaining all the desired temperatures stably within 1°C (2°F) of the desired set points.

Test 6 illustrates how the facility responds during heat-up from a cold state and achieves steady conditions for the desired primary (T_p) and secondary temperatures (T_s). The values of T_p and T_s (SC1, SS1, and ST1) for Test 6 are shown as a function of time in Fig. 33. During the first day, there was not enough time to reach steady state, as shown in Fig. 33 by the first peak at approximately 8 h, where T_p did not reach the desired 282°C (540°F). The test was continued the next day with the Model Boiler already at ≈93°C (200°F). The second peak in Fig. 6, at approximately 27 h, shows that both the primary (T_p) and secondary temperatures (SC1, SS1 and ST1) reached steady state, and the heater and fan controllers maintained this state for nearly 2 h, after which the test was stopped. During the 2-h steady-state operation, the heater power measured as a percent of full primary immersion heater power (40 kW) was 64%. Thus, the data acquisition system, immersion heater, trace heaters, and finned condenser/fan tower cooling system operated satisfactorily, and the primary and secondary chambers of the Model Boiler reached the desired pressures and temperatures. Similar behavior was exhibited in the other five tests.

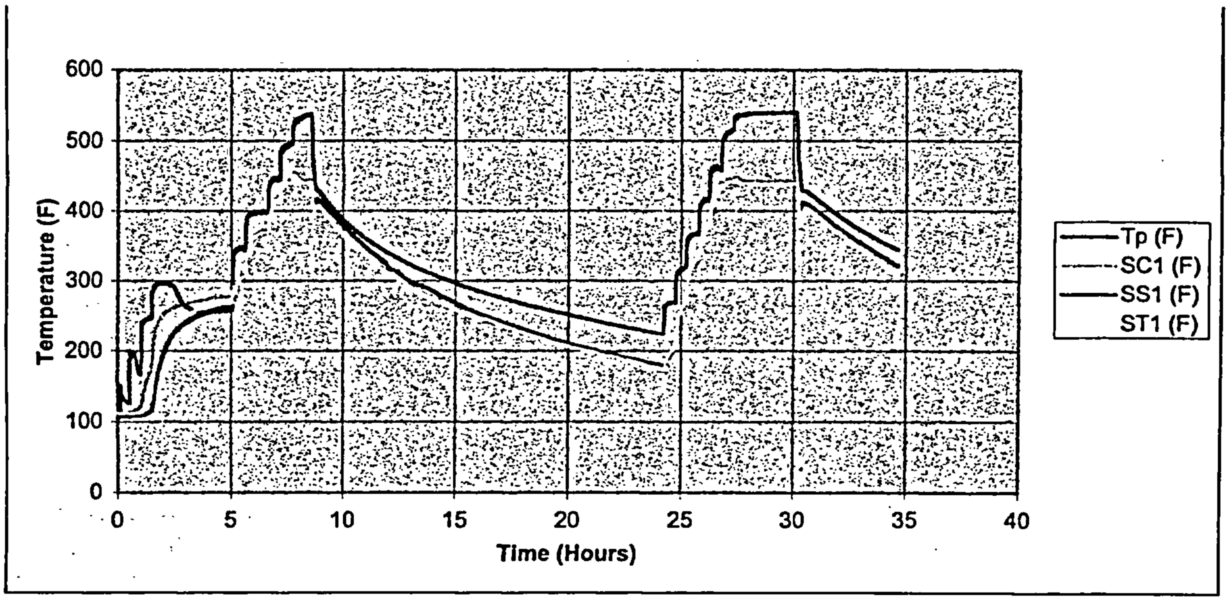


Figure 33. Bulk temperatures in primary and secondary chambers as a function of time for Model Boiler Shakedown Test 6.

In the following, the experimental data from the Model Boiler thermal duty (heater power at steady state) for the six tests of Table 4 are compared with predictions from the Argonne 1-D heat transfer model described in Section 3. This comparison is a check on the validity of the 1-D modeling used to design the facility and provides an assessment of whether prototypical heat transfer across the steam generator tubes is achieved in the Model Boiler.

In this comparison, only the average values of heat transfer coefficients associated with the nucleate boiling and condensation correlation models are used in the 1-D model. The literature on the boiling correlation, for example, states that the correlation coefficient can vary by ±20%. Additional parameter sensitivity studies will be performed on the 1-D model during the first phase of crevice hideout experiments to further assess the influence on predicted heat transfer across the tubes and crevices.

The 100% power reading from the immersion-heater controller power meter in the primary chamber corresponds to 40 kW, based on the manufacturer's nominal specifications. This power is experimentally determined once the primary and secondary chambers have reached equilibrium at the desired temperatures. These values are reported in Table 4 for the six tests. Additional studies using an independent traceable calibrated power meter will be made during the initial crevice tests to further validate the power meter because of the importance of accurately knowing thermal duty and its relationship to the crevice thermal conditions.

