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METALLOGRAPHIC INVESTIGATIONS
AND REPAIRS OF THE BONUS
STEAM DRYER PREHEATER PIPING

for
The United States Atomic Energy Commission
under
Contract AT (40 - 1) - 2674

NUCLEAR
DIVISION

COMBUSTION ENGINEERING, INC.

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for
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under
Contract AT(40-1)-2674

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Authorized Classifier Date

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FOREWORD

This report, prepared under AEC Contract AT(40-1)-2674, describes the non-destructive tests, metallographic analyses and repair work which were carried out during June and July of 1965 after cracks induced by stress corrosion had been found in a portion of the dryer preheater piping of the Boiling Nuclear Superheater (BONUS) plant. Southwest Research Institute, Oak Ridge National Laboratory and Combustion Engineering, Inc., have contributed the results of their independent but complementary findings on the various aspects of the investigation into the nature and cause of the failures.

The BONUS reactor at Rincon, Puerto Rico, was designed by General Nuclear Engineering Corporation, a subsidiary of Combustion Engineering, Inc., within the framework of a cooperative effort of the Atomic Energy Commission and the Puerto Rico Water Resources Authority (PRWRA). It was intended to demonstrate the technical and economic feasibility of producing superheated steam in an integral boiling-superheating nuclear system at temperature levels comparable to those of modern fossil-fueled plants.

The defects in the dryer preheater piping system were concluded to have largely been caused by the high-temperature oxygenated steam environment. Since it is felt that the results of the extensive analyses by J. McDonald, Jr., K. K. Speirs, P. D. Watson, R. D. Wiley and A. R. Whiting of Southwest Research Institute, E. L. Long of Oak Ridge National Laboratory, and A. S. Jameson and G. Zuromsky of Combustion Engineering Nuclear Division may be of general interest, the present report will replace the original summary of metallographic investigations and repairs of the BONUS steam dryer preheater system, CEND-256, which received only limited distribution.

A renewed inspection of the vessel preheater piping and steam outlet headers was made in April 1966 during a shutdown for installation of the control rod rack housing radiolytic gas vent system. Since the initial repairs and up to the time of the shutdown, the reactor had generated 5800 Mwd. The inspection revealed a through crack in the weld joining the No. 10 preheater supply pipe to the No. 10A header which had been made during the 1965 repair. Liquid penetrant tests showed the presence of cracks in individual headers 10B and 10C and large superheater outlet headers No. 12 and No. 14.

For details of the 1966 inspection, the faults detected, and the repairs made, reference is made to Southwest Research Institute Report "Examination and Repair of BONUS Superheater Piping," SwRI Project 07-4793, Topical Report No. 2.

I. DESCRIPTION AND EVALUATION OF BONUS PREHEATER PIPING DEFECTS

A. SUMMARY

The discovery of two cracked steam dryer preheater pipes during a routine air pressure test conducted to check the leak tightness of mechanical seals in the BONUS superheater fuel assembly steam outlet piping lead to an extensive investigation of all other preheater piping for material defects.

This investigation eventually resulted in the removal and replacement of eight of the sixteen preheater lines integral with the vessel steam outlet headers. In addition to the two lines that had full wall penetration cracks, three were removed because of defect indications detected during in-vessel ultrasonic testing. Three others were eliminated from the system because an analysis of drill samples taken from every elbow in the steam dryer preheater piping integral with the headers revealed the carbon content of the elbows to be higher than that specified for Type 304L stainless steel. All eight lines were replaced with components of double wall piping fabricated from Type 304L stainless steel ($< 0.035\% \text{ C}$).

Extensive nondestructive tests and metallographic examination of the steam dryer preheater sections removed from the vessel yielded the following results:

1. Both intergranular and, to a lesser degree, transgranular cracking was observed. The cracks resulted from in-service stress corrosion of the pipe material operating in the oxygenated (12 ppm) superheated steam environment, which in some instances was aggravated by the presence of high carbon stainless steel instead of the specified Type 304L. The fact that the preheater piping was exposed for a short time to chloride contaminants that entered the reactor vessel inadvertently during a reactor shutdown, combined with the frequent wetting and drying of the piping due to a fairly large

number of reactor shutdowns and power recoveries during the period of superheated steam operation, may have been contributing factors that could have accelerated the stress corrosion cracking.

2. Incipient intergranular and transgranular cracks found in nonsensitized, low carbon preheater piping components is evidence that future service may not be free of this problem and that more failures might occur. However, the probability of failures has been reduced by fabricating the replacement piping from low carbon Type 304L stainless steel. This is the material of construction of the balance of the preheater piping that is integral with the steam dryer and which nondestructive tests have disclosed to be free of defects.

3. Leaks that develop because of piping failures or mechanical seal failure are more serious if they occur in superheater fuel outlet piping systems upstream of the superheater flow orifices, since the fuel clad temperature increase for a given size leak is much greater in this case. Leaks in the preheater piping system downstream of the superheater flow orifices can result in a 20°F clad temperature increase at full power conditions. For an upstream leak, the corresponding clad temperature rise is about six to seven times greater for the same 20°F reduction in the measured superheater outlet steam temperature. By monitoring the superheater outlet temperature and flow, deviations from normal readings that are caused by leaks can be detected early enough to guide the reactor operator on the proper action to be taken before excessive superheater fuel clad temperatures are reached.

4. Dye penetrant and ultrasonic inspections performed on all of the Type 304 stainless steel control rod rack housings showed these to be free of any crack defects.

5. The pinhole leak found in one of the four octant steam outlet headers (No. 13) at a centering pin location was determined to have been caused by an error in fabrication that left insufficient weld metal for sealing the pin.

6. Metallographic examination of the pinhole leak in one of the Type 348 stainless steel superheater outlet connector pipes (No. 12C), which was also detected during air pressure testing, showed this defect to be attributable to a fault that occurred during the welding fabrication and was not initiated by stress corrosion.

B. INTRODUCTION

Upon completion of the reduced (24 assemblies) superheater core experiments in June 1965 and prior to installation of the final eight superheater fuel assemblies into the BONUS core, a routine air pressure test was conducted to determine the effect on the sealing ability of the different gasketed joints in the superheater assembly outlet steam lines of a total of 28,800 Mw(t)-hours of reduced core operation with superheated steam temperatures up to 815°F. Just prior to the start of reduced core operations it had been found that in order to obtain effective seal joints between the superheater nozzle and vessel header flanged joints, it was necessary to replace the originally installed 10-mil wall, nonpressurized, silver plated O rings with heavier wall (12 mils), self pressurized rings and to hand polish all mating seal surfaces. Previous tests had shown all other seals (flexitallic gasket type) in the superheater outlet lines to be pressure tight.

Regardless of seal type, the in-leakage of saturated steam (approximately 75 psi higher than the superheated steam) through the seal members has to be minimized since a leak has the effect of reducing the steam coolant flow through the superheater fuel and thus can cause a rise in fuel clad

temperatures. The magnitude of this rise will depend on the size of the leak, its location and the reactor power level. The routine method established for locating leaks from the seal joints was by air pressure tests, during which the superheater fuel and steam headers were internally pressurized to 90 psig, and the fuel and header piping were submerged under water. A test of this type was conducted and it was verified that all mechanical joints were acceptably leak tight.

During the test, however, air bubbles were observed to be streaming from the left unit of the east dryer and from the right unit of the west dryer (see Figure I-1 for the arrangement of the system). Closer inspection inside the vessel with the water level reduced to about one inch below the top of the control rod guide structure revealed that the air leaks came from the octant No. 12 return line and the octant No. 17 supply line in the fixed portion of the preheater piping which is integral with the steam outlet header. Both defects were checked by dye penetrant tests, and visual inspection showed them to be definite cracks in elbow base material. The crack in the No. 17 supply piping was in the elbow directly below the preheater connector flange and approximately $3/16$ inch from and parallel to the elbow-to-vertical pipe weld. The crack in the No. 12 return pipe was also in the elbow directly below the flange but parallel to and $3/16$ inch from the elbow-to-horizontal pipe run weld. Both cracks were approximately one inch long, with fine branch cracks emanating from the main defect.

1. Description of Steam Dryer Preheater and Piping

As an introduction to the discussion of the tests and operations within the reactor vessel which were initiated after detection of the piping failures, a brief description of the steam dryer preheater system and the design of the preheater piping is presented in the following.

The purpose of the steam dryer preheaters in the BONUS reactor is to slightly superheat the moist saturated steam from the boiler region before entry to the first pass of the four-pass superheater fuel assemblies and thereby prevent any solids that may be entrained in the steam from plating out on the superheater fuel element surfaces as the moisture evaporates. The undesirable effects of a deposition of solids on the cladding surfaces are higher clad temperatures due to scale heat transfer resistance and possible contamination of the external steam system due to scale breakaway and carry-over of the neutron-activated deposits.

