Remote Measurement of Corrosion Using Ultrasonic Techniques

**Karen M. Garcia
Allen M. Porter**

Published February 1995

**Idaho National Engineering Laboratory
Lockheed Idaho Technologies Company
Idaho Falls, Idaho 83415**

**Prepared for the
U.S. Department of Energy
Assistant Secretary for Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223**

MASTER

DISCLAIMER

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

Remote Measurement of Corrosion Using Ultrasonic Techniques

INEL-94/0162

Prepared by

K. M. Garcia, Engineering Specialist
Mechanical Engineering

Date

Reviewed by

F. W. Bruneel, Engineering Specialist
Mechanical Engineering

Date

Approved by

J. M. Beller, Project Manager
Waste Technology Development

Date

ABSTRACT

A major technical constraint of the supercritical water oxidation (SCWO) process is corrosion. Safe operation of a pilot plant requires monitoring of corrosion with critical components of the system. A method is needed for measurement of the corrosion rate taking place during operation. One approach would be to directly measure the decrease in wall thickness at critical points in the SCWO process. A piping system was assembled that created the corrosive conditions of an SCWO system as the fluid approached the transition zone from a subcritical phase to a supercritical phase. During the test, hydrochloric acid was mixed into deionized water and oxygen and run through the system. A flanged test section was monitored using an ultrasonic measurement system. After 40 hours the resulting corrosion was measured using witness wires and compared to the measurements taken by the ultrasonic system. The result was that the ultrasonic system saw no change in the wall thickness while the pipe wall and witness wire showed that corrosion and deposition had occurred.

CONTENTS

ABSTRACT	iii
1. INTRODUCTION	1
2. OBJECTIVE	3
3. TEST SETUP	4
4. EQUIPMENT	9
5. TECHNICAL APPROACH	10
6. RESULTS	13
7. DISCUSSION	14
8. OBSERVATIONS	16
9. CONCLUSIONS AND RECOMMENDATIONS	17
Appendix A—EDF OWTD-3YH061-074-RD, Remote Measurement of Corrosion in SCWO	A-1
Appendix B—EDF ID121217/1008	B-1
Appendix C—Test Procedure	C-1

FIGURES

1. Test section of the bench-scale unit	5
2. Temperature profile of test system	6
3. Fluid temperature profile	6
4. Test setup	7
5. Welded rod and Macor rod on flanged test section	8
6. Waveforms from Macor buffer	12
7. Waveforms from Inconel buffer	12

TABLE

TABLE

1. Data collected during the test	13
---	----

Remote Measurement of Corrosion Using Ultrasonic Techniques

1. INTRODUCTION

Supercritical water oxidation (SCWO) technology has the potential of meeting the U.S. Department of Energy's treatment requirements for mixed radioactive waste. A major technical constraint of the SCWO process is corrosion. Safe operation of a pilot plant requires monitoring of the corrosion rate of the materials of construction. A method is needed for measurement of the corrosion rate taking place during operation.

One approach is to directly measure the change in wall thickness or growth of oxide layer at critical points in the SCWO process. In FY-93, a brief survey of the industry was performed to evaluate nondestructive evaluation (NDE) methods for remote corrosion monitoring in supercritical vessels. As a result of this survey, it was determined that ultrasonic testing (UT) methods would be the most cost-effective and suitable method of achieving this. Therefore, the objective for FY-94 was to prove the feasibility of using UT to monitor corrosion of supercritical vessels remotely during operation without removal of the insulation. See Engineering Design File (EDF) OWTD-3YH061-074-RD, "Remote Measurement of Corrosion in SCWO" (Appendix A).

Information was gathered on a couple of potential methods. These methods included electromagnetic acoustic transducers (EMATs) and transient electromagnetic probing (TEMP). EMATs produce ultrasound electromagnetically and can be adapted for high temperature applications. However, development of special probe for our application would have been required, and there is some question about the reliability above 500°F. TEMP, a technique developed by ARCO, was designed to examine piping through insulation. In FY-94, contact was made with James Mitchell of ARCO to discuss the possibility of performing some feasibility tests. This technology has promise for inspecting components through insulation, but was not pursued any further in FY-94 because ARCO was in the middle of establishing a licensing agreement for the technology and did not have the resources to explore our application.

High component temperatures and difficult access to the components are the primary limitations for traditional use of transducers. For conventional ultrasonic transducers, continuous exposure to elevated temperatures will cause complete degradation of the crystal and bonding materials. Mounting an ultrasonic transducer beneath the insulation and directly on the component is not an option. Therefore, the goal of the experiment was to mount the transducer on a buffer that transmitted the ultrasonic signal through the insulation to the pipe wall. The buffer protected the transducer from the heat from the pipe.

The initial idea for an ultrasonic buffer was to use a machinable ceramic such as Macor (trade name for a specific alumina-based ceramic material). To adapt to potential attachment methods, several other ceramic materials (e.g., aluminum nitride) were also considered. Properties of concern were the thermal expansion coefficient and machinability. The other consideration was material cost and availability. After reviewing several possibilities, it was determined that Macor would best meet our needs. It was also determined that an Inconel buffer

would also be an effective buffer if the rod was long enough to expose several inches of material to air (for cooling purposes). This was confirmed by performing calculations using the expected component temperature and thermal properties of the Inconel.

Following selection of the buffer material, the coupling and attachment methods were considered. Although mechanical coupling using gold foil had been used successfully in the past, an alternate attachment method would be desirable so that mechanical clamping devices could be eliminated. Adhesives, brazing, and weld methods were considered.

2. OBJECTIVE

The objective was to prove the feasibility of using ultrasonic measurement to remotely monitor corrosion of vessels at high temperatures and pressures during operation without removal of the insulation. The measurement was taken at a location on the pipe where the pipe wall temperature was approximately 600°C and the corrosive fluid was approximately 300°C. These conditions represented the greatest challenge for the monitoring system and created the worst corrosion environment. The buffer had to (a) withstand 600°C temperature, (b) provide thermal isolation from the pipe and, (c) provide a path for transmitting the ultrasonic signal without significant attenuation of the sound beam. The two reflected signals from the buffer-pipe interface and the inside diameter of the pipe had to be accurate enough to determine that a wall thickness change had occurred. A corrosion rate of 0.1 mil/hr to 1.0 mil/hr was expected. The objective of the test was to determine if the signal accuracy could determine over several hours if a 1-mil-thickness change had occurred.

3. TEST SETUP

The test section consisted of an approximate 1.5-in. inside diameter (ID) pipe with 1/2-in.-thick wall. It was pressurized to 3,500 psi and heated up to 650°C. A corrosive fluid (dilute HCl—5,000 ppm of Cl^- in deionized water and oxygen) was run through the heated test section to produce corrosion on the walls of the pipe. The fluid temperature was approximately 300 to 350°C. As the fluid flowed through the test sections, ultrasonic transducers remotely mounted at four points along the test section took wall-thickness measurements.

The measurements were taken at opposite sides of the pipe at two locations on the test section of the system. The first measurement location was at the point where the fluid temperature was approximately 250 to 300°C. The second location was at the point where the fluid temperature was approximately 300 to 350°C. See Figure 1. The test section was approximately 4 ft long, flanged for easy removal, and made of Hastelloy C-276. The two large diameter pipe sections were 2.375-in. outside diameter (OD) and each 1 ft long; the small diameter pipe was 1/2-in. SCH 160 and 1 ft long. It was on these larger diameter sections that the ultrasonic measurements were taken. The pipe was covered with 3-in.-thick ceramic fiber insulation.

Prior to setting up the test, a temperature profile of the fluid was approximated by a fluid flow heat transfer model. See EDF ID121217/1008 (see Appendix B). The model calculated the fluid and pipe wall temperatures from assumed heat load, insulation, and flow rate. Because the test system had no provisions for measuring fluid temperature at the test section, fluid temperature was estimated using the actual pipe wall temperatures and the computer model. The model was verified by later tests on the test system that measured actual fluid temperatures. Figure 2 shows the pipe wall temperature profile. Pipe 3 was the pipe wall temperature at the end of the heater section that heated the fluid. Macor 1 and Macor 2 are the ultrasonic measurement locations. Pipe 4 was the pipe wall temperature on the test section between the large diameter sections. In order to keep the test section's wall temperature up to 600°C, approximately 300 watts of heat using heat tape was applied to the pipe at the measurement locations. Figure 3 shows the computer model temperature profile. Figures 4 and 5 show photographs of the test system.

Figure 2. Temperature profile of test system.

Figure 3. Fluid temperature profile.

Figure 4. Test setup.

Figure 5. Welded rod and Macor rod on flanged test section.

4. EQUIPMENT

The equipment for the test included:

- Two Markenrich Waveform Acquisition and Arbitrary Generator (WAAG) boards
- Panametrics 5055PR Pulser/Receiver
- IBM AT computer
- Krautkramer-Branson 5-MHz, 0.25-in.-diameter, MSWS transducers
- 6-ft BNC-to-Microdot cables
- Sonotech Sono 600 high temperature ultrasonic couplant.

Thickness determination was based on the transit time of the ultrasonic wave through the vessel wall. This was accomplished by digitizing the ultrasonic waveform and measuring the time difference between the front or OD surface signal and the backsurface or ID surface signal. The ultrasonic waveform was digitized for all four channels, once each hour of operation using the Markenrich WAAG boards and IBM computer. The transit time between the ID and OD echoes was measured on the digitized image using two cursors in the Markenrich program.

Standard off-the-shelf transducers were used due to cost, availability, and the ability of mounting the transducers directly on the buffers. The 5-MHz transducers were of medium bandwidth and designed to be used on lucite wedges for angle beam applications.

5. TECHNICAL APPROACH

The operating temperature (650°C) and insulation preclude the use of conventional ultrasonic testing (UT) approaches to monitor corrosion. Standard ultrasonic transducers will not withstand continuous contact at elevated temperatures. The use of UT transducers designed for instantaneous contact at elevated temperatures requires removal of the insulation, or the use of a mechanical device to deploy the transducer to the surface long enough to take a measurement and retract the transducer away from the hot component surface. As an inexpensive alternative, acoustic buffers were used to extend through the insulation and to isolate the UT transducers from the heat source (Figure 5). To be an effective buffer for this application, the buffer rod material must (a) withstand the elevated temperatures, (b) provide thermal isolation from the hot component (i.e., exhibit low thermal conductivity), and (c) provide a good path for transmitting ultrasound without significant attenuation of the sound beam. The transit time between the reflected signal from the buffer-pipe wall (or artificial reference reflector) and the inside diameter of the pipe could then be used to determine the thickness and/or corrosion rate. In preparation for this task a number of buffer rod configurations and attachment methods needed to be considered.

Two materials were selected to be used as buffers for the ultrasonic transducers: Macor ceramic and Inconel 625. (Hastelloy C-276 was found to be unacceptable in preliminary tests.) Four buffers (two of each material) were mounted on the test section. For the Macor buffer, bonding with ceramic adhesives and special brazes were tested. High temperature couplants were also considered, but the upper limit for commercial couplants was determined to be 900°F (480°C), which was insufficient (couplant is needed to transmit the acoustic energy from the buffer to the component). Adhesives would have offered the simplest solution, therefore, were the first tested. Several types of adhesives were tested considering the thermal expansion coefficients of the components, Macor, and adhesive. The adhesives used were selected to minimize the difference in thermal expansion. For each adhesive, a 1/2-in.-diameter Macor dowel was bonded to an Inconel plate. Once cured, each bond was ultrasonically tested to ensure sufficient adhesion and acoustic coupling. The samples were then placed in the oven and heated to 600°C, held at temperature for approximately 30 minutes, and then allowed to cool slowly. In all cases, the bonds popped off upon cooling.

Brazes containing a small percentage of an active element (Ti or Vn) were tested in a similar manner. These specialized braze materials were developed especially to bond ceramics and metals. To prevent contamination, brazing of the Macor dowels to the Inconel plate was performed in an inert gas furnace. Like the ceramic adhesives, these samples also popped off upon cooling. Inspection of the failed bonds indicated possible contamination, which may have caused the failures. It was speculated that the inert gas furnace was not clean and retesting was considered but not carried out. Although it appeared that brazing with the special braze materials had some potential, due to practical considerations this was not pursued. The surrounding environment is critical for this process. Therefore, the brazing must be done in either an inert gas environment or preferably under a vacuum. To effectively attach the Macor, a vacuum or inert gas furnace large enough to hold the SCWO vessel was needed. Because this facility was not available, the brazing approach was not pursued further. Therefore, a mechanical clamping device was designed and built to hold the Macor buffer in place and compress gold foil between the buffer and component to provide an acoustic couple to the component.