From the experimental thermal-duty (heater power) data in Table 4, the following trends are observed. Based on the fact that the primary-to-secondary temperature difference ($T_p - T_s$) is the driver for heat transfer across the six steam generator tubes, the data on measured thermal duty data should correlate with this parameter. Tests 1, 5, and 6, even though they have different primary and secondary temperatures, have nearly identical ($T_p - T_s$) values of nominally 58°C (104°F) and thermal duty values of 65, 63, and 64%. These nearly identical values of thermal duty correlate very well with the fact that the tests have almost identical driving temperature differences.

Tests 2, 3, and 4 have nearly the same primary and secondary temperatures and, hence, nearly identical ($T_p - T_s$) values of around 71°C (128°F), which is larger than for tests 1, 5, and 6. Tests 2, 3, and 4 should therefore have a higher thermal duty. In fact, the thermal duty values for these three tests are nearly identical at 80%, which is greater than the values for tests 1, 5, and 6.

The computed thermal duty (heater power) for each of the six tests in Table 4 is calculated from the 1-D heat transfer model for the experimental primary and secondary temperatures specified as input for no crevice simulators on the nominally 0.30-m (12-in.)-long SG tubes, as described in Section 3. The total predicted power is obtained by multiplying the result for one tube by six, which was the number of active tubes in the Model Boiler during shakedown testing. Predicted power data for the six shakedown tests are presented in column 3 of Table 5 for the 0.30-m (12-in.) tube length and the Prandtl number raised to the 1.7 power.

The % deviation in column 4 of Table 5 is the deviation of the computed power from the immersion heater (IH) power divided by the IH power. The deviation varies from 2.0 to 19.4% for these six tests, with the computed power or thermal duty being less than that measured. Note that the maximum error cases are associated with the highest temperature tests 2, 3, and 4 and possibly reflect larger heat losses to the ambient from the primary chamber (i.e., heat not passing through the tubes into the secondary chamber). This condition requires the 40-kW heater to produce more power to maintain the primary chamber at the desired temperature. For a first-cut assessment, the preceding constitutes reasonable agreement between experiment and the 1-D model.

To gain more insight on why the predicted thermal duties are less than the experimental values, the following additional potential factors were evaluated. The heat transfer correlation for nucleate pool boiling (described in Section 3) for use in the computer 1-D model of the Model Boiler was obtained from Ref. 2, in which Rohsenow was cited for the work. The correlation had the Prandtl number raised to the 1.7 power without any limitations on types of fluid. In Ref. 3, the same correlation has the Prandtl number raised to the first power for water and to the 1.7 power for all other fluids. Also, the correlation is stated to have a spread of nearly 20%. Power was computed for the six tests with the Prandtl number raised to the first power to assess the influence of this variable. The computed power with Prandtl number raised to the first power is, at most, 0.2 kW smaller than the computed power with Prandtl number raised to the 1.7 power. Thus, this effect is small.

Additionally, a one-dimensional heat conduction model was used to assess the heat transfer through the floor of the secondary chamber from the primary chamber, since the floor of the secondary chamber is the top of the primary chamber. The main heat input by the 40-kW heater is primarily transferred through the tubes to the secondary chamber, but, because of the temperature difference across the floor ($T_p - T_s$), some heat enters this chamber through the floor. The magnitude of the heat transferred through the floor of the secondary chamber was estimated to be nominally 0.55 kW for each of the six tests. As shown in the far right column of Table 5, the % deviation is smaller with this correction applied to obtain the actual heat transferred across the tubes.

Table 5. Comparison of 1-D model computed power with the measured primary (40-kW) immersion heater (IH) power for six SG tubes of 0.30-m (12-in.) length and the Prandtl number raised to the 1.7 power

Test No.	IH Power (kW)	Computed Power (kW)	% Deviation	% Deviation (corrected for floor heat transfer of 0.55 kW)
1	26.0	24.5	5.8	3.7
2	32.4	27.7	14.5	13.0
3	31.6	28.4	10.1	8.5
4	32.4	26.1	19.4	18.1
5	25.2	23.8	5.6	3.5
6	25.6	25.1	2.0	-0.2

5. Planned Initial Crevice Hideout Tests

The first crevice hideout tests in the Model Boiler are being conducted with two instrumented crevices having radial gaps of 0.38 and 0.50 mm (0.015 and 0.020 in.). The crevices are of concentric drilled-hole design and are closed at the bottom and nominally 25 mm (1 in.) deep.

The secondary chamber water consists of high-purity deionized water containing 20 ppm of NaOH bulk concentration. The bulk primary and secondary water temperatures will be prototypic and in the range of those explored during shakedown testing.

Each test will be run for several weeks, during which time all crevice instrumentation data from the thermocouples and electrochemical potential electrodes will be recorded, along with frequent crevice fluid samples being drawn by the micro-bore sampling tubes and analyzed. Over time, the preceding data, along with analogous measurement on the bulk secondary water, will reveal changes in crevice state caused by chemical hideout in the crevices. The crevices and the bulk water will be monitored to track the movement of trace chemicals from the bulk water to the crevices over time. Changes in the concentration of the trace chemicals in the bulk secondary water under conditions of an intentional cessation of the continuous water chemistry bleed/feed system or with batch changes will be correlated in time with changes in the temperature and chemistry data from the instrumented crevices.