The steam dryer preheater shown on Figure I-2 dries the steam in two stages. The water droplets entrained in the saturated steam are first mechanically extracted by passage of the steam through corrugated scrubber plates located in the upper portion of the unit; the remaining water droplets are evaporated and the steam is slightly superheated (approximately 2 to 4^oF) by passing the steam from the scrubbers over the heated surfaces of the preheater tube bundle before entry into the superheater fuel. The Inconel preheater is supplied with superheated steam from one fuel assembly (10A) for the No. 10 octant position, or from a group of four assemblies for all other octants (11 through 17). An orifice in the steam header creates the pressure drop required to divert part of the superheated steam flow through the preheater tubes. The cooler superheated steam leaving the tube bundle, after transferring part of its sensible heat to the steam flowing across the tube bundle to the superheater fuel inlet, is returned to the header downstream of the orifice where it mixes with the bulk of the steam leaving the superheater assembly or assemblies.

The mechanical assembly details of the preheater supply and return piping are shown on Figure I-3; the corresponding connections of the preheater piping to the vessel steam headers appear on Figure I-4 for the dryer in

octant 10, and on Figure I-5 for all other preheater octant locations.

Typical connections of superheater fuel assembly to the steam dryer and steam outlet header are illustrated on Figure I-6, which also shows the location of the various types of seals in the superheater outlet lines.

The supply and return piping are similar in design and feature double-wall type construction. Basically, each supply and return pipe is made up of a series of straight pipes and either 45° or 90° elbows, depending on the required end points, and short spool pieces are inserted between the elbows where necessary to tailor the component to the location. The outer 1-1/2 inch schedule 40S, Type 304 stainless steel pipe has a 1-1/4 inch OD x 14 gauge Type 304 stainless steel tubular inner liner that is maintained concentric with the pipe by Type 304 stainless steel spacer rings which also serve as weld backing rings for joining the pipe sections. The radial annular gap between the pipe and liner is normally filled with stagnant steam which acts as an insulating barrier to minimize the loss of heat from the nominally 900°F superheated steam in the liner to the 950 psig, 540°F saturated steam environment surrounding the preheater piping. As the liner is hotter than the piping to which it is attached at the insert rings, only one end of the liner is anchored and the free end is permitted to expand into the adjacent insert ring that guides the movement to allow for relative expansion of the liner. Holes in each section of the liner tubing provide drainage of condensate from the annulus; however, at the low points in the piping, condensate can only be removed by evaporation.

The maximum heat conduction from the liner to the pipe is at the insert-to-pipe butt weld sections, and this local section of the piping exhibits the largest thermal gradients. The calculated temperature profile at a typical

insert location for full power steaming rates is shown on Figure I-7; the corresponding thermal stress from this thermal gradient has been calculated as about ± 4700 psi. The total maximum stress at this section, not including built-in welding stresses, is the summation of the bending stress, plus or minus 10,000 psi due to the end constraint imposed by the differential expansion of the carbon steel vessel and the stainless steel preheater piping, and the aforementioned thermal stress; the resulting maximum stress value is lower than the yield strength for the stainless steel material at the nominal 540°F operating temperature, that is, 24,000 psi.

The composition of the saturated steam surrounding the external surfaces of the preheater piping is typical of a boiling water reactor environment. Measurements of the oxygen content resulting from the radiolytic decomposition of the water by the irradiation process have indicated an oxygen fraction of approximately 12 ppm. Similar measurements made for the superheated steam have shown its oxygen content to be of the same order. Although the flow liner is exposed to a hotter oxygenated steam environment, the stresses in the liner are only a small fraction of those in the piping member which operates at the lower, saturated steam temperature.

2. Reactor Superheat Operations Prior to Piping Failure

The fact that the actual failures of the preheater piping were not detected by tests prior to superheat operations leads to the conclusion that the piping cracks developed during the relatively short time of superheated steam production. Critical experiments for the 24 superheater assembly core began on February 15, 1965, and the first low power operation on February 21, 1965. Superheated steam temperatures in excess of 700°F were first achieved on April 12, 1965, and the maximum power of 40 Mw(t) was achieved May 26, 1965, with a maximum outlet steam temperature of about 815°F . As a special test, the reactor power was raised to 44 Mw for a few minutes, and the reactor steam

temperature increased to 835°F. Over the period from February 15 to the shutdown on June 11, a total of 28,800 Mw(t)-hr of power operation was achieved. Approximately 30 shutdowns and startups from various power levels occurred during this period.

On March 11, during one of the reactor shutdown periods, the reactor core spray valve was inadvertently opened and admitted 3100 gallons of non-demineralized water from the external fire protection storage tanks into the BONUS reactor vessel. The water had a nominal chloride content of approximately 80 ppm and a total solids content of approximately 600 ppm. Extensive flushing operations were carried out in order to remove the water and prevent the deposition of corrosion products. Flushing tests were terminated after there was no further reduction in the chloride and sodium content of the water sampled from the bottom drain of the main steam drop leg.

Except for this incident when contaminants entered the system, the quality of the reactor water exhibited the following high standards:

	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
pH	6.0	7.5	6.68
Conductivity, μ -mho/cm	0.34	1.95	0.64
Chloride ion, ppb	1.4	17.2	5.28

The preheater piping had been exposed to alternate wetting and drying because of a large number of reactor shutdowns and restarts occasioned by both intentional and inadvertent scrams. The wetting occurs during the voiding of superheaters at low operating pressures to remove condensate from the assemblies prior to establishing criticality. The drying follows once superheated steam is produced and passed through the preheater piping. This alternate wetting and drying of surfaces can result in a buildup of contaminants from the reactor water and steam and in a concentration of such con-

taminants in cracks or crevices which could accelerate the initiation and propagation of cracks. The surfaces of the annular gap between the outer pipe and inner liner, especially at the low points in the preheater piping, are particularly sensitive to this concentration of water impurities, since the only way to drain these areas is by evaporation of the condensate collected in the gap. The fact that the majority of the cracks observed were found to be on the inner surface of the pipe, even though the inner pipe and outer liner surfaces are exposed to the same oxygenated steam conditions, can be attributed to much lower stress levels in the liner piping sections.

C. IN-VESSEL TESTS AND OPERATIONS

1. Dye Penetrant Examination

After the visual detection of two leaks in the preheater piping, and the determination of the extent of the cracks by a local dye test, further investigations were made to establish if there were any partial penetration surface cracks. A complete dye penetrant inspection was made of all piping for the four steam dryer preheaters and yielded no other indications of defects, except for slight porosity at a few weld joints, in either the fixed piping supplied by the vessel fabricator (Pacific Coast Engineering Co.) or in the steam dryer preheater piping supplied by Dresser Ideco Co.

The Puerto Rico Water Resources Authority engaged Southwest Research Institute (SwRI) to inspect the pipe failures on-site, conduct an ultrasonic inspection of all preheater piping, make the destructive tests necessary to determine the cause of the failures, and generally assist in guiding the piping replacement. Although weld repairs of the cracks were feasible and would have returned the reactor to service earlier, it was decided to remove the cracked piping sections for metallographic appraisal to determine the nature and cause of the cracking.

2. In-Vessel Working Conditions and Protective Measures

Inspection and repair operations within the vessel, for which the top of the control rod guide structure served as a standing platform, were restricted due to the confined working space imposed by the control rod extensions and by the radiation and surface contamination levels. Radiation measurements made with the reactor water level three inches below the top of the guide structure were as follows: 1 inch above the water level, 320 mr/hr; 1 inch above the top of the structure in the center portion of the core, 170 mr/hr; 1 inch above the top of the structure in the corner sectors, 240 mr/hr; and 3 feet above the structure, 90 mr/hr. Smear samples from vessel dryer and piping surfaces gave a maximum count of 7000 dpm from beta activity.

After washing down the vessel and dryer surfaces, plastic sheeting was applied over the surfaces to minimize contamination pickup by the personnel engaged in inspection and repair operations. The sheeting also protected these surfaces from the dye penetrant used for inspection of the piping. Personnel exposure time within the vessel was limited to an integrated accumulated weekly dose of 300 mr as indicated by personnel dosimeters. One of the station area monitors was located in the vessel on top of the core structure and was set to annunciate if the dose rate exceeded background. This safety measure was adopted to warn personnel to leave the vessel if the water level should inadvertently be lowered. In addition, continuous air sampling and monitoring were provided with an MAP-5 air and particulate recording instrument to protect personnel from airborne contamination and to indicate when air masks were required. A safety officer and a health physicist were always on duty when personnel were inside the vessel.

As the work in the vessel progressed, the need for additional shielding and adequate protection for the rod extension shafts became apparent in view of the number of personnel entries into the vessel and the need to minimize the exposure of available site personnel with the crafts and expertise needed

to accomplish the work. A 1/2 inch thick carbon steel plate platform was mounted on top of the core structure and served as a working platform, in addition to providing improved shielding and reducing the chances of dropping tools, etc. into the core region. At each control rod location a pipe sleeve was threaded into pipe couplings attached to the plate; these sleeves served to protect the control rod extensions from bending damage by the personnel working in the confined space between the control rods. In addition, the sleeves provided further insurance against accidental withdrawal of control rods, although each control rod had been lashed down with nylon cord to the rod guide structure. With the platform in place, radiation dose rates were reduced by about a factor of two below previous levels.

3. Ultrasonic Inspection

Both lines containing the cracked elbows were removed from the vessel for metallographic inspection. The cutting was done with a standard pipe cutter modified only by shortening the handle to allow rotation amid the adjacent piping. Other types of cutting tools available at the site were considered but were eventually rejected in favor of the pipe cutter since its use would limit the spread of contamination throughout the vessel. Each cut location was established with a view to permitting optimum weld access for the installation of the replacement piping.