For the Inconel buffer, three attachment methods were considered: welding, brazing, and soldering. Attempts to braze and solder the rod to an Inconel plate were determined to be unsuitable. The attachments were either weak structurally, ineffective for transmitting ultrasound, or could not be made because it was not possible to get enough heat into the Inconel. To weld the Inconel buffer to an Inconel plate, several welding methods were considered, including friction welding and stud welding. However, standard arc welding appeared to be adequate; therefore, was the only method tested. The test weld provided a clean and continuous path for transmitting ultrasound.

The primary problem with using long acoustic buffers is mode conversion off the side walls, which creates a series of trailing echoes. The spaces of these trailing echoes (Δt) is a function of the material velocity ($v_1 v_s$) and the rod diameter (d):

$$\Delta t = d(v_1^2 - v_s^2)^{1/2} / v_1 v_s .$$

These trailing echoes can interfere with signal interpretation; therefore, it is desirable to minimize these if possible. Because velocity cannot be changed and only small changes in diameter were possible, modifications in the rod shape were tested (e.g., cone shapes and hour-glass shapes). A number of Inconel rods were machined and tested. Several configurations appeared to help minimize the trailing echoes, but did not eliminate them. Therefore, it was decided to stay with a straight rod. Knurling was also considered in an attempt to damp out the trailing echoes, but this appeared to have little or no effect.

The other problem with using a welded Inconel rod was the lack of a reference reflector at the interface. Therefore, several types of reflectors near the interface were tested (including notches and side-drilled holes). Based on the initial testing, it was determined that a side-drilled hole, approximately one-third of the way through the rod, would provide an adequate reflector.

Thickness determination was based on the transit time of the ultrasonic wave through the vessel wall. The transit time between the ID and OD echoes was measured on the digitized image using two cursors in the Markenrich program. Typical waveforms are shown in Figures 6 and 7. In Figure 6, RF Signal 1 represents the front or outside surface of the Hastelloy pipe, and RF Signal 2 represents the reflection from the back or inside surface of the pipe. In Figure 7, RF Signal 1 is the reflected signal from the side-drilled hole in the Inconel rod, and RF Signal 3 represents the signal from the inside surface of the pipe. RF Signal 2 is the first of multiple trailing echoes caused by the side-drilled hole. In both cases, the time between the RF Signal 1 and the signal reflected from the inside surface was used as an indication of the vessel wall thickness.

Figure 6. Waveforms from Macor buffer.

Figure 7. Waveforms from Inconel buffer.

6. RESULTS

The following measurements were collected during the test (see Table 1).

Table 1. Data collected during the test.

Section	Position	Baseline (in.)	Final (in.)	Change (in.)	Averages (in.)
1	2 in.—90 degrees	0.46	0.459	—0.001	—
1	2 in.—180 degrees	0.473	0.468	—0.005	—
1	2 in.—270 degrees	0.468	0.469	+0.001	—
1	2 in.—360 degrees	0.46	0.45	—0.010	—
1	3.625 in.—90 degrees	0.463	0.460	—0.003	—
1	5.25 in.—90 degrees	0.465	0.462	—0.003	—
1	7.125—270 degrees	0.469	0.469	0	—
1	10—90 degrees	0.463	0.462	—0.001	—
1	10—180 degrees	0.470	0.463	—0.007	—
1	10—270 degrees	0.466	0.466	0	—
1	10—360 degrees	0.466	0.457	—0.009	—
2	2 in.—90 degrees	0.464	0.461	—0.003	—
2	2 in.—180 degrees	0.453	0.450	—0.003	—
2	2 in.—270 degrees	0.462	0.458	—0.004	—
2	2 in.—360 degrees	0.478	0.474	—0.004	—
2	5.125 in.—270 degrees	0.462	0.460	—0.002	—
2	7.25 in.—90 degrees	0.465	0.460	—0.005	—
2	8.625 in.—90 degrees	0.465	0.462	—0.003	—
2	10.75 in.—90 degrees	0.465	0.460	—0.005	—
2	10.75 in.—180 degrees	0.452	0.452	0	—
2	10.75 in.—270 degrees	0.460	0.454	—0.006	—
2	10.75 in.—360 degrees	0.477	0.469	—0.008	—
					—0.0037

7. DISCUSSION

There were two objectives to performing the ultrasonic measurements on the mock-up test. The first and foremost objective was to prove the feasibility of using the chosen UT approach to provide continuous monitoring of corrosion on the ID surface of the test vessel. The secondary objectives were to observe the effectiveness and accuracy of UT for measuring wall loss due to corrosion and to measure the thickness of the resulting oxide layer.

The barriers associated with performing ultrasonic thickness measurements for this application are the component temperature (up to 650°C) and interference from the insulation. To gain access to the component surface and isolate the UT transducers from the heat, Inconel and ceramic buffer rods were used as shown in Figure 5. Both of the chosen buffer materials have low thermal conductivity, so it was expected that several inches of buffer exposed to air would provide sufficient cooling and isolate the transducers from the heat source. The primary considerations when using long buffer rods are attenuation of the ultrasonic wave in the rod and interference from mode converted or trailing echoes. The acoustic properties were favorable for both the Inconel 625 rod and the Macor ceramic material; therefore, attenuation of the sound beam was not a problem. However, trailing echoes did present some problems in initial buffer rod designs. In the case of the Macor buffer rod, the diameter had to be increased such that the time difference (Δt) between trailing echoes was larger than the Δt between the ID/OD echoes of interest. Δt for the buffer rod is a function of the diameter (d) and longitudinal and shear wave velocities (v_l and v_s) of the buffer material (see equation on page 11). This is a physical constraint that cannot be overcome in some situations. For the Inconel channels the time measurements fluctuations (error) were typically ± 50 nanoseconds (0.010 in.). For the Macor it was ± 25 nanoseconds (0.005 in.). This was due to the acquisition system used and is not considered typical of a UT system.

Because standard ultrasonic couplants cannot withstand temperatures above 480°C, an alternative coupling method was tested. This method employed 0.002-in.-thick gold foil compressed between the Macor buffer and vessel surface using the clamp shown in Figure 5. Each of the four bolts was tightened to 12–16 ft-lb to compress and deform the foil and allow an ultrasonic couple to be formed. The wall thickness could then be measured directly from the velocity of the Hastelloy and the Δt between the vessel OD surface signal and ID surface signal.

Coupling the Inconel rod to the vessel was provided by a full penetration weld to the vessel. The result was continuous metal from the end of the rod to the ID surface of the vessel. This situation creates two problems: (1) a temperature gradient from the hot vessel end, which is at or near the vessel operating temperature, to the cooler free end, which is near room temperature, and (2) the elimination of the reference signal produced by the acoustic interface at the outside surface of the vessel. The presence of a temperature gradient is a problem because ultrasonic sound velocity varies with temperature. Thus, the velocity within the rod cannot be reliably predicted, and a measurement error can be expected. The elimination of the reference signal occurs because two materials of similar acoustic properties are joined by a third. In most cases, an acoustic buffer with different acoustic properties is coupled to the component surface such that an acoustic interface exists. This interface reflects a portion of the energy and results in a "front surface interface" signal, as shown in Figure 6 (RF Signal 1). This signal is typically used as a reference from which to measure. Without the reference signal, there is no direct means of

measuring the wall thickness. Therefore, to provide a reference reflector near the vessel surface and to eliminate the potential source of error caused by the temperature gradient, a side drilled hole (SDH) was added near the base of the rod. Unfortunately, the hole had to be placed above the weld (approximately 0.25 in. above the vessel surface) so a direct measure of the thickness was not possible (the Δt between the SDH and ID surface does not represent the vessel wall thickness, but the wall thickness plus 0.25 in. of weld and Inconel rod). However, corrosion can still be monitored by comparing the overall thickness measured initially to measurements made during operation. This difference (final minus original overall thickness) was used to provide an indirect measure of the thickness.

Standard off-the-shelf transducers were used due to cost, availability, and the ability of mounting the transducers directly on the buffers. The 5-MHz transducers were somewhat narrow banded and designed to be used on lucite wedges for angle beam applications. Because of this, the transducers were not perfectly matched for mounting on the Inconel buffer. The result was excessive ringdown^a of the ultrasonic signal and decreased resolution. To overcome this, the transducers would have to be customized (by the manufacturer) to match the buffer material. Although this would increase the cost of the transducers, it would improve measurement effectiveness. Likewise, frequency and bandwidth should be considered and optimized for material under test, and to meet the test objectives or requirements.

The Markenrich acquisition system provided a means of digitizing waveforms for later evaluation. All measurements were taken using the digitized waveforms. This system was used because of availability and the capability of collecting the entire RF signal. The disadvantage of capturing raw RF waveforms is that thickness measurements were based on UT transit time as measured directly from the digital oscilloscope display. This is somewhat subjective and can be inconsistent and unreliable for making accurate (± 0.001 in.) thickness measurements. Based on the velocity of sound in the material, 1-mil measurement accuracy equates to a shift in time of less than 5 nanoseconds, which is a small amount of time that cannot be resolved without the use of electronic processing, or by averaging over several multiple echoes. Because the latter is not possible for most practical applications, electronic processing, such as that used in digital ultrasonic thickness gauges, is recommended to provide quantitative results of the thickness. The secondary goal of the test was to measure the oxide layer, which requires that we measure more than just the wall thickness (i.e., the oxide layer). In that instance the use of digital thickness equipment would not have provided enough information.

a. Excessive ringdown occurs when transducer damping is insufficient or when the sensor is poorly matched to the material. This results in extra cycles of the RF signal that may interfere with signal interpretation and reduce resolution.

8. OBSERVATIONS

The following observations were made:

- The most significant corrosion occurred at the top and bottom of the large pipe section. This was determined by visual examination and by UT thickness gauging that was performed prior to and following 40 hours of operation. This demonstrates the importance of selecting the correct measurement locations.
- Measurement of UT transit time by eye is inconsistent and unreliable. Therefore, electronic circuitry designed specifically for making ultrasonic thickness measurements is recommended to optimize measurement accuracy.
- Working with long ultrasonic buffers can present problems and requires careful planning to ensure that Δt spacing between trailing echoes do not interfere with relevant signals (i.e., ID surface signal).
- The acoustic properties of Hastelloy are much worse than those of Inconel due to increased attenuation and grain noise. Hence, working with frequencies above 5 MHz is not recommended for Hastelloy. This illustrates the importance of transducer characteristics (frequency and bandwidth) to optimize for the material under test.
- The velocity change of longitudinal waves in Hastelloy was determined to be approximately $-0.43\%/100^\circ\text{F}$.^b This correlates closely with the change of velocity for Inconel, which is approximately $-0.5\%/100^\circ\text{F}$. It is also concluded that working at elevated temperatures (600°C) is not a problem if temperature is held relatively constant.

b. Engineering Design File ID-121217-1022.

9. CONCLUSIONS AND RECOMMENDATIONS

Based on the test performed in FY-94, it is concluded that:

1. Ultrasonic transducers can be used to monitor generalized corrosion without removal of the insulation.

Both types of buffer rods effectively isolated the standard transducers from the high temperature component for measurement taking. This is a low-cost approach that requires a minimum of special equipment to perform. The primary detriment is that transducer placement is critical and this approach will not detect localized corrosion at other locations. This approach can be used to monitor general corrosion and used to indicate when periodic shutdowns are warranted. At that point, other techniques could be employed (e.g., radiography, TEMP)^c to examine the vessel through the insulation, or the insulation could be removed to perform a thorough ultrasonic inspection.

2. The accuracy of the measurements taken on the test system is not clear for two reasons: (1) the wall loss at the measurement locations was in the range of 1 to 9 mils with an average of 3.7 mils,^d and (2) the test was not set up to determine the accuracy of the measurement (i.e., there was not means of physical verification).

Because the corrosion was not as severe as expected, the effects of corrosion on the measurements could not be determined and were not evident. Severe corrosion will increase the surface roughness and scatter the sound rather than reflect it back. This would result in reduced echo amplitude and increased potential for measurement error.

Although the test was not designed to determine the accuracy under "in-service" conditions, some supplementary testing performed on laboratory test blocks indicates that the accuracy of UT is approximately 0.001 in. under ideal conditions.^c For conditions other than ideal, accuracy is expected to deteriorate and would probably be closer to ± 0.005 in. This is supported by the test data, which indicated small fluctuations in the measurements on the order of 0.005 in.