Once a reproducible set of crevice data is obtained, various changes in parameters such as ($T_p - T_s$) and bulk water NaOH concentration will be explored to gain an understanding of their influence on hideout. Additionally, the hideout data from the two different gap crevices will be compared to assess the influence of this important parameter. All crevice data will be compared with predictions from the 1-D heat transfer model and the MULTEQ code to assess adequacy of these codes relative to simulating the thermal and chemical state of the crevices.

6 Summary

A multiple-tube Model Boiler Facility has been built for the NRC to simulate SCC under prototypic nuclear SG conditions for the crevice geometries in the tube/support plate or tube/tubesheet. The facility is being used to gain a better understanding of the interplay between the tube material, thermal hydraulics, crevice geometry, crevice chemistry, and bulk-water chemistry that have caused nuclear steam generators to experience tube cracking and leaking for more than 20 years. The facility produces prototypic crevice conditions by simultaneously matching both crevice heat flux and temperature. The Model Boiler Facility is a simplified design involving no circulating primary or secondary loops and is designed for unattended long-term operation. This report describes Model Boiler design, operation, and shakedown testing.

The Model Boiler pressure vessel is designed according to ASME B&PV Code Sec. VIII, Div. 1, for a 20.7 MPa (3000 psi) MAWP at 360°C (680°F) and has been hydrostatically code tested by a third-party at room temperature to 31.0 MPa (4500 psi). The Model Boiler pressure vessel consists of a lower primary reflux boiler chamber, where steam is generated, and a secondary upper chamber, where boiling occurs on the outside of multiple 0.30-m (12-in.)-long SG tubes capped on the top and open on the bottom to the steam generated in this chamber. The primary steam condenses on the inner wall of the tubes, creating a boundary condition of high heat flux. Each tube is fitted with an instrumented crevice simulator where chemical hideout occurs. The reflux boiler chamber is driven by a 40-kW electrical heater that is sized to achieve prototypical heat fluxes across the tubes. The primary side is maintained at desired saturation temperature and pressure by a controller set point on the 40-kW heater that operates on a primary bulk water thermocouple. The secondary side is maintained at the desired saturation temperature and pressure by controlling heat rejection to the ambient from a finned fan-cooled steam condenser pipe that uses closed-loop control between a secondary bulk water thermocouple and a variable frequency/speed drive fan controller. The condenser is a Schedule 160, Alloy 800 pipe [4.0-m (13-ft.) long, 38-mm (1.5-in.) dia.] with stainless steel fins brazed to the outside surface. It is divided into three equal subsections, each having its own motor/fan. The condenser maintains ±2°C (±3°F) control of the secondary-side temperature. Primary-side deionized water having a low level of noncondensables is used to maximize the effectiveness of the condensation film heat transfer occurring inside the tubes. The secondary water simulates secondary-side water chemistries of interest to PWRs. Conditioning and monitoring of secondary-water chemistry are achieved by a bleed/feed system.

Facility shakedown thermal testing has been successfully completed. Stable facility thermal operation with prototypic SG primary and secondary temperatures and pressures, yielding prototypic across-tube heat fluxes, has been demonstrated using multiple Alloy 600 steam generator tube assemblies [0.30-m (12-in.) long, 22.2-mm (7/8-in.)-diameter]. The facility secondary chamber has been fitted with steam generator tubes and instrumented crevice simulator ring test assemblies, and the first chemical hideout benchmarking tests involving NaOH trace contaminants (20 ppm) have been initiated.

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J. Davis, NRC Project Manager

11. ABSTRACT (200 words or less)

A model boiler has been developed to simulate prototypical thermal hydraulics and bulk chemistry conditions on the secondary side of steam generators in pressurized water reactors. The facility produces prototypic crevice conditions by simultaneously matching both crevice heat flux and temperature. The model boiler is a simplified design involving no circulating primary or secondary loops. It is designed for unattended long-term operation. This report describes the design, operation, and shakedown testing of the model boiler. Stable operation with primary and secondary temperatures/pressures reasonably prototypical of actual steam generators and yielding prototypic across-tube heat fluxes has been demonstrated using multiple Alloy 600 tube test assemblies [0.30-m (12-in.) long, 22.2-mm (7/8-in.) diameter]. The facility secondary chamber has been fitted with steam-generator tube/instrumented crevice simulator ring test assemblies, and the first chemical hideout benchmarking tests involving 20 ppm NaOH additions to the bulk secondary water have been initiated. The model boiler will be used to better determine the physical and chemical conditions in crevices in the secondary side of steam generators as a function of bulk water chemistry and the thermal hydraulic conditions expected at different locations in steam generators. The crevice chemistry and physical conditions established from the model boiler studies will be used in other laboratory test systems to establish stress corrosion cracking (SCC) initiation times and crack growth rates of Alloy 600 and 690 specimens. This crack initiation and growth rate data will be used to develop predictive models. Once the predictive models are developed, the model boiler could be used to experimentally validate the models.

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