After the two cracked pipes had been removed from the vessel and the open ends plugged to prevent water entry into the superheater fuel assemblies, the reactor water level was raised for an ultrasonic test of the entire preheater piping. Prior to this test, the two cracked pipes were ultrasonically tested to establish a calibration standard for the ultrasound transducer and reflectoscope for cracks that fully penetrated the 0.145 inch thick pipe wall. Both failed pipes were also completely probed to determine if there were any subsurface crack defects; however, the tests did not reveal any other

flaws except those that fully penetrated the wall. The in-vessel ultrasonic tests were made by a SwRI ultrasonic inspection specialist suitably attired in wader pants, rubber gloves and plastic suiting to protect him from contact with the surrounding radioactive reactor water. In addition to the film badge worn on the chest, personnel dosimeters were worn at the ankle, hip and head to monitor the dose received while carrying out the ultrasonic probe.

The ultrasonic tests indicated defects at three locations in the preheater piping attached to the steam headers. No indications were detected in the preheater piping furnished by the steam dryer preheater fabricator. Two possible flaws were indicated in the No. 13 octant. One was in the preheater supply pipe at the connector-to-pipe weld and adjacent to the vessel wall. A second indication was found directly below the connector in the return line at the first 90° elbow-to-pipe weldment. A third defect indication in octant No. 16 was in the return line at the lower 90° elbow-to-pipe vertical weldment. These three indications were the only suspected defect areas in both the steam header and steam dryer preheater piping. Since subsurface defects can propagate and eventually result in failure, it was agreed to remove the piping involved. Subsequently, SwRI and ORNL established by metallographic examination that the ultrasound indications represented lack of fusion and hot tears in No. 13 return and No. 16 return and a crack in No. 13 supply.

4. Material Sampling of Preheater Elbows

Metallographic evaluation of the failed No. 12 return and No. 17 supply piping by SwRI indicated that the material of the cracked elbows was not the specified type stainless steel (304L) but a stainless steel with a higher carbon content which had been sensitized in fabrication by exposure to temperatures up to approximately 1400°F. This conclusion was verified by chemical analyses made at

ORNL which showed that the material of the failed elbows had a carbon content of 0.13% as compared to a maximum of 0.035% for Type 304L and 0.08% for Type 304. Since sensitization to cracking from stress corrosion is a function of the carbon content of stainless steel, it was decided to take material samples from every 90° and 45° elbow in the steam header-to-preheater piping.

The first hand-filed material samples were rejected because they were too contaminated with other carbon bearing materials such as lint, hair, paper, etc. for a reliable and accurate determination of carbon content. The second set of samples was taken with a speed controlled 1/4 inch to 5/16 inch diameter drill bit. Each elbow sample consisted of the drill chips from three holes drilled to a depth of 1/16 to 3/32 inch. Special precautions were taken to minimize contamination of the drill chips. The surface of each elbow at the sample location was acid etched to clean metal, followed by acetone and demineralized water cleaning. Nylon coveralls and caps were worn instead of cotton clothing, and rubber instead of cotton gloves. All drill samples were collected on aluminum foil instead of the plastic sheeting used for the first samples. Each drill bit was carefully cleaned before use and a new drill bit was used for each elbow sample.

Chemical analysis of the samples at ORNL showed that in addition to the cracked octant pipes No. 12 return and No. 17 supply, the following elbows also had a high carbon content:*

<u>Octant No.</u>	<u>Line</u>	<u>Type & Location</u>	<u>Carbon Content(%)</u>
10	Supply	90° Elbow at Header	0.105
10	Supply	90° Elbow below Connector	0.120
10	Return	90° Elbow below Connector	0.126
14	Return	45° Elbow	0.093

*See Table V-1 for the carbon content of all drill samples.

On the basis of these findings, it was agreed to remove the piping sections containing the elbows and to procure the replacement parts - pipe, fittings and tubing - from Type 304L stainless steel, which was the material used in the preheater piping furnished by the steam dryer preheater fabricator. Although Inconel would have been preferable for the replacement piping, the long delivery time for Inconel components ruled this out. However, ORNL agreed to fabricate the replacement for the No. 14 return from Inconel, and it was to be installed if its fabrication did not hold up the piping replacement schedule. This section was intended as a control sample in addition to one Inconel elbow in the No. 10A supply line at the header. It was eventually furnished to the site but was received too late for inclusion in the system.

5. No. 13 Steam Header Defect

During air leak testing of the superheater fuel assemblies, air bubbles had also been observed to issue from the vicinity of the No. 13A superheater assembly and from the No. 12C superheater outlet connector pipe. A close inspection of the area near the 13A fuel assembly revealed that the air was issuing from a minute hole in the No. 13 steam header.* The presence of the hole was confirmed by dye check and ultrasonic tests and the defect was located approximately 1/4 inch upstream of the orifice plate in the header and at approximate position 5 o'clock when viewed from the capped end of the header. A review of the header design drawings showed that the leak had occurred in the vicinity of a 1/4 inch diameter stainless steel set screw that centered the flow liner inside the header and was plug welded and ground flush with the header surface.

*See Figure VI-18 for the location of the leak.

The set screw was located by hand grinding the surface down to set screw base metal and electro-polishing the surface to distinguish the header material from that of the set screw. After a number of unsuccessful attempts to drill into the set screw to remove it, the screw was eventually removed by trepanning the header with a 5/8 inch diameter, slow speed, motor driven hole saw. A chemical analysis of both the header and set screw materials from the trepanned sample was made by ORNL and their tests showed that the materials were as specified, i.e., Type 304 stainless steel. It was postulated that the leak developed because the flush grinding operations had minimized the weld metal seal, and subsequent thermal expansion of the header and liner during operation caused break-through of the seal. The hole left by the trepanning operation was filled with a Type 304L stainless steel 5/8 inch nominal diameter plug and heliarc-welded to the header. Dye check and air tests were made to verify that the weld was crack free and air pressure tight.

6. No. 12C Superheater Outlet Connector Defect

The air leak that was found in the No. 12C superheater outlet connector pipe was verified by dye check and ultrasonic inspection after the connector pipe had been removed from the vessel. The leak was quite minute and could only be detected by close scrutiny of the defect region. The pinhole leak in the Type 348 stainless steel elbow was sectioned and metallographically examined by SwRI. It was judged to have occurred during fabrication and was attributed to an accidental weld strike out of the weld zone by the welder during construction. At the lower bracket-to-pipe weld, an 85 mils deep crack was detected which did not leak due to the weld metal above the crack. This crack was also attributed to a welding defect. However, transgranular branch cracking resulting from stress corrosion was observed along the weld defect. A chemical analysis of the connector pipe material verified that the chemical composition corresponded to Type 348 stainless steel.

D. SCOPE OF METALLOGRAPHIC EXAMINATIONS

1. Dryer Preheater Piping

The preheater piping sections that were removed from the reactor vessel because of noted through cracks, defect indications detected by in-vessel ultrasonic tests, and elbows with higher than specified carbon content, were exhaustively examined by Southwest Research Institute, Oak Ridge National Laboratory, and Combustion Engineering.

Southwest Research Institute analyzed the preheater piping containing the cracked 90° elbows of octant No. 12 return and octant No. 17 supply, and the No. 10 return and supply lines that were removed because of the high carbon content of the elbows. SwRI made and examined a total of 140 sections through the high and low carbon elbows, the pipe, tubing liner and pipe weldments; the results and conclusions of their metallographic studies* appear in Section III.

A portion of the octant No. 17 supply piping was also examined by Combustion Engineering, Inc., and their analysis** (see Section IV) essentially substantiated the findings and conclusions of SwRI. The preheater piping lines that were removed because of ultrasonic indications at weldments during in-vessel tests, that is, octants No. 13 return, No. 13 supply and No. 16 return, and the No. 14 return pipe with high carbon content were ultrasonically and metallographically evaluated by Oak Ridge National Laboratory. The results of their examinations are presented in Section V, together with the results of the carbon chemical analysis of material samples which were taken from all of the preheater piping elbows.***

*Cf. SwRI Report No. 1, "Metallurgical Examination of BONUS Steam Dryer Preheater Piping," by J. McDonald et al., SwRI Project No. 07-184-00-0816 (September 1965).

**CEND-253, "Metallurgical Evaluation of Failed Elbow From BONUS Steam Dryer Preheater Octant 17 Inlet Piping", by G. Zuromsky, AEC Contract AT(40-1)-2674 (July 1965).

***ORNL-TM-1282, "Examination of BONUS Preheater Dryer Piping," by E. L. Long, Jr., Contract No. W-7405-eng-26, Metals and Ceramics Div. (October 1965).

2. Other Austenitic Stainless Steel Reactor Components

In view of the fact that cracks did appear in the austenitic stainless steel piping system of the preheater and that leaks were also noted in the Type 304 stainless steel header No. 13 and in the Type 348 stainless steel superheater outlet connector No. 12C, it was decided to inspect all seventeen of the Type 304 stainless steel control rod rack housings and thirteen of the Type 348 stainless steel superheater outlet connector pipes, of which nine had previously been in service and four were spare, unused assemblies.