3. The oxide layer was not resolvable with the test technique used. This is not a surprise, considering that by direct observation the oxide layer appeared to be several mils (< 0.010 in.) thick. This equates to roughly 50 nanoseconds, which cannot be resolved on the oscilloscope with the human eye. Although the oxide could not be resolved, it does add to the apparent thickness.

c. Engineering Design File ID-121217-1021.

d. Based on ultrasonic thickness measurements taken before and after 40 hours of operation and visual examination of the vessel.

Appendix A

EDF OWTD-3YH061-074-RD Remote Measurement of Corrosion in SCWO

Project File Number

OWTD-3YH061-074-
RD

EDF Serial Number

I0121717-1003

Functional File Number

ENGINEERING DESIGN FILE

Project/Task SCWO R&D ProjectSubtask Conceptual Design StudiesEDF Page 1 of TITLE: Remote Measurement of Corrosion in SCWO
SUMMARY See TDF Cover Sheet

This EDF reviews four proposed methods of corrosion measurement for the SCWO process. These methods are ultrasonic, radiographic, electromagnetic, and electrochemical. There is no commercial information available on any of these systems and techniques. Several vendors have been contacted so it is hoped that more information will become available. Three of the methods hold potential of being useful. These are ultrasonic, electromagnetic, and electrochemical. Within the electrochemical category both electrical resistance, and potential-pH methods hold promise. All of these methods need further work in the laboratory except for the electromagnetic method. Further discussions with ARCO are needed for use of their TEMP system.

Distribution (complete package): J.M Beller, T.R. Charlton, C.M. Barnes, R.W. Marshall, Jr., C. Shapiro, K.M. Garcia

Distribution (summary page only): Dave Crandall

Author Karen M. Garcia <i>Karen M. Garcia</i>	Dept. B420	Reviewed Carolyn Shapiro <i>Carolyn Shapiro</i>	Date	Approved John M. Beller <i>[Signature]</i>	Date <i>10/7/83</i>
---	---------------	---	------	--	------------------------

Purpose

A major technical constraint of the SCWO process is corrosion. Safe operation of a hazardous waste pilot plant (HWPP) requires monitoring on the corrosion resistance of the materials of construction. A method is needed for measurement of the corrosion rate taking place during operation. One approach would be to directly measure the decrease in wall thickness or growth of oxide layer at critical points in the SCWO process. An indirect method would be to measure the pH and polarization of the fluid. These methods are discussed below.

Background

The need for remote measurement techniques for monitoring the rate of corrosion and deposition of corrosion products within SCWO pressure vessels has been identified. Perhaps the oldest and still the most extensively used nonelectrochemical technique for corrosion monitoring is weight loss determination. Weight loss data does not provide real time information on the rate of corrosion and does not reveal when corrosion damage occurs in a complex cycle. Hence, potential non-destructive evaluation including electrochemical techniques were evaluated. Basic assumptions used during this evaluation are

- 1) reactor insulation cannot be removed,
- 2) the vessels are fabricated from Inconel or a similar material.
- 3) operating temperature (max) is 800°C,
- 4) operating pressure (max) is 4000 psig
- 5) maximum reactor dimensions will be 10 inches in diameter and 2.5 inch wall thickness,
- 6) acceptable techniques must be effective for a variety of pressure vessel configurations

The primary technical challenges for this task are

- a) component temperature,
- b) component thickness
- c) surrounding insulation
- d) component pressure
- e) corrosive nature of fluid

The detection method needs to measure a parameter that indicates the presence of corrosion activity. General corrosion causes the change in thickness of pipe walls and local corrosion will cause cracks. A measurement is useful when it indicates either the presence of corrosion by measuring corrosion rate or the effect of corrosion by measuring the change in the pipe wall. The accuracy of the measurement need only be enough to clearly distinguish it from baseline conditions. For example, if measurement of the wall can be done with an accuracy of .001" then the accuracy of the change in wall thickness will also be .001".

Discussion

1. Ultrasonic Methods¹:

Ultrasonic testing methods are commonly used for thickness measurements and corrosion monitoring in heavy walled vessels and piping. They are relatively inexpensive, commercially available, accurate, reliable, and readily adaptable to a variety of configurations. Ultrasonic soundwaves are most commonly generated by piezoelectric transducers. Piezoelectric devices

convert electric polarity that induces pressure on a crystalline material contained between two capacitive plates. Ultrasonic waves are received by the reverse process. The sound wave propagates through the material until it reaches an interface with different acoustic properties (such as the pipe surface). Upon striking the interface, the sound energy is reflected and scattered. Reflected energy that reaches the receiving transducer is displayed on a cathode ray tube (CRT) or as a digital thickness readout.

Component temperature and access are the primary limitations. For isotropic materials with low or moderate acoustic attenuation, ultrasound can penetrate many inches of material, so material thickness should not be a concern. For conventional ultrasonic transducers, continuous exposure to elevated temperatures will cause complete degradation of the crystal and bonding materials. Although there are some commercially available transducers that can operate up to 550°C with intermittent contact, continuous contact is not feasible. Most commonly used piezoelectric materials have a Curie temperature of 190 - 360°C. Above this temperature the crystals will depolarize. One ceramic material, lithium niobate, does have a Curie temperature of 1210° C. However, it also has an extremely narrow bandwidth, which is an undesirable characteristic for making thickness measurements and resolving the oxide layer on the inside diameter surface. Bonding materials and crystal backing materials are also temperature limited and cannot survive the expected temperatures. Mounting an ultrasonic transducer beneath the insulation, directly on the component is not an option.

If the transducer is mounted outside the insulation, with a glass or ceramic buffer (delay line) to extend through the insulation the buffer would act as both a wave guide (to direct ultrasonic energy to the component) and a thermal insulator (to isolate the transducer from the heat source). One material that has been successfully used for high temperature applications is a ceramic material known by the trade-name Macor. It is relatively easy to machine, and has good thermal and acoustic properties.

Ultrasonic coupling of the buffer to the component is also a problem at elevated temperatures. Most liquids will burn or dry out at high temperatures. One high-temperature coupling method utilizes a thin (~.004") gold foil compressed between the buffer and the test surface. Sufficient compressive force is required to deform the gold and fill the air gaps between the two surfaces. This is shown schematically in Figure 1. A threaded collar is welded to the component surface with a threaded cap to compress the foil between the surface and the buffer.

The expected costs (excluding engineering and design costs) are:

Transducer	\$ 350
Buffer	\$ 300
Gold Foil	\$ 250
Mounting Hdwre	\$ 200
Total	\$1100

The configuration of the data collection system will depend on the number of channels (sensors) needed, the data acquisition requirements, and the cost limitations. An economical approach would be a single channel ultrasonic instrument with a junction box to interface to individual sensors. Since continuous and simultaneous measurements are not required, a simple and inexpensive system could be provided by stepping through one channel at a time and recording the ultrasonic data (from the CRT) on a thermal printer. A multiple channel instrument is available that can operate 16 channels

FIGURE 1. Ultrasonic Measurement with Buffer Rod and High Temperature Coupling

continuously and simultaneously with a PC to digitize and store the data. The expected costs of these options are:

Thermal Printer:	\$3K
Single Channel Ultrasonic Instrument	\$10 - 15K
<hr/>	
Multi- Channel Ultrasonic Instrument	\$60 - 100K

The primary disadvantage of using ultrasonics is that only local measurements are taken. Sensor placement is critical and coverage becomes a function of the number of sensors installed. 16 or more separate sensors are possible depending on the desired complexity of the acquisition system. On a straight pipe reactor this would be a limitation. The sensors would have to be concentrated along 10 ft of the pipe in order to get meaningful data.

2. Radiographic Methods¹:

Studies have shown that radiographic methods could be used for qualitative assessment but costs would be excessive ($\approx \$1M$). The fundamental restriction for radiography techniques is the non-uniform penetration through heavy-walled, cylindrical vessels. The thin outermost sections will be severely underexposed in order to obtain sufficient radiography density in the thickest section tangent to the bore. Although radiography has been used effectively to monitor corrosion and erosion in thin-walled (<1 inch) components, it is less effective for heavy-walled components because of attenuation. All radiographic methods would be based on a projected image through the vessel. The quality of this image would be complicated by geometric factors, the insulation, and the lower density oxides on the ID surface.

3. Electromagnetic Methods¹:

ARCO has developed a technique capable of detecting wall thinning through insulation in heavy-walled piping. The technique, called Transient Electromagnetic Probing (TEMP), was evaluated by EPRI in report #TR-101680 and found to be an effective inspection method for detecting and quantifying generalized corrosion in piping up to 1.75 inches thick. Thicknesses greater than this are also possible by altering the probe configuration and test frequency. The technique measures the phase lag of the remote eddy current field and has been used successfully by ARCO to detect thinning in tanks and piping. A detailed review of the technology is not available due to ARCO being in the middle of licensing negotiations. It appears this approach has potential for monitoring wall thicknesses of SCWO vessels.

4. Electrochemical Techniques

Electrochemical analysis can also be used to measure corrosion. Chemical reactions involve charge transfer among the atomic constituents of the system. Damage occurs at a part of the system called the anode where metal atoms lose electrons as they move from the surface of the metal into an electrolytic solution in contact with the surface. This electron loss mechanism is oxidation. At the cathode charge transfer occurs in the opposite direction, positive ions in the electrolyte recombine with electrons from the metallic cathode to form neutral species. The process of electron capture by positive ions at the cathode is called reduction. The connection between electrochemistry and corrosion is based on Faraday's Law - one gram equivalent of a metal is deposited or dissolved (depending on the direction of the current) by the passage of 96,487 coulombs of charge.^{2 p749}

$$\text{Rate of corrosion} = \text{Constants} \times \text{Corrosion Current}$$

-----The corrosion current is related to the polarization resistance. The inverse of the polarization resistance is nearly proportional to the instantaneous corrosion rate.

$$\text{Corrosion current} = \text{Constants} / \text{Polarization resistance}$$

Measurement of the polarization resistance is the critical step in many electrochemical corrosion monitoring techniques.

Perhaps the most commonly used method for linear polarization measurements is the small amplitude cyclic voltametric (SACV) technique, in which a small

amplitude voltage signal is put across the interface and the resulting current is measured.^{2 p.752} If the electrodes are corroding at a high rate with metal ions passing easily into solution, a small potential applied between the electrodes produces a high current or low polarization resistance. Conversely, if the electrodes are corroding at a low rate with the ions passing only slowly into solution, a small potential applied between the electrodes produces only a low current or high polarization resistance. Existing commercial systems (Cortest and Cosasco) are limited to about 200° C and require a liquid medium. An alternative technique employs electrical resistance electrodes. The electrical resistance method is used when the process solution is a poor conductor such as gases and vapors. The electrical resistance probe has an external element exposed to the corrosive fluid, and a protected element sealed within the probe body. Measurement is made of the ratio of the exposed element's resistance to the protected element's resistance. Commercial systems are presently in use in environments as harsh as the SCWO process. Further information is being gathered on these systems.

Another approach to electrochemical measurement is to use pH measurements, hydrogen monitoring, and electrode potentials. A process may be defined as in equilibrium when the electrical potential stays the same. The system's equilibrium between reactants and products can be defined in terms of the potential of the system at a certain temperature and pH. The material and solution have an interface and an electrochemical potential exists between them. The rate at which the metal dissolves to produce ions depends on the electrochemical potential of the metal/solution interface. From an electrochemical point of view the main characteristic of general corrosion is the fact that metal dissolution takes place without physical separation, even at the microscopic level, of anodic and cathodic areas.^{2 p.768} Equilibrium exists when the sum of the electrochemical potentials of the reactants equals the sum of the electrochemical potentials of the products.^{2(p.697)}

The standard hydrogen electrode (SHE) is defined as having zero potential at all temperatures. The potential of all other electrodes are scaled against the SHE. The standard convention of measurement is the cell voltage which is defined as the potential of the right hand electrode minus the potential of the left hand electrode. The electrodes measure the electrochemical potential of a system's reactions. In deriving equilibrium relationships for redox reactions the equilibrium potential is calculated against the SHE using thermodynamic data. The potential is then expressed as a function of pH as

$$E = E^\circ_T + a \log a_R + b \log a_P + c(\text{pH})$$

where E°_T is the standard potential, a_R and a_P are the activities of the reactant and product. The coefficients are related to $2.303 RT/F$ by stoichiometric coefficients. Of the terms on the right side of the equation only the first must be calculated since a_R , a_P , and pH are regarded as independent variables. The standard potential is derived from Gibbs free energy equation. A plot of the potential vs pH for a fixed reactant (A) and product (B) yields a line that defines the conditions of equilibrium between A and B. The potential-pH diagrams are labeled by region with respect to corrosion activity. An example is Figure 2 below. Iron is well known to passivate in strong nitric acid, even though thermodynamics predicts that the stable species are dissolved ions (Fe^{2+} or Fe^{3+}) and that the metal should

EG&G Idaho, Inc.