The dye penetrant, borescope, and ultrasonic tests made by SwRI at the site confirmed the soundness of the control rod rack housings.*

Ultrasonic tests on the superheater outlet connectors did not reveal any discernible indications beyond those due to the geometry of the weldments.**

E. EFFECT OF LEAKS ON SUPERHEATER CLAD TEMPERATURE

An analysis of the effect of the size of leak paths that allow saturated steam to enter the steam headers or preheater piping was made to determine the size of holes that could be tolerated and the corresponding increase in the temperature of the superheater fuel cladding. Two cases were analyzed for leaks occurring on the downstream side of the superheater flow orifices. Table I-1 shows, for reactor startup and normal operating pressures and power levels, the hole size for the case of a leak in the octant No. 10 preheater piping that would produce a measurable 20°F decrease in the superheated steam exit temperatures. Table I-2 shows similarly what would occur if a leak developed in the preheater piping of a dryer supplied by steam from the four superheater assemblies in an octant.

*For a detailed discussion, cf. SwRI Report No. 3, "Inspection of the BONUS Control Rod Drive Housings," by J. McDonald, Jr., and A. R. Whiting, SwRI Project No. 07-184-00-0816 (August 1965).

**See SwRI Report No. 2, "Investigation of Type 348 Connector Pipes from the BONUS Reactor," by J. McDonald et al., SwRI Project No. 07-184-00-0816 (August 1965).

The data show that for a preheater piping leak (or for a gasket leak downstream of the superheater flow nozzle) in a preheater octant supplied with steam from either one or four fuel assemblies, the increase in fuel cladding temperature corresponding to a 20°F decrease in exit superheated steam temperature is relatively small. For example, Table I-1 indicates that a leak equivalent in hole size to 0.13 inch diameter in the No. 10 octant preheater piping or header gasketed joint would produce only a 2.3°F rise in the clad temperature at full reactor power, and this condition would be indicated by a 20°F drop in the outlet superheated steam temperature. According to Table I-2, a hole 0.33 inch in diameter, similarly located but in an octant supplied by four fuel assemblies, would produce a 21°F rise in the clad temperature for the same steam temperature decrease.

Table I-1. OCTANT NO. 10A FUEL ASSEMBLY PREHEATER STEAM PIPING LEAK EFFECTS*
Leak Downstream of the Superheater Flow Orifice

Reactor Power (Mw)	Reactor Pressure (psig)	Power Split (%)	% In-Leakage Flow for -20°F	Decrease in Assembly Flow(%)	Net Increase in Total Flow(%)	+ ΔT Clad (°F)	Hole Diam. (In.)
3	120	20	15.0	1.6	13.6	3.8	0.39
4	120	20	11.5	1.1	10.4	3.6	0.34
5	120	20	9.8	1.0	8.8	2.5	0.32
10	950	20	8.9	0.9	8.0	2.8	0.18
30	950	20	6.3	0.6	5.7	2.6	0.16
50	950	20	6.2	0.6	5.6	3.2	0.16
10	950	23	7.6	0.7	6.9	2.0	0.15
30	950	23	4.9	0.4	4.5	2.1	0.14
50	950	23	4.5	0.4	4.1	2.3	0.13

*Based on 250°F feedwater temperature. A feedwater temperature of 354°F and power split of 26% at 50 Mw is about equivalent to the last case shown in the table.

Table I-2. SUPERHEATER OCTANT PREHEATER STEAM PIPING LEAK EFFECTS*
Leak Downstream of the Superheater Flow Orifice

Reactor Power (Mw)	Reactor Pressure (psig)	Power Split (%)	% In-Leakage Flow for -20°F	Decrease in Octant Flow(%)	Net Increase in Total Flow(%)	+ ΔT Clad (°F)	Hole Diam. (In.)
3	120	20	57.0	7.0	50	17	0.71
4	120	20	46.0	5.0	41	11	0.63
5	120	20	41.0	4.7	36.3	11	0.61
10	950	20	48.0	5.7	42.3	18	0.41
30	950	20	40.0	4.6	35.4	20	0.37
50	950	20	40.0	4.6	35.4	24	0.37
10	950	23	36.0	3.7	32.3	12	0.35
30	950	23	32.0	3.6	28.4	18	0.33
50	950	23	32.0	3.6	28.4	21	0.33

*Based on 250°F feedwater temperature. A feedwater temperature of 354°F and power split of 26% at 50 Mw is about equivalent to the last case shown in the table.

The hole sizes shown in the tables are relatively large and it is difficult to see how they could result from the type of cracking that has occurred. The branching nature of the cracks themselves prevents a true separation at the fracture. The stresses in the piping are such that if cracks occur they will not tend to open further since the stresses are of the restraint type.

As each of the four assemblies in every octant group has a different power level and is connected to the same header, the flow through each superheater fuel assembly for the same exit steam temperature is established by the size of the flow orifice in the exit from the assembly and the resulting pressure drop across it. Since the superheater fuel assemblies in the "A" positions have the lowest power and the least coolant flow, and correspondingly the maximum pressure drop across the flow orifice, a leak that occurs upstream of the flow orifice can produce higher clad temperatures than a leak downstream since

the leak results in a greater reduction of the coolant flow that passes through the superheater fuel assembly. Table I-3 illustrates the effect of a postulated leak upstream of the octant No. 10A flow orifice, e.g., a hole in the superheater outlet connector pipe or a leak in one of the flexitallic gaskets at each end of the pipe.

Table I-3 shows that for the full power, 23% power split case, a temperature drop of 20°F in the superheated steam exit temperature can be indicative of a 133°F rise in clad temperature if the leak is upstream of the superheater flow orifice, as compared to a very small rise for the same operating conditions if the leak occurs downstream. Figure I-8 is a nomograph that was developed to show the effects on the clad and exit steam temperatures at full

Table I-3. OCTANT 10A FUEL ASSEMBLY STEAM PIPING LEAK EFFECTS*
Leak Upstream of the Superheater Flow Orifice

Reactor Power (Mw)	Reactor Pressure (psig)	Power % Split (%)	In-Leakage Flow for -20°F	Decrease in Assembly Flow (%)	Net Increase in Total Flow (%)	+ ΔT Clad (°F)	Hole Diam. (In.)
3	120	20	71	44	27	111	0.79
4	120	20	50	30	20	70	0.66
5	120	20	40	24	16	56	0.60
10	950	20	57	35	22	115	0.71
30	950	20	53	32	21	162	0.68
50	950	20	50	30	20	176	0.66
10	950	23	47	28	19	80	0.64
30	950	23	42	25	17	130	0.62
50	950	23	38	23	15	133	0.36

*Based on 250°F feedwater temperature. A feedwater temperature of 354°F and power split of 26% at 50 Mw is about equivalent to the last case shown in the table.

operating conditions of leak rates upstream of the superheater flow orifice in the No. 10A fuel assembly (worst case leak).

By monitoring both the superheated steam flow and exit temperature from each of the superheated steam octant lines, some clues can be obtained as to the probable location of a leak and its effect on superheater fuel performance. The magnitude of the exit superheated steam flow increase associated with a leak depends on where in the superheater outlet piping the leak occurs. This can be seen by comparing the steam leakage and coolant flow data in Tables I-1 and I-3 which are both applicable to leak cases originating in the superheater No. 10A outlet line. At full power, 26% power split conditions, a leak that produces a 20°F reduction in the exit superheated steam temperature will result in an approximately 4% increase in the outlet steam flow if the defect is located downstream of the superheater flow orifice, and an approximately 15% increase if the leak source is upstream of the same orifice.

Much larger flow changes can be postulated if leaks occur in octants containing four superheater fuel assemblies; Table I-2 shows for the same power conditions and temperature decrease of 20°F that a flow increase of about 28% would be associated with a leak in the piping system downstream of the superheater flow orifices, and still larger flow changes would occur if the leak were on the other side of the orifice. Although the exact magnitude of the flow increase for this situation has not been calculated, it can be inferred from the calculations made for the effects of leaks into the individual 10A octant that leaks upstream of the superheater orifices will be accompanied by much larger flow increases than downstream leaks.

Figure I-1. Identification of steam dryer preheater and superheater fuel octants

1. CORRUGATED DRYER PLATES
2. REMOVABLE PREHEATER
3. SUPERHEATED STEAM HEADER
4. INLETS TO SUPERHEATER FUEL ASSEMBLIES
5. OUTLETS FROM SUPERHEATER FUEL ASSEMBLIES
6. PREHEATER PIPE COUPLINGS
7. REMOVED MOISTURE DRAIN PIPE
8. DRYER PREHEATER SUPPORT BRACKET
9. LIFTING LUGS
10. INSPECTION COVER PLATE
11. SUPERHEATER CONNECTOR PIPES
12. EMERGENCY COOLING PIPE

Figure I-2. Perspective view of north steam dryer preheater

Figure 1-3. Design details of the vessel steam header preheater piping

Figure I-4. Design details of the small superheated steam outlet headers for octant No. 10

Figure 1-5. Design detail of the reactor vessel superheated steam header for octants Nos. 11 through 17

BILL OF MATERIAL			
ITEM	NAME	DESCRIPTION	MATERIAL
1	VESSEL	64 1/2" DIA. 16'-11 1/2" H.	
2	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
3	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
4	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
5	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
6	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
7	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
8	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
9	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
10	STEAM DRYER	48" DIA. 16'-11 1/2" H.	
11	STEAM DRYER	48" DIA. 16'-11 1/2" H.

Figure 1-6. Superheater fuel assembly connections to the steam dryer and vessel steam outlet header

Figure 1-7. Calculated temperature profile in preheater piping in vicinity of insert ring

Figure I-8. Nomograph for determining effect of a saturated steam leak in the outlet of Type "A" superheater fuel assembly upstream of orifice

II. ON-SITE NONDESTRUCTIVE TESTING

This section describes the support provided by Southwest Research Institute in the areas of nondestructive testing and on-site examinations. The results of the metallographic investigation of the preheater pipes that were forwarded to SwRI are discussed in Section III.

A. ON-SITE INSPECTION OF FAILED PREHEATER PIPES

The failed preheater pipes, No. 12 return and No. 17 supply, were inspected in-place. Both failures consisted of circumferential cracks approximately one inch long. The cracks were adjacent to welds and were confined to the 90° elbows of the two pipes. They were readily discernible by observation of air bubbles through the water during pneumatic testing and by dye penetrant inspection. The distance of the cracks from the welds varied from 1/8 to 5/16 inch. Figure II-1 shows the dye penetrant inspection of the cracked elbows from these two preheater pipes. The indications are clearly visible.

The consequences of a major failure in the preheater piping made it imperative that the nature of the two failures be established. It was decided to remove the two failed pipes from the system and to determine, on the basis of a metallographic investigation, whether the failures were due to fabrication defects or material deficiencies associated only with the failed 90° elbows, or whether additional failures could be expected to occur throughout the preheater piping as the result of an unexpectedly aggressive environment.

B. ULTRASONIC INSPECTION OF PREHEATER PIPING

The results of the pneumatic and dye penetrant inspections indicated that the remainder of the preheater piping was free of leaks or of external surface defects such as cracks or pinholes. These tests, however, did not provide the needed assurance that the piping was safe for operation and that additional failures were not imminent as a result of undetected defects initiating on the inside surfaces. In-reactor radiographic inspection of

the preheater piping was ruled out due to the limited accessibility of the piping, especially of those sections of the preheater supply pipes which lie below the superheated steam headers.

Consideration of the preheater pipe circumferential weld joint design and the location of the cracks observed in the two failed elbows relative to the circumferential welds indicated that ultrasonic inspection was feasible. The two failed components which had been removed from the reactor were inspected ultrasonically and it was demonstrated that an immersion, pulse-echo, shear wave technique readily detected the circumferential cracks in the elbows.

1. Ultrasonic Inspection Procedure

The two failed pipe elbow components from the preheater piping system were used as standards for the ultrasonic inspection. The amplitude of the return signal from the through-cracks was set at full screen magnitude on the CRT screen of the ultrasonic unit.

The in-reactor ultrasonic inspection of the preheater piping was carried out using a Sperry Model UM 700 Reflectoscope as the power source to drive a 1/2 inch x 1/2 inch, 2.25 megacycle, lead zirconate inspection transducer. A water immersion, pulse-echo ultrasonic technique was employed. The transducer was waterproofed with silicon grease and mounted on lucite runners to maintain the incident angle necessary to produce a 70° shear wave within the metal.

As can be seen from the preceding sketch, the inspection was primarily intended to locate defects whose major dimension was parallel to the diameter of the tubing and which propagated through the tubing wall. Areas adjacent to pipe-to-flange connector and pipe-to-elbow welds were of main concern.

2. In-Reactor Ultrasonic Inspection of the Preheater Piping

The water level in the reactor vessel was raised above the level of the connectors so that the entire fixed portion of the preheater piping was immersed. This placed the water level approximately 40 inches above the top of the core support structure. The SwRI ultrasonic specialist entered the reactor vessel wearing the full-length rubber suit and shoulder-length waders shown on Figure II-2.

The connector-to-pipe welds and most of the remaining welds between the connector and the headers were inspected ultrasonically with the immersion technique described in the previous section. This inspection included all of the fixed portions of the preheater piping in octants 10, 11, 12, 13, 14, 15, 16 and 17. Ultrasonic indications of potential defects were discovered in three preheater pipes during this inspection. The welds of the 90° elbow connecting the No. 10 supply preheater pipe to the underside of nozzle 10A were not inspected at the time because they were too deeply immersed. These welds were inspected at a later time after the water level had been lowered.

The water level in the reactor vessel was raised to a sufficient depth to allow the removable portion of the preheater piping, i.e., from the connector to the dryer flange, to be inspected ultrasonically. Each weld in the supply and return pipes above the connector was then inspected ultrasonically using the 70° immersion technique. During these inspections, the Sperry Model UM 700 Reflectoscope was suspended from the overhead crane, as shown on Figures II-3 and II-4.

3. Ultrasonic Inspection Results

Due to the combined effect of component geometry and lack of accessibility, it was not possible to carry out a complete ultrasonic inspection of each weld in the preheater piping, although approximately eighty percent of the weld area in both the fixed and the removable portions of the preheater piping were inspected. Only three ultrasonic indications were found in the nearly 300 welds so inspected. The location, magnitude and extent of these indications are described in the following:

Ultrasonic indication at lower connector-to-pipe weld junction on side of No. 13 supply pipe adjacent to vessel wall. This was essentially a point indication of a magnitude approximately equal to that of failed specimens; it was located ultrasonically only from the pipe side of the weld.

Ultrasonic indication at lower 90° elbow-to-pipe weld of No. 13 return preheater pipe. Indication extended for 45° on side adjacent to vessel wall, with a magnitude approximately 1/3 that indicated by failed pipes. This defect appeared to be very near the weld on the pipe side.

Ultrasonic indication at lower 90° elbow-to-pipe weld of No. 16 return pipe. Indication extended 15° circumferentially around the pipe, with the maximum indication appearing at the bottom horizontal position. The magnitude of the indication was approximately 1/3 that of the failed pipes. This indication was found from the elbow side of the weld.

4. Interpretation of Ultrasonic Inspection Results

The two failed preheater pipes, No. 12 return and No. 17 supply, were forwarded to Southwest Research Institute for metallurgical examination. A review of the preheater pipe circumferential welds was made after sectioning to formulate conclusions regarding the origin of the ultrasonic indications obtained during the in-reactor inspection.

Sectioning indicated that geometrical conditions existed in some of the preheater piping circumferential welds that provided reflective surfaces for the ultrasonic beam. These surfaces, oriented normal to the vessel wall, resulted from failure to completely fuse the 1/16 inch wide shoulder of the

backing ring of the circumferential joints. This condition was associated only with the joint detail designated as 8A on Figure I-3. As illustrated in the preceding sketch, these indications would be detected ultrasonically only from the side of the weldment in which the welding discontinuity existed. Figure II-5 shows the cross section of a circumferential weld from No. 12 return preheater pipe illustrating lack of fusion. A cross section of a

weld in which complete penetration was obtained is shown on Figure II-6.

Since lack of fusion was common in the circumferential welds of the sectioned preheater pipes, it was assumed that the same condition existed in similar locations of the other preheater pipes. On the basis of these findings, a preliminary evaluation of the in-reactor ultrasonic indications was carried out which yielded the following results:

The ultrasonic indication at the connector-to-pipe circumferential weld of the No. 13 supply pipe was a point indication without circumferential length and positioned in or very near the weld. This indication was detected only from the pipe side of the weld. It was thus decided that this ultrasonic indication was not produced by a defect removed from the weld, such as the gross cracks of the failed pipes, but by a welding discontinuity such as porosity or slag within or close to the fusion line of the weld.

The ultrasonic indication at the elbow-to-pipe weld of No. 13 return preheater pipe extended 45° circumferentially and was detected from the pipe side of the pipe-to-elbow weld. The source of this indication appeared to be at or very near the weld. It was concluded that there probably was a lack of fusion at this location similar to that shown on Figure II-5, and that the ultrasonic indication was not indicative of cracking.

The ultrasonic indication at the lower elbow-to-pipe weld on the No. 16 return preheater pipe extended 15° circumferentially around the pipe and was found from the elbow side. The indication appeared to be slightly removed from the weld on the elbow side. Although

the magnitude of the indication was not as great as that of the failed elbows, the fact that the indication was on the elbow side and slightly removed from the weld led to the conclusion that this elbow contained a crack similar to that of the failed elbows.

5. Metallographic Correlation of Ultrasonic Indications

The three preheater pipes with ultrasonic indications of possible defects were removed from the reactor and sent to ORNL for sectioning and metallographic examination. While the results of the ORNL metallographic investigation are discussed in detail in Section V, the correlation established between the ultrasonic inspection and actual defects is described in the following:

The ultrasonic indication at the connector-to-pipe circumferential weld on the No. 13 supply preheater pipe was found to be an intergranular crack approximately 0.075 inch in depth propagating from the inside diameter of the pipe. The circumferential length was approximately 1/8 inch and its radial location was in close agreement with that indicated by the in-reactor ultrasonic inspection. The location of this crack, however, was found to be 1/4 inch from the weld instead of within or at the edge of the weld, as had been indicated by the ultrasonic inspection. This discrepancy is attributed to the fact that the crack was on the vessel wall side of the pipe, and that this location limited the operator's ability to accurately judge the position of the transducer during the in-reactor inspection.