FORM EGG-2631#

(Rev. 01-92)

corrode freely. The diagram is an extrapolation of the $\text{Fe}_3\text{O}_4/\text{Fe}$ equilibrium line into the Fe^{2+} stability field.^{2 p701} Extensive work has been done on thermodynamics of the nickel-water system at elevated temperatures. Nickel becomes increasingly active as the temperature is raised. See Figure 3 below.

- Region 1—Corrosion, no passivity possible.
- Region 2—Possible passivity by metastable Fe₃O₄.
- Region 3—Possible passivity by metastable Fe₃O₄ and/or Fe₂O₃.
- Region 4—Possible passivity by stable Fe₃O₄.
- Region 5—Possible passivity by stable Fe₂O₃ or metastable Fe₃O₄.
- Region 6—Immunity, no corrosion possible.

Figure 2:² Potential - pH Diagram for an Iron - Water System

Figure 3²: Potential - pH Diagram for Ni-H₂O System at 300°C

Various reference electrodes have been used to measure electrode potentials. There are two types: Internal electrodes in which the reference element is maintained at the system temperature and pressure, and external electrodes where the electroactive elements exist at ambient temperature, but is in electrolytic communication with the high temperature system through a nonisothermal electrolyte bridge. Because the internal reference electrodes operate isothermally, their potentials with respect to the SHE may be calculated if the necessary thermodynamic data are known. The long term stability of these electrodes in highly corrosive environments is unreliable. The advantage of the external electrodes is that the reference element is not subject to thermal degradation. An external pressure balanced reference

electrode (EBRE) has been developed, but a liquid junction is used to connect an inner chamber to the external environment, resulting in drift and causing the external electrodes to be limited in use for plant environment. Further work is being done by the Center for Advanced Materials at Pennsylvania State University to account for this problem.³

The accurate measurement of pH in high temperature aqueous systems is not yet developed for plant monitoring. A ceramic membrane pH electrode has been developed in the laboratory at Pennsylvania State University and is very reliable, but further work is needed. The yttria-stabilized zirconia membrane pH sensor is able to respond despite changes in the potential or the presence of metal corrosion products. This sensor is shown in Figure 4. This sensor will be fabricated from vespel graphite and lava in order to operate above 320°C. This development work is being done by Pennsylvania State University.

Figure 4³: Yttria-stabilized zirconia pH sensor

Recommendations and Conclusions

The ultrasonic, electromagnetic, and electrochemical methods are all possible measurement techniques for SCWO in a pilot plant environment. Further investigations are needed to develop operating data. The instrumentation needs to be tested for capability to handle the harsh environment. Of the three techniques the electrochemical methods appear to provide the greatest amount of information, while the ultrasonic method seems the most straightforward. The following tasks are recommended:

1. Set up test of ultrasonic technique with ceramic buffers.
2. Establish communication with ARCO to evaluate the use of TEMP.
3. Evaluate the performance of the potential and pH electrodes for use in a plant environment.

EG&G Idaho, Inc.

FORM EGG-2631#

(Rev. 01-92)

REFERENCES

1. Porter, Allen M., SCWO Corrosion and Deposition Monitoring, Draft Report, May 1993
2. MacDonald, Digby D., Chapter 9 Corrosion of Steam Cycle Materials, The ASME Handbook on Water Technology for Thermal Power Systems, Paul Cohen Editor, 1989
3. MacDonald, Digby D., Corrosion of Metals and Alloys in Supercritical Aqueous Systems, TTP, March 1993
4. EPRI Report # TR-101680, 1991

Appendix B

EDF ID121217/1008

EG&G Idaho, Inc
FORM EG&G-2631 (Rev. 12-88)

Project File Number WTD-121217-029

EDF Serial Number ID121217-1008

Functional File Number _____

Date December 10, 1993

ENGINEERING DESIGN FILE

Project/Task Remote Measurement of Corrosion
using Ultrasonic Transducers

Subtask Thermal Analysis

EDF Page 1 of 33

Subject: Thermal Analysis of a SCWO Preheater and Cool-Down Heat Exchanger (Supporting the Design of the Test Apparatus for the Remote Measurement of Corrosion using Ultrasonic Transducers)

Abstract:

Thermal analyses of a preheater and a cool-down heat exchanger were performed in support of the design of the test apparatus for the 'Remote Measurement of Corrosion using Ultrasonic Transducers'. A corrosive water mixture at 24.1 MPa (3500 psia) is to be brought to at least 400°C (751°F), and the pipe wall temperature up to 600°C (1111 °F) in order to produce a corrosive environment. The temperature is to be returned to about 60°C (139°F) at the piping exit. Other requirements were developed during the design process. For this short-duration test in limited lab space, the cost and size were the controlling parameters in the design of the two components. The water flow was 1.719×10^{-3} kg/s (3.79×10^{-3} lbm/s). To avoid plugging, the pipe size must be no smaller than 1 cm ID (3/8" Sch 80 pipe). The smallest pipe to which the transducer can be attached is 6 cm OD (2" Sch XX pipe). The SINDA Thermal Analyzer code was used to model the components, and perform parametric studies. The results were a preheater consisting of a 2.3 m (7.5 ft) length of (uniformly) electrically heated (4680 W) 3/8" Sch 80 pipe to bring the water to 400°C, followed by a 30 cm (1 ft) length of electrically heated (264 W) 2" Sch XX pipe to bring the wall to 600°C. The cool-down heat exchanger consisted of a 3.7 m (12 ft) straight length of 2" Sch XX pipe contained within a 3.5" Sch 5 outer pipe. Air at 0.12 kg/s (0.265 lbm/s) in the outer pipe flows in counterflow to the water. Heat transfer is enhanced by the use of cooling fins in the air passage over 2/3 of the length.

Distribution:	C. M. Barnes, MS 3625	R. J. Kochan, MS 3123
	J. M. Beller, MS 3710	K. H. Liebelt, MS 3625 (3)
	F. W. Bruneel, MS 3765	J. J. McCarthy, MS 3625
	K. M. Garcia, MS 3765	SCWO Project File, MS 3710

Author	Dept. B820	Reviewed	Date	Approved	Date
<i>Ken Liebelt</i>		<i>RJ Kochan</i>	<i>12/17/93</i>	<i>K. M. Garcia</i>	<i>12/20/93</i>
K. H. Liebelt		R. J. Kochan		K. M. Garcia	

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 2 of 33

Blank Page

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 3 of 33

Thermal Analysis of a SCWO Preheater and Cool-Down Heat Exchanger
(Supporting the Design of the Test Apparatus for the
Remote Measurement of Corrosion using Ultrasonic Transducers)

Introduction

This task has the purpose of verifying the feasibility of an externally mounted ultrasonic transducer to measure corrosion occurring in a supercritical water oxidation (SCWO) environment. The conditions for the test had been chosen to be similar to a certain previous proprietary test wherein the corrosion was measured. Specifically, the fluid to be used in the proposed test will be predominantly water in the supercritical state, with hydrochloric acid and oxygen added to simulate the corrosion environment of a waste stream. It is the intent to measure the progression of the corrosion under two temperature conditions, wall temperatures of 400°C (751°F) and 600°C (1111°F), each for a forty-hour period.

The thermal design was performed as a joint effort with the Principal Investigator, Karen Garcia, and the Mechanical Engineer, Frank Bruneel. The concerns of each were factored into the design based on review of the preliminary thermal results.

Requirements

For this test, a preheater is needed to bring the flowing mixture from room temperature to operating conditions. Then, after passing the transducer location, a cool-down heat exchanger is needed to bring the mixture back to about 60°C (139°F) at which point the gas is separated from the liquid, while still under pressure.

Because of the short duration of the test, the objective was to minimize the design and construction costs of the two devices, with operating cost of secondary importance. However, because of the limited laboratory space, the overall size (length) of the test apparatus is limited, so that both efficiency and heat exchanger effectiveness were also important. The thermal analysis was performed as part of an iterative design process to arrive at the best compromise. A Quality Level C analysis was requested since its primary purpose was to size the equipment.

It was agreed that using the material properties of pure water would be adequate for design purposes. Also, no account was

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 4 of 33

taken in these calculations for the possible presence of deposits on the walls of the pipes.

Testing would be done at a single flow rate of 1.719×10^{-3} kg/s (3.79×10^{-3} lbm/s, or 6.245 cu.in./min @ room temp) at 24.1 Mpa (3500 psia).

Modeling Approach

Rather than rely on hand-calculations, it was decided to invest effort into development of computer models of the components for the following reasons:

- a) Thermodynamic and transport properties are highly temperature dependent during the heating and cooling processes, when the water passes near its critical point (374.15°C, 22.12 MPa),
- b) Flow conditions could range from laminar to fully turbulent for the given conditions, resulting in the need to calculate a number of different heat transfer coefficients, and
- c) A significant number of iterative calculations were anticipated before a satisfactory design would be found.

The models did, in fact, prove useful for the tens of cases run before arriving at the final designs.

The analysis tool chosen for modeling was the SINDA thermal analyzer code from Network Analysis Associates, SINDA/1987/ANSI. The code is under EG&G Software Configuration Control at a high Quality Level (A or B), and is especially suited to parametric studies of this type. The SINDA steady-state finite difference solver 'SNHOSS' was used. Runs compiled and executed in about 5 seconds on the HP 9000/735 workstation 'einstein'.

Description of Preheater Model

Early discussions led to the decision to use simple electric resistance heating on a single straight pipe, if possible. Direct ohmic heating of the pipe was also considered, but not pursued.

The SINDA model, listed in Appendix A, is seen to be well annotated and somewhat self-explanatory. It will be described here in brief. The model was written in SI units. It subdivides

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 5 of 33

the heater into 100 sections of equal length in the flow direction. Each section consists of 4 nodes in the radial direction: water, pipe ID (water/pipe interface), pipe OD (pipe/insulation interface), and insulation OD (insulation/ambient air interface).

The nodes are connected by various conductors representing the major heat (and mass) transfer paths as follows:

- a) water flow (axial)
- b) axial conduction in pipe
- c) water forced convection at pipe ID (radial)
- d) radial conduction in pipe
- e) radial conduction in insulation
- f) air natural convection at insulation OD.

Input data include water mass flow and inlet temperature (25°C), air temperature (25°C), and total length. Diameters and heater power were input into arrays so that they could be varied along the length of the pipe. The heat source terms were applied directly to the pipe OD nodes. Thermodynamic properties (density, specific heat, enthalpy, and coefficient of expansion) of water vs. temperature were obtained from the RELAP5 'sth' water properties package which has been adapted for use with SINDA and used extensively in the past for other SINDA analyses.

Water transport properties (viscosity and thermal conductivity) vs. temperature were obtained from the 'G1' program, a PC-based program. Its formulations are based on the ASME Steam Tables, 4th edition. Values were input manually into SINDA data arrays.

The pipe was modeled as INCONEL 625 using thermal conductivity values from the ASME code, Section II, Part D. For thermal insulation, Thermal Ceramics brand KAOWOOL blanket at 6 lbm/cuft was assumed, using thermal conductivity values from the product information bulletin of 3/91.

It was found that using the smallest allowable pipe size, 3/8" Sch 80, in the main portion of the preheater increased the Reynolds number of the water, and hence the heat transfer coefficient, resulting in better performance than the 2" Sch XX pipe. Even so, the water is in laminar flow ($Re < 2100$) at the entrance, increasing to transition flow ($2100 < Re < 10,000$) as the water heats up and expands, never reaching fully turbulent

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 6 of 33

conditions. Thus both laminar flow and turbulent flow heat transfer correlations were calculated, and applied based on the local Reynolds number. After bringing the water to 400°C the pipe size is changed to the 2" Sch XX where the transducer is mounted. An additional heat source is needed there to bring the wall temperature to the required 600°C.

Because the flow rates were so low, a check was made for the presence of free convection heat transfer by comparing Reynolds number to a free convection parameter ($GrPrD/L$), as done in Figure 8-11 of Reference (1). Based on that figure, the system would operate slightly within the mixed convection region (part forced and part free convection); nevertheless, free convection correlations were not added to the model because of the expected small effect it would have on the results.

All pertinent information was printed to the output file to aid in the review of the model, and the results were stored in a data file for later plotting.

Description of Cool-Down Heat Exchanger Model

The SINDA model is listed in Appendix B. This model utilized most of the same coding as the preheater model. The heat sources and the insulation modeling were removed and replaced with an outer pipe through which traveled cooling air in counterflow to the water. Water was assumed to enter at 400°C at one end, and air at 1.013×10^5 Pa (14.7 psia) and 25°C at the other.