The ultrasonic indication at the elbow-to-pipe weld of the No. 13 return preheater pipe proved to be a geometrical welding

discontinuity (lack of fusion), as initially postulated. A small crack (hot tear) was found to propagate from the discontinuity into the weld. The location and extent agreed well with the ultrasonic inspection.

The ultrasonic indication at the lower elbow-to-pipe weld of the 90° elbow in the No. 16 return preheater pipe was found to be a geometrical welding discontinuity similar to the one in No. 13 return; here, too, a small crack propagated from the discontinuity into the weld. The location and circumferential position correlated well with the ultrasonic inspection. The ORNL metallographic investigation also disclosed two small cracks (8 - 10 mils deep) at the machined location on the inner surface of the short nipple between the 90° and the 45° elbows. These microcracks were not detected during the in-reactor inspection, as they were in one of the areas which could not be inspected completely due to limitations imposed on the ultrasonic inspection procedure by the geometry of the components.

Figure II-1. Dye penetrant indications of cracks in 90° elbows of failed BONUS preheater pipes

Figure II-2. Rubber suit and waders worn for the immersed in-reactor inspection of the BONUS preheater piping

Figure II-3. Ultrasonic unit suspended from overhead crane

Ultrasonic Unit —

Figure II-4. In-reactor ultrasonic inspection of the BONUS preheater piping

SwRI 3316

Mag. 11X

Figure II-5. Cross section of a preheater pipe circumferential weld in which the backup ring was not completely fused

Mag. 11X

Figure II-6. Cross section of a preheater pipe circumferential weld with 100 percent penetration

III. SWRI METALLOGRAPHIC EXAMINATION OF BONUS STEAM DRYER PREHEATER PIPING

A. INTRODUCTION

In the course of an inspection of the internal piping of the BONUS reactor, cracking was discovered in the dryer preheater pipes of octants 12 and 17. The Department of Materials Engineering of Southwest Research Institute was requested to inspect the cracked preheater pipes and to make recommendations regarding their possible in-place repair by welding or replacement of the failed sections. The two failed preheater pipes were removed from the reactor and forwarded to Southwest Research Institute for metallographic examination. Six additional preheater pipes were subsequently removed on the basis of ultrasonic indications of possible defects and discovery of other high carbon, Type 302 stainless steel elbows in the pipes. Of these six preheater pipes, Nos. 10 return and 10 supply were examined at Southwest Research Institute. Oak Ridge National Laboratory made the metallographic investigation of the other four pipes. (See Section V).

The results of the examination by SwRI of the four preheater pipes, Nos. 12 return, 17 supply, 10 supply and 10 return, are presented in this section.

B. VISUAL EXAMINATION

The four sections submitted for examination are shown on Figures III-1 to III-4. Figures III-1 and III-2 show the two failed pipes. The outer surface of these two pipes, which are identified as No. 12 return and No. 17 supply, was inspected by the dye penetrant technique, and the approximately 1 inch long cracks are clearly visible in the 90° elbow adjacent to the circumferential butt weld. Figures III-3 and III-4 show the No. 10 return and No. 10 supply preheater pipes. The shallow holes in the elbows were drilled to obtain samples for chemical analysis of the elbow material.

A more thorough inspection of the cracked areas on both the outside and inside surfaces of No. 12 return and No. 17 supply revealed additional details of the cracks. Figures III-5 and III-6 show a closeup of the cracks after a fluorescent penetrant inspection. Figures III-7 and III-8 show red dye penetrant indications on the outside and inside surfaces of the two failed elbows.

In general, the cracks were longer on the inside surface than on the outside surface. The cracks on the inside surface also exhibited more branching. Although a portion of one crack appeared to be at the weld fusion line, the major portion of the cracking was removed from the weld by $1/8 - 3/16$ inch. The sections from No. 10 supply and return were inspected by both dye penetrant and ultrasonic techniques. No defects were observed.

The four preheater pipes were cut into a series of smaller pieces for ease of examination and to free the liners. A typical photograph of the sections is shown on Figure III-9. This particular pipe, No. 10 return, was chosen to illustrate two additional conditions observed. In joining the 90° elbow to the 45° elbow, a short spool piece had been inserted. The welds on both ends of this spool piece were found to contain cracks (see Figures III-10 and III-11). It was later confirmed that this piece was Inconel rather than Type 304 stainless steel. The second condition is a patch of rust, shown by an arrow on Figure III-9, which is evidence that there may have been a water pocket at this location despite the drainage holes provided.

C. METALLOGRAPHIC EXAMINATION

Because of the pattern of observed defects, the metallographic examination is most usefully divided into the following general categories:

1. High carbon stainless steel elbows
2. Low carbon stainless steel elbows
3. Stainless steel outer pipe
4. Stainless steel liner and liner elbows
5. Welds

Table III-1 shows a breakdown of the total number of metallographic sections examined during the investigation.

Table III-1. NUMBER OF METALLOGRAPHIC SECTIONS
EXAMINED BY SwRI

Material Type	Preheater Assembly Number			
	No. 12 Return	No. 17 Supply	No. 10 Supply	No. 10 Return
High Carbon Elbow	7	4	9	3
Low Carbon Elbow	3	0	0	3
Pipe	11	6	10	8
Liner	9	3	10	7
Welds	15	4	16	12

1. High Carbon Elbows

The two failed elbows were examined metallographically to determine the nature of the failure. Early in the course of the examination, it was determined that the material could not be Type 304L stainless steel, as specified, since there was severe sensitization due to intergranular carbide precipitation. This assumption was confirmed by the ORNL chemical analysis, which

indicated carbon contents of 0.09 to 0.13 percent in five out of a total of 30 elbows analyzed. Since such carbon contents greatly exceed the specified limit of 0.035 percent for Type 304L and are even beyond the 0.08 percent limit for Type 304, it was concluded that the elbows were fabricated from Type 302 stainless steel.

A cross section through the crack in the failed elbow from No. 12 return is shown on Figure III-12. The crack is located approximately $1/8$ inch from the weld. Metallographic examination showed that the cracking was intergranular, as illustrated on Figures III-13 and III-14. Etching revealed severe sensitization in the elbow adjacent to the weld. The degree of sensitization and the width of the sensitized area varied considerably around the circumference. At one point the width of the band was approximately 1 inch from the weld fusion zone.

A cross section through the other crack in the failed elbow from No. 17 supply showed that it had essentially the same structure; see Figures III-15 and III-16. The cracking in this case exhibited considerably more branching and initiated at the inside surface of the pipe. In the center of the No. 17 elbow, the microstructure was not sensitized; see Figure III-17. Heat treating at 1250°F for one hour produced the structure shown on Figure III-18 which is indicative of severe sensitization. A half section of the failed elbow in No. 17 supply was metallographically examined by Combustion Engineering. The results of their examinations (Section IV) showed substantial agreement on the finding of intergranular cracking and sensitization of the elbow material.

One other crack was observed in the No. 12 return elbow during the metallographic examination; see Figures III-19 and III-20. The crack is transgranular, approximately 0.005 inch deep and occurred in a sensitized area.

A detailed study of the other high carbon elbows from No. 10 supply and return was not made.

In summary, the examination of the elbows indicated severe intergranular cracking in the sensitized area adjacent to the welds of two elbows of the five high carbon elbows examined. The width of the band suggested that the elbows may have been heated after solution annealing on the ends to effect a rounding operation. The presence of a transgranular crack in a sensitized area indicates that either mode of cracking may be experienced, depending on the specific conditions.

A brief study was made on the failed elbow from No. 17 supply to determine the possibility of intergranular attack due to pickling procedures. The investigation confirmed that the sensitized elbow material would be attacked by a nitric hydrofluoric acid pickling bath at 140°F for 30 minutes. The depth of attack was 3 - 4 grains. See Figures III-21 and III-22. It is not likely, however, that this mechanism was involved in the observed cracking.

2. Low Carbon Elbows

Two 45° elbows in the pipes examined at SwRI were analyzed as Type 304L. They were part of No. 10 return and No. 12 return. No cracking was observed in these elbows.

3. Type 304 Pipe

Thirty-five metallographic samples were taken of the Type 304 pipe material in the straight sections. In these samples only one stress corrosion crack was observed; see Figure III-23. The limited occurrence and the extremely short length and shallow depth of the crack make it difficult to judge statistical distribution. The crack was on the inside surface of the No. 10 supply pipe and located more than 0.5 inch from the nearest weld. There was no obvious point of stress concentration. The nature of the crack was similar to cracks observed by ORNL in their examination.

The Type 304 material was partially sensitized adjacent to welds but relatively free away from the welded joint, as illustrated by the structure in Figure III-24. Even after a 1250°F treatment, the structure exhibits only limited carbide precipitation; see Figure III-25.

4. Liners

Since during reactor operation the temperature level of the liners exceeds that of the outer pipe, their condition was given much attention in the examination. Again, as for the Type 304 pipe material, only one transgranular crack could be found. The crack was in the outside surface of the liner from No. 10 return, as shown on Figure III-26.

5. Welds

The welds in this system were difficult to manufacture because of the geometry involved; hence the presence of defects was not altogether unexpected. The types of defects observed may be separated into two broad classes, i.e., lack of penetration and hot cracking. The first type is illustrated in Figure III-27. Failure of the welder to fuse into the back-up ring left a sizeable mechanical notch. See also Figure III-29. Short hot cracks proceeded from some of these notches, as shown in Figure III-28. There was no evidence of a propagation of these defects as the result of service, except on the high carbon elbow side of the joint, where CEND observed propagation due to stress corrosion cracking.

The hot cracking observed in two welds on the No. 10 return pipe joining Inconel to stainless steel can be explained by the chemistry of the weld deposit. These cracks, shown in Figures III-10 and III-11, are caused by liquation effects at the dendrite boundaries near the solidus temperature. The largest was approximately 0.045 inch in depth from the outside surface, or 1/3 of the thickness. The highly austenitic structure which is formed by

mixing Type 308L stainless steel and Inconel is quite susceptible to hot cracking.

The Inconel spool piece was thoroughly examined and no evidence of cracking or corrosion was observed outside of the weld metal.

D. CONCLUSIONS

The following conclusions can be drawn from the investigation:

1. The failures in the 90° elbows from Nos. 12 return and 17 supply pipes are the result of intergranular stress corrosion. They were accelerated by the extreme sensitization caused by the high carbon content of the elbows. The elbow material in question was out of specification for Type 304 stainless steel and typical of Type 302 stainless steel.
2. There were small transgranular stress corrosion cracks in the nonsensitized Type 304 material. These were found in the straight pipes and the liners. Although the number of cracks was relatively small, their presence confirms the assumption that the environmental conditions are such that stress corrosion cracking can occur.
3. The Inconel spool piece examined showed no evidence of stress corrosion; however, the amount of surface area involved is a poor statistical sample. Nevertheless, the high nickel alloy is usually considered superior to the 300 series stainless steels in environments promoting stress corrosion cracking.
4. Interdentritic welding defects (hot tears) were found on the inside and outside surfaces of the circumferential welds of the

preheater pipes examined. No evidence of in-service propagation of these defects was found.

5. There were many observed welding deficiencies consisting of cracks, voids, incomplete penetration, poor fit-up, etc. Some were the result of the design and the selection of the method of installation of the back-up ring, while others were the result of poor control of fabricating practices and improper materials. None of these deficiencies, however, contributed to the observed failures.
6. The probability of additional failures is high, although it cannot be statistically established because the nature of the corrodent is not known. These general observations can be made:

One incident occurred where water containing chlorides was introduced into the reactor.

The boiling water reactor environment characteristically contains high oxygen.

The stainless steel piping was not stress-relieved after manufacture; hence yield level residual stresses are present.

In the superheater, conditions of alternate wetting and drying occurred due to the scram history of the unit in the early operating period.

The 300 series stainless steels are susceptible to stress corrosion cracking under the above conditions.

Even if additional chlorides are not introduced into the system, it is possible that cracking will continue, although at a decreased rate. If the unit can be operated at temperatures which will leave the surfaces dry, the rate of cracking will presumably decrease. The cracks will not progress mechanically in the absence of corrosion since the operating stresses are determined to be low, and in any case, failure will more likely take place at welds which have larger notches and hence higher stresses.

SwRI 3336

Figure III-1. Failed preheater pipes removed from BONUS reactor

SwRI 3270

Figure III-2. Dye penetrant indications of cracks in wrought elbows of failed BONUS preheater pipes

SwRI 3481

Figure III-3. BONUS No. 10 return preheater pipe. The material used for the spool piece joining the 90° and 45° elbows was Inconel

SwRI 3480

Figure III-4. BONUS No. 10 supply preheater pipe. Drillings from shallow holes in elbows were analyzed at ORNL for carbon content of elbow material

SwRI 3271

Figure III-5. Fluorescent penetrant indication of crack in elbow of BONUS No. 12 return preheater pipe

SwRI 3269

Figure III-6. Fluorescent penetrant indication of crack in elbow of BONUS No. 17 supply preheater pipe

Sw RI 3264

a) Inside surface

Sw RI 3265

b) Outside surface

Figure III-7. Dye penetrant indications of cracking in failed elbow from No. 12 return preheater pipe

Sw RI 3267

a) Inside surface

Sw RI 3268

b) Outside surface

Figure III-8. Dye penetrant indications of cracking in failed elbow from No. 17 supply preheater pipe

SwRI 3484

Figure III-9. BONUS No. 10 return preheater pipe as sectioned

SwRI 3493

Electrolytic Chromic
Etch

Mag. 75X

Figure III - 10. Liquation cracking on outer diameter of 90° elbow to Inconel make - up piece weld on No. 10 return pre - heater pipe

SwRI 3494

Electrolytic Chromic
Etch

Mag. 50X

Figure III - 11. Liquation cracking on outer diameter of 45° elbow to Inconel make - up piece weld on No. 10 return pre - heater pipe

Figure III-12. Cross section of failed elbow from BONUS No. 12 return preheater pipe. Cracks initiated at the inside surface and propagated to the outside surface. Note poor fit-up of elbow and liner to ring

Figure III-13. Intergranular cracking propagating from the inside surface of failed elbow from No. 12 return preheater pipe

SwRI 3306

Unetched

Mag. 500X

Figure III - 14. Photomicrograph of cracked area of elbow from BONUS No. 12 return preheater pipe showing intergranular cracking and grain boundary precipitates

Figure III-15. Cross section of failed elbow from BONUS No. 17 supply preheater pipe. Cracks initiated at the inside surface of elbow and propagated intergranularly. Note the three distinct areas of cracking

Figure III-16. Intergranular attack on inside surface of failed elbow from No. 17 supply preheater pipe. This location corresponds to area #1 of Figure III-15. Cracks in this region propagated to the outside surface of the elbow

SwRI 3323

ID

Aqua Regia Etch

Mag. 100X

Figure III-17. Structure of failed wrought elbow from BONUS No. 17 supply pre-heater pipe. Specimen removed from center of outside bend of elbow equidistant to the welded ends of the elbow

SwRI 3325

Aqua Regia Etch

Mag. 100X

Figure III-18. Structure of wrought elbow from BONUS No. 17 supply pre-heater pipe after sensitization at 1250° F for one hour

SwRI 3338

ID

Unetched

Mag. 500X

Figure III-19. Transgranular cracking in a sensitized area of the 90° elbow of No. 12 return preheater pipe

SwRI 3339

ID

Aqua Regia Etch

Mag. 500X

Figure III-20. Same area as shown in Figure III-19 but etched to show the transgranular nature of the crack

SwRI 3331

Unetched

Mag. 100X

Figure III-21. Outside surface of specimen from elbow of preheater pipe No. 17 supply after pickling in an HNO_3 - HF solution

SwRI 3332

Unetched

Mag. 100X

Figure III-22. Inside surface of specimen from elbow of preheater pipe No. 17 supply after pickling in an HNO_3 - HF solution

Sw RI 3505

Electrolytic Chromic
Etch

Mag. 750X

Figure III-23. Transverse cracking initiating on the inside surface of the Type 304 preheater pipe, No. 10 supply

Figure III - 24. Structure of heat affected zone in Type 304 pipe. Specimen from a location directly across the weld from the cracked region of the wrought elbow of No. 12 return preheater pipe

Figure III - 25. Structure of Type 304 preheater pipe from BONUS No. 12 return after a sensitizing heat treatment of one hour at 1250°F

SwRI 3504

Electrolytic Chromic
Etch

Mag. 500X

Figure III-26. Transgranular cracking on the outer diameter of liner make-up piece of No. 10 return preheater pipe

Mag. 11X

Figure III-27. Cross section of a preheater pipe circumferential weld in which the backup ring was not completely fused

Figure III-28. Typical example of hot tearing resulting from a poor root condition

Figure III-29. Photomicrograph showing groove in the back-up ring that was not fused during welding on No. 10 supply

IV. CEND METALLOGRAPHIC EXAMINATION OF FAILED ELBOW FROM NO. 17 SUPPLY BONUS STEAM DRYER PREHEATER PIPING

A. INTRODUCTION

In addition to the investigations of the dryer preheater piping material conducted by ORNL and SwRI, Combustion Engineering Nuclear Laboratories made an analysis of a half section of elbow No. 17 to determine the cause and nature of the defect.

B. METALLOGRAPHIC EXAMINATIONS

A view of the as-received section of elbow No. 17 is shown on Figure IV-1. The cut surfaces at one end of the elbow section were lightly polished and etched to reveal the cracks indicated by arrows A and B on the figure. Both dye penetrant and visual (to 40 magnification) inspections disclosed indications of cracks on the outer diameter of the inner bent portion of the elbow. The specimens identified numerically on Figure IV-1 were removed from seven locations for metallographic examination.

Transverse sections through the weld at one end of the elbow at locations 4, 1 and 7 are shown on Figures IV-2, IV-3, and IV-4. Intergranular cracks were present at similar locations, 180° apart, in the base metal of the elbows immediately adjacent to the weld of specimens No. 4 and 1, as indicated by arrows on Figures IV-2 and IV-3. Additional intergranular failures in the elbow had occurred to a shallow depth on the inner diameter (indicated by a bracket on Figure IV-2) and as an extensive pattern of cracks from the outer diameter, as evident on Figure IV-3. Indentations on the inner diameter of the elbow, to the left of the cracks on Figures IV-2 and IV-3, are saw cuts from sectioning of the thermal sleeve from the elbow. Specimen No. 7,

located 90° from specimens Nos. 4 and 1, did not exhibit defects; see Figure IV-4. A transverse section through the weld at the opposite end of the elbow (specimen No. 3) likewise did not reveal any defects; see Figure IV-5.