Temperature dependent air properties (heat capacity, viscosity, and thermal conductivity) were obtained from Ref (1). Density was calculated using the equation of state for a perfect gas.

The outer pipe (air jacket) was assumed to be perfectly insulated on the outside. The heat losses from the pipe which will exist in the real case lend conservatism to the results presented below.

Only fully turbulent air flow is allowed in the model. The run is stopped if a Reynolds number less than 10,000 is encountered on the air side. Thus, only the well-known Dittus-Boelter turbulent heat transfer correlation was needed. To establish the benefit of fins in reducing heat exchanger length it was assumed that fins were added to the exterior of the water pipe over the cooler 2/3 of the active length. An enhancement of two in the conductance ($h \cdot A$) was assumed to result from the use of the fins because their actual configuration had not yet been determined.

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 7 of 33

Air pressure drop was calculated along the annular flow path; however, the effect of the fins on pressure drop was not accounted for because (again) their design was unknown.

All other portions of the model were the same as in the preheater model discussed above.

Preheater Results

The results are summarized in Figure 1. The first objective of obtaining 400°C water (and wall) temperatures was met by applying 4680 Watts uniformly over 2.286 m (7.5 ft) of the 3/8" Sch 80 pipe. The large variations in the pipe wall temperatures apparent in Fig. 1 are due to (a) the flow changing from laminar to turbulent conditions as it is heated, and (b) large variations in water properties near the critical temperature. From 1.04 m (3.4 ft) to 1.37 m (4.5 ft) the heat transfer changes from fully laminar to predominately turbulent, and the wall temperature undergoes a sharp drop. It cannot be guaranteed what the actual flow conditions will be due to the simplicity of the present calculations. However, these results are judged to be conservative in terms of maximum wall temperature because of the following argument. Between Reynolds numbers of 2100 and 10,000 the laminar and turbulent coefficients are blended, the turbulent coefficient being the larger of the two over most of the range. Since the maximum calculated Reynolds number was 7285 (at the exit), the turbulent contribution never exceeded 73%. In actuality the flow would likely be fully turbulent at a Reynolds number less than 10,000.

A 0.15 m (1/2 ft) unheated length is assumed between heated zones, allowing for the possibility that no heating would be done in the transition between pipe sizes. Axial heat conduction in the pipe is an important factor in this region. An additional 264 Watts of heat is needed in the second zone to bring the wall temperature to 600°C.

The analysis was also done using the 2" Sch XX pipe in the heating zone, but it was found to result in higher wall temperatures because the flow was laminar over the entire length. Since it was desirable to keep both wall temperature and preheater length to a minimum, the larger pipe would be less desirable. A second advantage of the smaller pipe is that the same heat rate can be used along the entire length. Attempts to shorten the heated length by using a number of different heat rates along the length proved difficult to achieve; and, they rely strongly on the accuracy of the heat transfer correlations, which, in fact, are not accurately known and should not be relied

Figure 1 Preheater temperature and heat source profiles for a water flow rate of 1.719×10^{-3} kg/s and total heat source of 4944 watts.

upon to answer a safety question (maximum wall temperature).

Note that simple one-dimensional heat transfer is assumed throughout. Thus at the transition to the larger pipe the heat transfer rate, and thus the wall temperature, may not be accurately predicted.

Detailed results are available from the output file, but are not included in this report.

Cool-Down Heat Exchanger Results

For the heat exchanger it was found that the larger pipe (2") was more effective than the smaller (3/8"). (It was not desired to use other than these two pipe sizes to minimize material costs.) The results for the 2" and 3/8" pipe sizes are summarized in Figures 2 and 3, respectively. The better performance of the larger size was judged to be due to the fact that here the heat transfer was poor on both sides of the pipe, so that it was more important to increase the surface area to help the conductance on both surfaces than to use a small pipe to increase the Reynolds number on the inside of the pipe, at the expense of the surface area, as was done on the preheater. For the large-pipe case, the air jacket was sized to limit the air velocity, resulting in a value below 25 m/s (82 ft/s), which is, in general, good design practice. A similar approach was used for the small-pipe design.

As mentioned above for the preheater, the non-uniform variations in pipe temperature along the length are due to changes in the flow regime and water properties.

As seen in Figs. 2 and 3, the first 0.61 m (2 ft) of the model had no air cooling. This was added to the model only to illustrate the magnitude of the axial temperature drop that would exist in the pipe if there were to be an abrupt transition from no cooling to full cooling. The active heat exchanger length was 3.66 m (12 ft).

The air flow rate was 0.12 kg/s (0.265 lbm/s) and the pressure drop, about 800 Pa (0.1 psid). This results in a pumping power requirement of about 80 Watts (0.1 hp); but, this does not include any other pressure drops in the air ducting system. The air pressure at the inlet was assumed to be 1 atmosphere. The actual pressure in the system would depend on the total system design.

References

- 1) Frank Kreith, Principles of Heat Transfer, 3rd edition, Intext Press, Inc, 1973.

Figure 2 Large-pipe cool-down heat exchanger temperature profiles for a water flow rate of 1.719×10^{-3} kg/s and air flow rate of 0.12 kg/s.

Figure 3 Small-pipe cool-down heat exchanger temperature profiles for a water flow rate of 1.719×10^{-3} kg/s and air flow rate of 0.12 kg/s.

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 12 of 33

Blank Page

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 13 of 33

Appendix A

SINDA MODEL OF PREHEATER

FOR

REMOTE MEASUREMENT OF CORROSION USING ULTRASONIC TRANSDUCERS

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 14 of 33

SINDA MODEL OF PREHEATER
FOR
REMOTE MEASUREMENT OF CORROSION USING ULTRASONIC TRANSDUCERS

```
BCD 3THERMAL LPCS
C      123456123456123456123456123456123456123456123456
BCD 9Inlet pipe of Super Critical Water Oxidation (SCWO)
BCD 9Corrosion Test for Karen Garcia by Ken Liebelt 10/93
END
BCD 3NODE DATA
C
GEN 1001,100,1,273.0,1.      $100 fluid nodes
GEN 2001,100,1,273.0,1.      $100 wall ID nodes
GEN 3001,100,1,273.0,1.      $100 wall OD nodes
GEN 4001,100,1,273.0,1.      $100 insulation OD nodes
      -1000,      298.15,1.      $inlet water temp, 25 C (77 F)
      -4000,      298.15,1.      $ambient air temp, 25 C (77 F)
END
C
BCD 3CONDUCTOR DATA
C
C convection conductors, G=h*A
      GEN 1001,100,1,1001,1,2001,1,0.0
C flow conductors, G=mdot*Cp
      1,-1000,1001,0.0
      GEN 2,99,1,-1001,1,1002,1,0.0
C axial conduction in pipe, G=k*A/dx
      GEN 102,99,1,2001,1,2002,1,0.0
C wall radial conduction conductors, G=2*pi*k*L/ln(ro/ri)
      GEN 2001,100,1,2001,1,3001,1,0.0
C insulation radial conduction conductors, G=2*pi*k*L/ln(ro/ri)
      GEN 3001,100,1,3001,1,4001,1,0.0
C air natural convection conductors, G=h*A
      GEN 4001,100,1,4001,1,4000,0,0.0
END
C
BCD 3CONSTANTS DATA
C
      NDIM=90000
C CAUTION-Some input numbers are found in VARIABLES1
C
C Input dimensions in inches
      1 =1.503*.0254      $pipe inner diameter,meters
      2 =120.0*.0254      $total pipe length,meters
      3 =100      $number of nodes axially
C Flow: want velocity of 44.45 in/min @ room temp. in a 0.423 in. ID pipe
C      Area=0.1405 in**2 = 90.66e-6 m**2, Standard Temp.=298.15 K,
C      rho=62.91 lbm/ft**3 = 1007.7 kg/m**3, vel=0.01882 m/s
C      mdot=0.001719 kg/s
      4 =0.001719      $mass flow, kg/s
      PTEST =3.1416      $pi
      QTEST=0.0      $Heater power,Watts
C
END
C
BCD 3ARRAY DATA
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 15 of 33

```
C
C**** A1- pipe ID,meters
C**** A2- pipe OD,meters
C**** A3- insulation OD,meters
C      Schl60 ID=1.503in=0.038176m OD=2.375in=0.060325m ins=8.375in=0.212725m
C      Schl80 ID=0.423in=0.010744m OD=0.675in=0.017145m ins=6.675in=0.169545m
C      ID=0.302in=0.007671m
C      ID=0.215in=0.005461m
C      1, 0.010744,REPEAT,74
C          0.010744,REPEAT,4
C          0.038176,REPEAT,9
C          0.038176,REPEAT,9,END
C      2, 0.017145,REPEAT,74
C          0.017145,REPEAT,4
C          0.060325,REPEAT,9
C          0.060325,REPEAT,9,END
C      3, 0.169545,REPEAT,74
C          0.169545,REPEAT,4
C          0.212725,REPEAT,9
C          0.212725,REPEAT,9,END
C**** A4- Heater power,Watts per inch of length
C      4, 52.0,REPEAT,74
C          0.0,REPEAT,4
C          22.0,REPEAT,9
C          0.0,REPEAT,9,END
C**** A11- temp(K) vs water density,rho(kg/m3) @ 24.1 MPa(RELAP5)
C      11,SPACE,60,END
C**** A12- temp(K) vs water heat capacity,Cp(J/kg*K) @ 24.1 MPa(RELAP5)
C      12,SPACE,60,END
C**** A13- temp(K) vs water viscosity,mu(Pa*sec) @ 24.1 MPa(G1 program)
C      13, 273.4,1.727e-3,373.,2.891e-4, 473.,1.393e-4, 523.,1.113e-4
C          573.,9.144e-5, 593.,8.410e-5, 603.,8.033e-5, 613.,7.639e-5
C          623.,7.215e-5, 633.,6.732e-5, 643.,6.108e-5, 647.,5.765e-5
C          648.,5.531e-5, 649.,5.370e-5, 650.,5.039e-5, 651.,4.666e-5
C          653.,4.148e-5, 658.,3.336e-5, 663.,2.971e-5
C          668.,2.860e-5, 673.,2.820e-5, 678.,2.799e-5, 683.,2.790e-5
C          693.,2.793e-5, 703.,2.810e-5, 713.,2.835e-5
C          773.,3.044e-5, 823.,3.240e-5, 873.,3.438e-5, 973.,3.827e-5,END
C**** A14- temp(K) vs water conductivity,k(W/m*K) @ 24.1 MPa(G1 program)
C      14, 273.4,0.575, 373.,0.692, 473.,0.683, 523.,0.646
C          573.,0.579, 593.,0.543, 603.,0.522, 613.,0.501
C          623.,0.478, 633.,0.452, 643.,0.423, 647.,0.411
C          648.,0.413, 649.,0.421, 650.,0.452, 651.,0.457
C          653.,0.433, 658.,0.301, 663.,0.241
C          668.,0.210, 673.,0.168, 678.,0.145, 683.,0.137
C          693.,0.124, 703.,0.115, 713.,0.111
C          773.,0.099, 823.,0.099, 873.,0.103, 973.,0.114,END
C**** A15- temp(K) vs water Prandtl number @ 24.1 MPa
C      15,SPACE,60,END
C**** A18- temp(K) vs water enthalpy @ 24.1 MPa(RELAP5)
C      18,SPACE,60,END
C**** A19- temp(K) vs water beta @ 24.1 MPa(RELAP5)
C      19,SPACE,60,END
C**** A20- Reynolds number
C      20,SPACE,100,END
C      21,SPACE,30,END
C      22,SPACE,30,END
C**** A23- Nusselt number (Turbulent)
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 16 of 33

```

                23,SPACE,100,END
C**** A24- Grashof number
                24,SPACE,100,END
C**** A25- Free Convection (GrPrD/L) number
                25,SPACE,100,END
C**** A26- Nusselt number (Laminar)
                26,SPACE,100,END
C**** A54- temp(K) vs INCONEL 625 conductivity,k(W/m*K) (ASME,SecII,PartD)
                54, 294.,9.9,      422.,11.8,      589.,14.2,      756.,16.6
                922.,19.0,      1089.,22.,END
C**** A64- MEAN temp(K) vs KAOWOOL blanket(6 lb/cu ft) conductivity,k(W/m*K)
C              (Thermal Ceramics, 3/91 product information)
                64, 367.,0.043,      589.,0.079,      811.,0.130,      1033.,0.199
                1255.,0.274,END
C
C              END
C
C              BCD 3EXECUTION
C
C              SAVE
F              REAL*8 TBLS,S
F              LOGICAL ERR
F              COMMON/TABLES/ TBLS(20000),S(26)
C
C Calculate Pr Number and Look up properties
F              OPEN(UNIT=15,FILE='/disk3/users/einstein/khl/d.selp7c/envr1/sth2xt
F              *',STATUS='OLD',FORM='UNFORMATTED',ERR=5)
F              OPEN(UNIT=31,FILE='plotdata',STATUS='NEW',FORM='FORMATTED',ERR=6)
F              GO TO 10
F              5 WRITE(6,*) 'ERROR IN OPENING WATER PROPERTIES FILE'
F              GO TO 5005
F              6 WRITE(6,*) 'ERROR IN OPENING PLOT DATA FILE'
F              GO TO 5005
F              10 CONTINUE
C INPUT USER OPTION TO PRINT THE WATER PROPERTY TABLES (0,1)
F              IDUMP=0
F              NUSE = 20000
C INITIALIZATION CALL TO WAGNER'S RELAP5 PROPERTY ROUTINES
F              CALL STH2XI(TBLS,15,NUSE)
F              IF(IDUMP.EQ.1) CALL DUMPTB
M              j=IA13/2
CM             write(6,*) 'IA13,j=',IA13,j
M             if(IA11.ne.IA13) stop
M             if(IA12.ne.IA13) stop
M             if(IA14.ne.IA13) stop
M             if(IA15.ne.IA13) stop
M             if(IA18.ne.IA13) stop
M             if(IA19.ne.IA13) stop
C
M             do i=1,j
F             KTEST=2*i
M             A(11+KTEST-1)=A(13+KTEST-1)
M             A(12+KTEST-1)=A(13+KTEST-1)
M             A(15+KTEST-1)=A(13+KTEST-1)
M             A(18+KTEST-1)=A(13+KTEST-1)
M             A(19+KTEST-1)=A(13+KTEST-1)
C
C CALCULATE BETA AND ENTHALPY AT 3500 PSIA USING RELAP PROPERTY ROUTINES
```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 17 of 33

```

C  --GET SINGLE-PHASE WATER PROPERTIES VS T,P
M      S(1)=A(13+KTEST-1)      $Temperature(K)
M      S(2)=24.1E6              $Pressure(Pa)
F      CALL STH2X3(TBLS,S,IT,ERR)
F      IF(ERR) THEN
F          WRITE(6,*) 'GOT ERR IN STH2X3.  S=',S
F          WRITE(6,*) 'IT=',IT
F          GO TO 5005
F      ENDIF
M      A(11+KTEST)=1./S(3)      $density(kg/m3)
M      A(12+KTEST)=S(8)         $specific heat(J/kg-K)
M      A(18+KTEST)=S(5)         $enthalpy(J/kg)
M      A(19+KTEST)=S(6)         $beta(1/K)
C
C  Prandtl number
M      A(15+KTEST)=A(12+KTEST)*A(13+KTEST)/A(14+KTEST)
CM     write(6,*) 'KTEST,ARRAY(15+KTEST)=' ,KTEST,A(15+KTEST)
F      enddo
C
C  Integrate sp ht curve to get delta-h (273-973 K)
      SPLIT(10,A(12+1),A(21+1),A(22+1))
      TRPZDA(10,A(21+1),A(22+1),HTEST)
F      write(6,*) HTEST,'(should be 1681000.)'
      SPLIT(14,A(12+19),A(21+1),A(22+1))
      TRPZDA(14,A(21+1),A(22+1),HTEST)
F      write(6,*) HTEST,'(should be 1013000.)'
      SPLIT(08,A(12+45),A(21+1),A(22+1))
      TRPZDA(08,A(21+1),A(22+1),HTEST)
F      write(6,*) HTEST,'(should be 1050000.)'
      SPLIT(30,A(12+1),A(21+1),A(22+1))
      TRPZDA(30,A(21+1),A(22+1),HTEST)
F      write(6,*) '*****'
F      write(6,*) '!!Integral of Specific Heat Curve (A12)'
F      *      ' yields delta-h=',HTEST,' J/kg'
F      write(6,*) '!!Should be ~3.74E+6 J/kg'
F      write(6,*) '*****'
C  *** CONTROL VALUES
M      TMPZRO=0.                $Set value of absolute zero,K
M      NLINPP=50
F      ARLXCA=.0001
F      DRLXCA=.0001
F      DTMPCA=5.
F      NLOOP=4000
F      TIMEO=0.
      SNHOSS
F5005 CONTINUE
C
      END
C
      BCD 3VARIABLES 1
C
C  Heat sources
F      QTEST=0.0
M      do i=1,K3
M      Q(3001+i-1)=(A(4+i)/0.0254)*(XK2/K3)
M      QTEST=QTEST+Q(3001+i-1)
F      enddo
C

```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 18 of 33

```
F      rhosum=0.0
F      xmusum=0.0
F      xmussum=0.0
F      pransum=0.0
F      betasum=0.0
F      t1sum=0.0
F      t2sum=0.0
F      reysum=0.0
M      do i=1,K3
M      if(i.eq.1) then
          D1DEG1(T(1000),A11,rho)
          D1DEG1(T(1000),A12,spht)
          D1DEG1(T(1000),A13,xmu)
          D1DEG1(T(1000),A13,xmus)
          D1DEG1(T(1000),A14,cond)
          D1DEG1(T(1000),A15,pran)
          D1DEG1(T(1000),A19,beta)
M      t1sum=t1sum+T(1000)
M      t2sum=t2sum+T(1000)
F      else
          D1DEG1(T(1001+i-2),A11,rho)
          D1DEG1(T(1001+i-2),A12,spht)
          D1DEG1(T(1001+i-2),A13,xmu)
          D1DEG1(T(2001+i-2),A13,xmus)
          D1DEG1(T(1001+i-2),A14,cond)
          D1DEG1(T(1001+i-2),A15,pran)
          D1DEG1(T(1001+i-2),A19,beta)
M      t1sum=t1sum+T(1001+i-1)
M      t2sum=t2sum+T(2001+i-1)
F      endif
F      rhosum=rhosum+rho
F      xmusum=xmusum+xmu
F      xmussum=xmussum+xmus
F      pransum=pransum+pran
F      betasum=betasum+beta
F      rhobar=rhosum/i
F      xmubar=xmusum/i
F      xmusbar=xmussum/i
F      pranbar=pransum/i
F      betabar=betasum/i
F      t1bar=t1sum/i
F      t2bar=t2sum/i
C
C Flow conductors
M      G(1+i-1)=XK4*spht
C
C Reynolds number(D*mdot/xmu/A)
M      flowarea=PTEST*A(1+i)*A(1+i)/4.
M      A(20+i)=A(1+i)*XK4/xmu/flowarea
M      rey=A(20+i)
F      reysum=reysum+rey
F      reybar=reysum/i
C
C Grashof*Prandtl*D/L
M      A(24+i)=betabar*rhobar**2*(t2bar-t1bar)*A(1+i)**3
M      * /xmubar**2
M      A(25+i)=A(24+i)*pranbar*A(1+i)/(i*(XK2/K3))
C
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 19 of 33

```
C Heat transfer coefficients (Krieth, 3rd ed)
F   hturb=0.0
F   hlam=0.0
C Laminar (eq. 8-28)
M   if(rey.lt.10000.) then
M     A(26+i)=1.86*(reybar*pranbar*A(1+i)/(i*XK2/K3))**0.33
M     * (xmubar/xmusbar)**0.14
M     if(i.eq.1) then
M       xmulocal=A(26+i)
M     else
M       xmulocal=A(26+i)*i-A(26+i-1)*(i-1)
M       if(xmulocal.lt.4.36) xmulocal=4.36
M     endif
M     hlam=(cond/A(1+i))*xmulocal
F   endif
C Turbulent
M   if(rey.gt.2100.) then
M     A(23+i)=0.023*rey**0.8*pran**0.333
M     if(A(23+i).lt.4.36) A(23+i)=4.36
M     hturb=(cond/A(1+i))*A(23+i)
M   endif
C
F   if(rey.lt.2100.-) then
F     htc=hlam
F   elseif(rey.gt.10000.) then
F     htc=hturb
F   else
F     fraclam=(10000.-rey)/7900.
F     htc=hlam*fraclam + hturb*(1.-fraclam)
F   endif
M   htarea=PTEST*A(1+i)*XK2/K3
M   G(1001+i-1)=htc*htarea
C
C Axial conduction conductors
F   if(i.gt.1) then
M     area=PTEST*(A(2+i)**2-A(1+i)**2)/4.
M     D1MDG1(T(2001+i-2),T(2001+i-1),A54,cond)
M     dx=XK2/K3
M     G(102+i-2)=cond*area/dx
F   endif
C
C START RADIAL CONDUCTORS
M     D1MDG1(T(2001+i),T(3001+i),A54,cond)
M     G(2001+i-1)=2.*PTEST*cond*(XK2/K3)/alog(A(2+i)/A(1+i))
M     D1MDG1(T(3001+i),T(4001+i),A64,cond)
M     G(3001+i-1)=2.*PTEST*cond*(XK2/K3)/alog(A(3+i)/A(2+i))
C air natural convection(1e3<Gr<1e9, eq7-27, Kreith,3rd ed)
M   deltatf=(T(4001+i-1)-T(4000))*1.8
F   if(deltatf.lt.0.1) deltatf=0.1
M   diamft=A(3+i)/0.0254/12.
F   htcbtu=0.27*(deltatf/diamft)**0.25
F   htc=htcbtu*5.67
M   htarea=PTEST*A(3+i)*XK2/K3
M   G(4001+i-1)=htc*htarea
F   enddo
C
C   END
C
```


EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 20 of 33

```

      BCD 3VARIABLES 2
C
      END
C
      BCD 3OUTPUT CALLS
C
F      if(LOOPCT.gt.1) then
C          QIPRNT
C          TOPLIN
F      write(6,*) 'A11 = DENSITY(kg/m3) VS TEMP(K) '
          APRINT(11)
F      write(6,*) 'A12 = SPECIFIC HEAT(J/kg-K) VS TEMP(K) '
          APRINT(12)
F      write(6,*) 'A15 = PRANDTL NUMBER VS TEMP(K) '
          APRINT(15)
F      write(6,*) 'A18 = ENTHALPY(J/kg) VS TEMP(K) '
          APRINT(18)
          TOPLIN
F      write(6,*) 'A19 = BETA(1/K) VS TEMP(K) '
          APRINT(19)
F      write(6,*) 'A20 = REYNOLDS NUMBER'
          APRINT(20)
F      write(6,*) 'A23 = NUSSELT NUMBER (TURBULENT) '
          APRINT(23)
          TOPLIN
F      write(6,*) 'A24 = GRASHOF NUMBER'
          APRINT(24)
F      write(6,*) 'A25 = FREE CONVECTION (GrPrD/L) NUMBER'
          APRINT(25)
F      write(6,*) 'A26 = NUSSELT NUMBER (LAMINAR) '
          APRINT(26)
          TOPLIN
          GPRINT
          KPRINT
          TOPLIN
          TPRINT
F      write(6,*) '*****'
F      write(6,*) 'TOTAL APPLIED HEATER POWER =',QTEST,' Watts'
F      write(6,*) '*****'
C
C Create data files for xmgr plotting
M      do i=1,K3
M          dxft=XK2/K3/0.0254/12.
M          write(31,10) i*dxft,T(1001+i-1)-273.15,T(2001+i-1)-273.15
M          *,T(3001+i-1)-273.15,T(4001+i-1)-273.15
M          *,A(1+i),A(2+i),A(4+i)
M          *,A(20+i),A(23+i),A(24+i),A(25+i),A(26+i)
F      10 format(13E10.3)
F      enddo
C
F      endif
C
      END
C
      BCD 3SUBROUTINES
C
      SUBROUTINE FRIC(RE,F)
      SAVE

```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 21 of 33

```
      IF(RE.GT.1.E4)GO TO 10
      IF(RE.LT.1.82E3)GO TO 20
      F=8.8E-3
      GO TO 30
C
10 F=0.0024+0.358*(1./RE)**0.437
   GO TO 30
C
20 F=16./RE
30 CONTINUE
   RETURN
   END
C
   SUBROUTINE DUMPTB
   SAVE
   REAL*8 TBLS,S
   COMMON/TABLES/ TBLS(20000),S(26)
   WRITE(6,1) TBLS
1  FORMAT(2X,10(1PE12.4))
   RETURN
   END
C
   END
C
   BCD 3END OF DATA
```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 22 of 33

Blank Page

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 23 of 33

Appendix B

SINDA MODEL OF COOL-DOWN HEAT EXCHANGER

FOR

REMOTE MEASUREMENT OF CORROSION USING ULTRASONIC TRANSDUCERS

EDF No. ID121217/1008
 K. H. Liebelt
 December 10, 1993
 Page 24 of 33

SINDA MODEL OF COOL-DOWN HEAT EXCHANGER
 FOR
 REMOTE MEASUREMENT OF CORROSION USING ULTRASONIC TRANSDUCERS

BCD 3THERMAL LPCS
 C 123456123456123456123456123456123456123456123456
 BCD 9Outlet pipe of Super Critical Water Oxidation (SCWO)
 BCD 9Corrosion Test for Karen Garcia by Ken Liebelt 10/93
 END

C
 C SCHEMATIC OF NODE AND CONDUCTOR LAYOUT
 C
 C T4001 T4002 T4099 T4100 T4101
 C air *---<---* *---<---*---<---*
 C | G402 | | G500 | G501
 C | hA | hA | hA | hA G3100
 C | | | | |
 C pipe OD *---<---* *---<---* T3100
 C | | | | |
 C | G | G | G | G G2100
 C | | | | |
 C pipe ID *---<---* *---<---* T2100
 C | | | | |
 C | hA | hA | hA | hA G1100
 C | | | | |
 C | G1 | G2 | | G100 |
 C water *--->---* *--->---*
 C T1000 T1001 T1002 T1099 T1100
 C

BCD 3NODE DATA
 C
 GEN 1001,100,1,273.00,1. \$100 water nodes
 GEN 2001,100,1,273.00,1. \$100 wall ID nodes
 GEN 3001,100,1,273.00,1. \$100 wall OD nodes
 GEN 4001,100,1,273.00,1. \$100 air nodes
 -1000, 673.15,1. \$water inlet temp, 400 C (751 F)
 -4101, 298.15,1. \$air inlet temp, 25 C (77 F)
 END

BCD 3CONDUCTOR DATA
 C
 C water convection conductors, $G=h*A$
 GEN 1001,100,1,1001,1,2001,1,0.0
 C wall radial conduction conductors, $G=2*pi*k*L/ln(ro/ri)$
 GEN 2001,100,1,2001,1,3001,1,0.0
 C air convection conductors, $G=h*A$
 GEN 3001,100,1,3001,1,4001,1,0.0
 C water flow conductors, $G=mdot*Cp$
 GEN 1,100,1,-1000,1,1001,1,0.0
 C air flow conductors, $G=mdot*Cp$
 GEN 402,100,1,4001,1,-4002,1,0.0
 C axial conduction in pipe, $G=k*A/dx$
 GEN 102,99,1,2001,1,2002,1,0.0
 END

BCD 3CONSTANTS DATA

EDF No. ID121217/1008
 K. H. Liebelt
 December 10, 1993
 Page 25 of 33

```

C
      NDIM=90000
C CAUTION-Some input numbers are found in VARIABLES1
C
C Input dimensions in inches
      1 =1.503*.0254      $pipe inner diameter,meters
      2 =168.0*.0254      $total pipe length,meters
      3 =100              $number of nodes axially
C Flow: want velocity of 44.45 in/min @ room temp. in a 0.423 in. ID pipe
C      Area=0.1405 in**2 = 90.66e-6 m**2, Standard Temp.=298.15 K,
C      rho=62.91 lbm/ft**3 = 1007.7 kg/m**3, vel=0.01882 m/s
C      mdot=0.001719 kg/s
      4 =0.001719          $water mass flow, kg/s
      5 =0.120000          $air mass flow, kg/s
      6 =28.964            $air molecular weight, kg/kmol
      7 =1.0*1.013e5        $air inlet pressure, Pa
      PTEST =3.1416        $pi
      END
C
      BCD 3ARRAY DATA
C
C**** A1- pipe ID,meters
C**** A2- pipe OD,meters
C**** A3- air jacket ID,meters
C      ID=1.503in=.038176m OD=2.375in=.060325m j=3.834in=.097384m
C      ID=0.423in=.010744m OD=0.675in=.017145m j=1.185in=.030099m
C      ID=0.302in=.007671m
C      ID=0.215in=.005461m
      1, 0.038176,REPEAT,99,END
      2, 0.060325,REPEAT,99,END
      3, 0.097384,REPEAT,99,END
C**** A11- temp(K) vs water density,rho(kg/m3) @ 24.1 MPa(RELAP5)
      11,SPACE,60,END
C**** A12- temp(K) vs water heat capacity,Cp(J/kg*K) @ 24.1 MPa(RELAP5)
      12,SPACE,60,END
C**** A13- temp(K) vs water viscosity,mu(Pa*sec) @ 24.1 MPa(G1 program)
      13, 273.4,1.727e-3,373.,2.891e-4, 473.,1.393e-4, 523.,1.113e-4
      573.,9.144e-5, 593.,8.410e-5, 603.,8.033e-5, 613.,7.639e-5
      623.,7.215e-5, 633.,6.732e-5, 643.,6.108e-5, 647.,5.765e-5
      648.,5.531e-5, 649.,5.370e-5, 650.,5.039e-5, 651.,4.666e-5
      653.,4.148e-5, 658.,3.336e-5, 663.,2.971e-5
      668.,2.860e-5, 673.,2.820e-5, 678.,2.799e-5, 683.,2.790e-5
      693.,2.793e-5, 703.,2.810e-5, 713.,2.835e-5
      773.,3.044e-5, 823.,3.240e-5, 873.,3.438e-5, 973.,3.827e-5,END
C**** A14- temp(K) vs water conductivity,k(W/m*K) @ 24.1 MPa(G1 program)
      14, 273.4,0.575, 373.,0.692, 473.,0.683, 523.,0.646
      573.,0.579, 593.,0.543, 603.,0.522, 613.,0.501
      623.,0.478, 633.,0.452, 643.,0.423, 647.,0.411
      648.,0.413, 649.,0.421, 650.,0.452, 651.,0.457
      653.,0.433, 658.,0.301, 663.,0.241
      668.,0.210, 673.,0.168, 678.,0.145, 683.,0.137
      693.,0.124, 703.,0.115, 713.,0.111
      773.,0.099, 823.,0.099, 873.,0.103, 973.,0.114,END
C**** A15- temp(K) vs water Prandtl number @ 24.1 MPa
      15, SPACE,60,END
C**** A18- temp(K) vs water enthalpy @ 24.1 MPa(RELAP5)
      18, SPACE,60,END
C**** A19- temp(K) vs water beta @ 24.1 MPa(RELAP5)

```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 26 of 33

```

      19, SPACE,60,END
C**** A20- water Reynolds number
      20,SPACE,100,END
      21,SPACE,30,END
      22,SPACE,30,END
C**** A23- water Nusselt number (Turbulent,local)
      23,SPACE,100,END
C**** A24- water Grashof number (mean)
      24,SPACE,100,END
C**** A25- water Free Convection (GrPrD/L) number (mean)
      25,SPACE,100,END
C**** A26- water Nusselt number (Laminar,mean)
      26,SPACE,100,END
C**** A32- temp(K) vs air heat capacity,Cp(J/kg*K) (Kreith)
      32, 273.,1005., 311.,1005., 367.,1009., 422.,1017.
          478.,1026., 533.,1034., 589.,1047., 644.,1059.
          700.,1072., 756.,1084., 811.,1097., 1089.,1156.
      END
C**** A33- temp(K) vs air viscosity,mu(Pa*sec) (Kreith)
      33, 273.,17.3e-6, 311.,19.1e-6, 367.,21.4e-6, 422.,24.0e-6
          478.,26.0e-6, 533.,28.1e-6, 589.,29.8e-6, 644.,31.8e-6
          700.,33.5e-6, 756.,35.1e-6, 811.,36.8e-6, 1089.,44.6e-6
      END
C**** A34- temp(K) vs air conductivity,k(W/m*K) (Kreith)
      34, 273.,.0242, 311.,.0267, 367.,.0301, 422.,.0334
          478.,.0367, 533.,.0400, 589.,.0433, 644.,.0464
          700.,.0495, 756.,.0524, 811.,.0552, 1089.,.0692
      END
C**** A35- temp(K) vs air Prandtl number
      35, SPACE,24,END
C**** A40- air Reynolds number
      40,SPACE,100,END
C**** A41- air pressure (Pa)
      41,SPACE,100,END
C**** A42- air velocity (m/s)
      42,SPACE,100,END
C**** A43- air Nusselt number (Turbulent,local)
      43,SPACE,100,END
C**** A54- temp(K) vs INCONEL 625 conductivity,k(W/m*K) (ASME,SecII,PartD)
      54, 294.,9.9, 422.,11.8, 589.,14.2, 756.,16.6
          922.,19.0, 1089.,22.,END
C
      END
C
      BCD 3EXECUTION
C
      SAVE
      F REAL*8 TBLS,S
      F LOGICAL ERR
      F COMMON/TABLES/ TBLS(20000),S(26)
C
C Calculate Pr Number and Look up properties
      F OPEN(UNIT=15,FILE='/disk3/users/einstein/khl/d.selp7c/envr1/sth2xt
      F *',STATUS='OLD',FORM='UNFORMATTED',ERR=5)
      F OPEN(UNIT=31,FILE='plotdata',STATUS='NEW',FORM='FORMATTED',ERR=6)
      F GO TO 10
      F 5 WRITE(6,*) 'ERROR IN OPENING WATER PROPERTIES FILE'
      F GO TO 5005

```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 27 of 33

```
F 6 WRITE(6,*) 'ERROR IN OPENING PLOT DATA FILE'
F GO TO 5005
F 10 CONTINUE
C INPUT USER OPTION TO PRINT THE WATER PROPERTY TABLES (0,1)
F IDUMP=0
F NUSE = 20000
C INITIALIZATION CALL TO WAGNER'S RELAP5 PROPERTY ROUTINES
F CALL STH2XI(TBLS,15,NUSE)
F IF(IDUMP.EQ.1) CALL DUMPTB
M j=IA13/2
CM write(6,*) 'IA13,j=',IA13,j
M if(IA11.ne.IA13) stop
M if(IA12.ne.IA13) stop
M if(IA14.ne.IA13) stop
M if(IA15.ne.IA13) stop
M if(IA18.ne.IA13) stop
M if(IA19.ne.IA13) stop
C
M do i=1,j
F KTEST=2*i
M A(11+KTEST-1)=A(13+KTEST-1)
M A(12+KTEST-1)=A(13+KTEST-1)
M A(15+KTEST-1)=A(13+KTEST-1)
M A(18+KTEST-1)=A(13+KTEST-1)
M A(19+KTEST-1)=A(13+KTEST-1)
C
C CALCULATE BETA AND ENTHALPY AT 3500 PSIA USING RELAP PROPERTY ROUTINES
C --GET SINGLE-PHASE WATER PROPERTIES VS T,P
M S(1)=A(13+KTEST-1) $Temperature(K)
M S(2)=24.1E6 $Pressure(Pa)
F CALL STH2X3(TBLS,S,IT,ERR)
F IF(ERR) THEN
F WRITE(6,*) 'GOT ERR IN STH2X3. S=',S
F WRITE(6,*) 'IT=',IT
F GO TO 5005
F ENDIF
M A(11+KTEST)=1./S(3) $density(kg/m3)
M A(12+KTEST)=S(8) $specific heat(J/kg-K)
M A(18+KTEST)=S(5) $enthalpy(J/kg)
M A(19+KTEST)=S(6) $beta(1/K)
C
C Prandtl number
M A(15+KTEST)=A(12+KTEST)*A(13+KTEST)/A(14+KTEST)
CM write(6,*) 'KTEST,ARRAY(15+KTEST)=',KTEST,A(15+KTEST)
F enddo
C
C Integrate sp ht curve to get delta-h (273-973 K)
SPLIT(10,A(12+1),A(21+1),A(22+1))
TRPZDA(10,A(21+1),A(22+1),HTEST)
F write(6,*) HTEST,'(should be 1681000.)'
SPLIT(14,A(12+19),A(21+1),A(22+1))
TRPZDA(14,A(21+1),A(22+1),HTEST)
F write(6,*) HTEST,'(should be 1013000.)'
SPLIT(08,A(12+45),A(21+1),A(22+1))
TRPZDA(08,A(21+1),A(22+1),HTEST)
F write(6,*) HTEST,'(should be 1050000.)'
SPLIT(30,A(12+1),A(21+1),A(22+1))
TRPZDA(30,A(21+1),A(22+1),HTEST)
```


EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 28 of 33

```
F      write(6,*) '*****'
F      write(6,*) '!!Integral of Specific Heat Curve (A12)'
F      *      ' yields delta-h=',HTEST,' J/kg'
F      write(6,*) '!!Should be ~3.74E+6 J/kg'
F      write(6,*) '*****'
C air pressure
      STFSQS(XK7,100,A(41+1))
M      j=IA32/2
M      if(IA33.ne.IA32) stop
M      if(IA34.ne.IA32) stop
M      if(IA35.ne.IA32) stop
F      do i=1,j
F      KTEST=2*i
M      A(35+KTEST-1)=A(32+KTEST-1)
C air Prandtl number
M      A(35+KTEST)=A(32+KTEST)*A(33+KTEST)/A(34+KTEST)
F      enddo
C *** CONTROL VALUES
M      TMPZRO=0.          $Set value of absolute zero,K
M      NLINPP=50
F      ARLXCA=.0001
F      DRLXCA=.0001
F      DTMPCA=5.
F      NLOOP=4000
F      TIMEO=0.
      SNHOSS
F5005 CONTINUE
C
      END
C
      BCD 3VARIABLES 1
C
C START WATER-SIDE CALCULATIONS
F      rhosum=0.0
F      xmusum=0.0
F      xmussum=0.0
F      pransum=0.0
F      betasum=0.0
F      t1sum=0.0
F      t2sum=0.0
F      reysum=0.0
M      do i=1,K3
M      if(i.eq.1) then
          D1DEG1(T(1000),A11,rho)
          D1DEG1(T(1000),A12,spht)
          D1DEG1(T(1000),A13,xmu)
          D1DEG1(T(1000),A13,xmus)
          D1DEG1(T(1000),A14,cond)
          D1DEG1(T(1000),A15,pran)
          D1DEG1(T(1000),A19,beta)
M      t1sum=t1sum+T(1000)
M      t2sum=t2sum+T(1000)
F      else
          D1DEG1(T(1001+i-2),A11,rho)
          D1DEG1(T(1001+i-2),A12,spht)
          D1DEG1(T(1001+i-2),A13,xmu)
          D1DEG1(T(1001+i-2),A13,xmus)
          D1DEG1(T(1001+i-2),A14,cond)
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 29 of 33

```

      D1DEG1(T(1001+i-2),A15,pran)
      D1DEG1(T(1001+i-2),A19,beta)
M      t1sum=t1sum+T(1001+i-1)
M      t2sum=t2sum+T(2001+i-1)
F      endif
F      rhosum=rhosum+rho
F      xmusum=xmusum+xmu
F      xmusum=xmusum+xmus
F      pransum=pransum+pran
F      betasum=betasum+beta
F      rhobar=rhosum/i
F      xmubar=xmusum/i
F      xmusbar=xmusum/i
F      pranbar=pransum/i
F      betabar=betasum/i
F      t1bar=t1sum/i
F      t2bar=t2sum/i
C
C Flow conductors
M      G(1+i-1)=XK4*spht
C
C Reynolds number(D*mdot/xmu/A)
M      flowarea=PTEST*A(1+i)*A(1+i)/4.
M      A(20+i)=A(1+i)*XK4/xmu/flowarea
M      rey=A(20+i)
F      reysum=reysum+rey
F      reybar=reysum/i
C
C Grashof*Prandtl*D/L
M      A(24+i)=betabar*rhobar**2*(t2bar-t1bar)*A(1+i)**3
M      *
M      /xmubar**2
M      A(25+i)=A(24+i)*pranbar*A(1+i)/(i*(XK2/K3))
C
C Heat transfer coefficients (Krieth, 3rd ed)
F      hturb=0.0
F      hlam=0.0
C Laminar (eq. 8-28)
M      if(rey.lt.10000.) then
M      A(26+i)=1.86*(reybar*pranbar*A(1+i)/(i*XK2/K3))**0.33
M      *
M      *(xmubar/xmusbar)**0.14
M      if(i.eq.1) then
M      xnulocal=A(26+i)
M      else
M      xnulocal=A(26+i)*i-A(26+i-1)*(i-1)
M      if(xnulocal.lt.4.36) xnulocal=4.36
F      endif
M      hlam=(cond/A(1+i))*xnulocal
F      endif
C Turbulent
M      if(rey.gt.2100.) then
M      A(23+i)=0.023*rey**0.8*pran**0.333
M      if(A(23+i).lt.4.36) A(23+i)=4.36
M      hturb=(cond/A(1+i))*A(23+i)
M      endif
C
F      if(rey.lt.2100.) then
F      htc=hlam
F      elseif(rey.gt.10000.) then
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 30 of 33

```
F      htc=hturb
F      else
F      fraclam=(10000.-rey)/7900.
F      htc=hlam*fraclam + hturb*(1.-fraclam)
F      endif
M      htarea=PTEST*A(1+i)*XK2/K3
M      G(1001+i-1)=htc*htarea
C
F      enddo
C
C START AIR-SIDE CALCULATIONS
M      do i=1,K3
M      rho=A(41+i)*XK6/8314.3/T(4001+i)      $rho=P/RT
          D1DEG1(T(4001+i),A32,spht)
          D1DEG1(T(4001+i),A33,xmu)
          D1DEG1(T(4001+i),A34,cond)
          D1DEG1(T(4001+i),A35,pran)
C
C Flow conductors
M      G(402+i-1)=XK5*spht
C
C Reynolds number(D*mdot/xmu/A)
M      flowarea=PTEST*(A(3+i)**2-A(2+i)**2)/4.
M      A(40+i)=(A(3+i)-A(2+i))*XK5/xmu/flowarea
M      rey=A(40+i)
C
C Heat transfer coefficients (Krieth, 3rd ed)
F      hturb=0.0
F      hlam=0.0
C Laminar (eq. 8-28)
M      if(rey.lt.10000.) then
F      write(6,*) 'REYNOLDS NUMBER LESS THAN 10000,Re=',rey
F      stop
M      if(i.eq.1) then
M      xmulocal=A(26+i)
M      else
M      xmulocal=A(26+i)*i-A(26+i-1)*(i-1)
M      if(xmulocal.lt.4.36) xmulocal=4.36
F      endif
M      hlam=(cond/A(1+i))*xmulocal
F      endif
C Turbulent
M      if(rey.gt.2100.) then
M      A(43+i)=0.023*rey**0.8*pran**0.333
M      if(A(43+i).lt.4.36) A(43+i)=4.36
M      hturb=(cond/(A(3+i)-A(2+i)))*A(43+i)
M      endif
C
F      if(rey.lt.2100.) then
F      htc=hlam
F      elseif(rey.gt.10000.) then
F      htc=hturb
F      else
F      fraclam=(10000.-rey)/7900.
F      htc=hlam*fraclam + hturb*(1.-fraclam)
F      endif
M      htarea=PTEST*A(2+i)*XK2/K3
C ADD FINS TO DOUBLE EFFECTIVE SURFACE AREA ON COOL END OF PIPE
```

EDF No. ID121217/1008

K. H. Liebelt

December 10, 1993

Page 31 of 33

```
C 2ft of uncooled pipe, 4ft w/o fins, 8ft w/ fins
F   if(i.le.14) htc=0.0
F   if(i.gt.43) htc=2.*htc
M   G(3001+i-1)=htc*htarea
C
C air velocity
M   A(42+i)=XK5/rho/flowarea
C
C START WALL RADIAL CONDUCTORS
      D1MDG1(T(2001+i),T(3001+i),A54,cond)
M   G(2001+i-1)=2.*PTEST*cond*(XK2/K3)/alog(A(2+i)/A(1+i))
F   enddo
C
C update air pressure
F   do i=100,2,-1
M   rho=A(41+i)*XK6/8314.3/T(4001+i)      $rho=P/RT
      D1DEG1(T(4001+i),A33,xmu)
M   flowarea=PTEST*(A(3+i)**2-A(2+i)**2)/4.
M   rey=(A(3+i)-A(2+i))*XK5/xmu/flowarea
F   call fric(rey,ff)
M   dp=4.*ff*(XK2/K3)*rho*A(42+i)**2/(A(3+i)-A(2+i))/2.
M   A(41+i-1)=A(41+i)-dp
C
C Axial conduction conductors
F   if(i.gt.1) then
M   area=PTEST*(A(2+i)**2-A(1+i)**2)/4.
      D1MDG1(T(2001+i-2),T(2001+i-1),A54,cond)
M   dx=XK2/K3
M   G(102+i-2)=cond*area/dx
F   endif
C
F   enddo
C
      END
C
      BCD 3VARIABLES 2
C
      END
C
      BCD 3OUTPUT CALLS
C
      if(LOOPCT.gt.1) then
C          QNPRNT
C          TOPLIN
F          write(6,*) 'A11 = WATER DENSITY(kg/m3) VS TEMP(K)'
            APRINT(11)
F          write(6,*) 'A12 = WATER SPECIFIC HEAT(J/kg-K) VS TEMP(K)'
            APRINT(12)
F          write(6,*) 'A15 = WATER PRANDTL NUMBER VS TEMP(K)'
            APRINT(15)
F          write(6,*) 'A18 = WATER ENTHALPY(J/kg) VS TEMP(K)'
            APRINT(18)
            TOPLIN
F          write(6,*) 'A19 = WATER BETA(1/K) VS TEMP(K)'
            APRINT(19)
F          write(6,*) 'A20 = WATER REYNOLDS NUMBER'
            APRINT(20)
F          write(6,*) 'A23 = WATER NUSSELT NUMBER (TURBULENT)'
```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 32 of 33

```

        APRINT(23)
        TOPLIN
F      write(6,*) 'A24 = WATER GRASHOF NUMBER'
        APRINT(24)
F      write(6,*) 'A25 = WATER FREE CONVECTION (GrPrD/L) NUMBER'
        APRINT(25)
F      write(6,*) 'A26 = WATER NUSSELT NUMBER (LAMINAR)'
        APRINT(26)
        TOPLIN
F      write(6,*) 'A40 = AIR REYNOLDS NUMBER'
        APRINT(40)
F      write(6,*) 'A41 = AIR PRESSURE (Pa)'
        APRINT(41)
F      write(6,*) 'A42 = AIR VELOCITY (m/s)'
        APRINT(42)
        TOPLIN
F      write(6,*) 'A43 = AIR NUSSELT NUMBER (TURBULENT)'
        APRINT(43)
        TOPLIN
        GPRINT
        KPRINT
        TOPLIN
        TPRINT

C
C Create data files for xmgr plotting
M      do i=1,K3
M      dxft=XK2/K3/0.0254/12.
M      write(31,10) i*dxft,T(1001+i-1)-273.15,T(2001+i-1)-273.15
M      *,T(3001+i-1)-273.15,T(4001+i-1)-273.15
M      *,A(1+i),A(2+i)
M      *,A(20+i),A(23+i),A(24+i),A(25+i),A(26+i)
M      *,A(40+i),A(41+i),A(42+i),A(43+i)
F 10  format(18E10.3)
F      enddo
C
F      endif
C
        END
C
        BCD 3SUBROUTINES
C
        SUBROUTINE FRIC(RE,F)
C      FANNING FRICTION FACTOR
        SAVE
        IF(RE.GT.1.E4)GO TO 10
        IF(RE.LT.1.82E3)GO TO 20
        F=8.8E-3
        GO TO 30
C
10  F=0.0024+0.358*(1./RE)**0.437
        GO TO 30
C
20  F=16./RE
30  CONTINUE
        RETURN
        END
C
        SUBROUTINE DUMPTB

```

EDF No. ID121217/1008
K. H. Liebelt
December 10, 1993
Page 33 of 33

```
SAVE
REAL*8 TBLS,S
COMMON/TABLES/ TBLS(20000),S(26)
WRITE(6,1) TBLS
1 FORMAT(2X,10(1PE12.4))
RETURN
END
```

C

END

C

BCD 3END OF DATA

Appendix C

Test Procedure

Appendix C

Test Procedure

The following test plan was used during the test:

1. Mount transducer and verify measurement capability by measuring wall thickness.
2. Run water only through system. Verify measurement capability at wall temperature of 400°C and atmospheric pressure.
3. Run HCl, water, and oxygen through system.
 - a. Bring water temperature up to 400°C and 3,500 psi.
 - b. Bring wall temperature to 400°C.
 - c. Verify measurement of corrosion every 15 minutes until 10 mils is measured by the transducer or 20 hours of testing
4. Run water only through system. Verify measurement capability at wall temperature of 600°C.
5. Run HCl, water, and oxygen through system.
 - a. Bring water temperature up to 400°C.
 - b. Bring wall temperature up to 600°C.
 - c. Verify measurement of corrosion every 15 minutes until 40 mils is measured by the transducer or 40 hours of testing
6. Disassemble.
7. Measure wall thickness by sectioning pipe. Data will be compared to measurement of transducer.