A higher magnification of the intergranular crack in specimen No. 4 is shown on Figure IV-6. The failure appears to have initiated at a shallow separation between the weld and elbow at the inner diameter (arrow on Figure IV-6) and progressed intergranularly within the heat-affected zone of the elbow base metal. Further crack propagation was halted by the widened portion of the weld crown at the outer diameter. The base metal of the elbow was uniformly sensitized (carbide precipitation at the grain boundaries) over a considerable distance from the weld. Intermittent oxidation within the crack indicated that the elbow had been exposed to relatively high temperatures following failure; see Figures IV-7 and IV-8.

The similar crack in specimen No. 1 had originated at a crevice region at the weld and extended through the sensitized heat affected zone of the elbow as shown on Figure IV-9. The weld crown prevented complete propagation of the crack through the wall of the elbow. The base metal of the elbow was highly sensitized by grain boundary carbide precipitation.

The typically intergranular nature of failures in the base metal at both the inner diameter (specimen No. 4) and outer diameter (specimen No. 1) of the elbow is shown on Figure IV-10. The more extensive failure at the outer diameter was accompanied by intergranular cracks visible even in the low magnification view of Figure IV-3. These cracks were detected by dye penetrant inspections. The failures were in highly sensitized areas.

The pipe material on the opposite side of the weld of specimen No. 4 was typical of a solution annealed austenitic stainless steel; see Figure IV-11.

As can be seen on Figures IV-12 and IV-13, the structure was transformed from a solution annealed to a sensitized structure at a location approximately 1/4 inch from the weld. Intergranular failures were not observed in the base metal of the piping material. In view of the close resemblance of the notch-like separations on both sides of the weld apparent on Figure IV-2, it is noteworthy that crack propagation had not occurred in the nonsensitized structure adjacent to the weld. Similar observations apply to two other regions at the welds where no cracks developed from shallow separations in base metal that was also in the nonsensitized condition; refer to Figures IV-4 and IV-5.

Sampling of the midportion of the elbow (specimens Nos. 2, 5, and 6) disclosed solution annealed structures with no evidence of cracks or intergranular attack; Figure IV-14. The spacer at the location of specimen No. 4 was lightly sensitized, while solution annealed structures were observed for the corresponding locations of specimens Nos. 1, 3, and 7. All portions of the thermal sleeve were in the solution annealed condition. The relative degrees of sensitization determined by metallographic examination are shown in the diagram on Figure IV-15.

C. CONCLUSIONS

Metallographic examinations revealed that intergranular failures had occurred within localized, highly sensitized regions of the elbow. Two factors had prominently contributed to the failures; i.e., use of high carbon stainless steel instead of the required Type 304L, and probable localized preheating which had sensitized the solution annealed structure. The preheating was probably conducted on the base metal prior to welding, as indicated by the presence of sensitized structures immediately adjacent to the weld deposit. The increase in grain size in the sensitized region (compare Figures IV-10 and IV-14) suggests that the elbow was probably heated locally to temperatures of 1400 to 1600°F.

Figure IV - 1. View of as-received evaluation sample, No. 17 supply

Etched

Mag. 4.5X

Figure IV-2. Transverse section, specimen No. 4

Etched

Mag. 4.5X

Figure IV-3. Transverse section, specimen No. 1

3407

Etched

Mag. 4.5X

Figure IV-4. Transverse section, specimen No. 7

3405

Etched

Mag. 4.5X

Figure IV-5. Transverse section, specimen No. 3

Nos. 3399 to 3402

Mag. 100X

Figure IV-6. Specimen No. 4. Higher magnification of crack shown in Figure IV-2

3392

Unetched

Mag. 350X

Figure IV-7. Specimen No. 4. Oxidation of portion of crack shown in Figure IV-6.

3397

Etched

Mag. 350X

Figure IV-8. Specimen No. 4. Same view as Figure IV-7 following etching to show location of crack

Etched

Mag. 50X

Figure IV-9. Specimen No. 1. Higher magnification of crack shown in Figure IV-3

Etched

Mag. 350X

Figure IV - 10. Intergranular failure in base metal of elbow

3403

Etched

Mag. 350X

Figure IV - 11. Specimen No. 4. Closeup of Pipe Weld
on Figure IV - 2

3410

Etched

Mag. 100X

Figure IV - 12. Microstructure of piping material near failed end of elbow

3408

Etched

Mag. 350X

Figure IV - 13. Sensitized structure of piping material

3409

Etched

Mag. 350X

Figure IV-14. Solution annealed structure typical of middle portion of elbow

Figure IV - 15. Sensitization distribution within failed elbow No. 17 supply

V. ORNL CHEMICAL ANALYSIS AND METALLOGRAPHIC EXAMINATION OF BONUS DRYER PREHEATER PIPING

A. INTRODUCTION

In support of the investigation by Southwest Research Institute of the failed dryer preheater piping, an examination of four sections of piping from the dryer preheater system was performed at ORNL. The sections of piping removed from the reactor and forwarded to ORNL for examination were Nos. 13 return, 13 supply, 14 return, and 16 return. The examination consisted of ultrasonic inspection of the piping followed by metallographic examination of suspected defect regions and regions that were apparently defect free.

Also, carbon analyses were performed on drillings taken from all elbows in the dryer preheater piping. Chemical analyses were performed on various samples for material identification. In addition, one of the piping sections was checked for possible chloride contamination.

B. CHEMICAL ANALYSES

Drill chips were taken from each of the elbows in the dryer preheater piping in the BONUS pressure vessel and were transferred to ORNL for carbon analysis. The results are given in Table V-1. In addition, more thorough chemical analyses were made of samples from the elbows, pipes, and liners from the Nos. 12 supply and 17 return lines that had been removed from the reactor and transferred to SwRI for examination. The results of these analyses are listed in Table V-2.

A portion of the No. 14 return line was removed from the reactor system after chemical analyses showed one of the elbows to be high in carbon. Subsequently, this portion of piping was likewise forwarded to ORNL for destructive examination. Prior to destructive examination, scrapings for an activation analysis for possible chloride contamination were taken from the inner

surface of the pipe in a region that appeared to bear a water mark. The results of this analysis showed the chloride-ion concentration to be less than $0.3 \mu\text{g}/\text{cm}^2$.

Iron-nickel-chromium chemical analyses were made on the drillings from the 90° elbow at the header in the return line of octant No. 10. Construction records indicated that this particular elbow was of Inconel. The results of the wet-chemical analyses confirmed this (6.22 wt % Fe - 77.2 wt % Ni - 14.8 wt % Cr).

During pressure testing of the dryer preheater piping, a pinhole leak was noted in the No. 13 header close to the orifice plate. The leak was determined to be at a set screw location. The set screw and a portion of the header were removed with a hole saw and transferred to ORNL for material identification. The carbon contents of the set screw and the header were determined to be 0.070 and 0.063 wt %, respectively. Spectrographic analysis showed that both the set screw and pipe were Type 304 stainless steel. Subsequent wet-chemical analyses confirmed these results, which are included in Table V-2.

C. EXAMINATION OF THE PIPING

1. No. 16 Return

An ultrasound indication of a defect in a 90° elbow detected by SWRI personnel at the reactor site was confirmed at ORNL. The affected region can be seen in a section of piping removed from the No. 16 return line and shown on Figure V-1. A longitudinal section was made through the pipe, weldment, and elbow at the location of the suspected defect. Similar sections were made at about 60° and 180° from the suspected defect. Metallographic examination of these three sections showed that the indication of a defect registered during the ultrasound inspections was a result of incomplete fusion of the elbow to the spacer ring. The three sections are shown on Figure V-2. Examination of this weld yielded an example of the inconsistent quality of the welds.

Table V-1. CARBON CONTENT OF DRILLINGS TAKEN FROM VARIOUS ELBOWS IN THE BONUS DRYER PREHEATER PIPING

(wt %)

Function	Location	Octant No.							
		10	11	12	13	14	15	16	17
Supply	90° elbow below connector	0.120*	0.033	0.037	0.037**	0.038	0.034	0.033	0.036
Supply	90° elbow at middle position		0.034	0.037	0.038	0.034	0.036	0.031	0.033
Supply	90° elbow at header	0.105*	0.035	0.035	0.038	0.035	0.032	0.032	0.034
Return	90° elbow below connector	0.126*	0.035	0.131**	0.032**	0.036	0.033	0.033**	0.137**
Return	45° elbow	0.032	0.037	0.037**	0.035**	0.093*	0.036	0.038**	0.035
Return	90° elbow at header	0.038							

* Subsequently removed and replaced with Type 304L stainless steel

** Removed because of either visual evidence or ultrasound indications of defects. Replaced with Type 304L stainless steel components

Table V-2. CHEMICAL COMPOSITION OF SAMPLES TAKEN FROM THE DRYER PREHEATER
PIPING OF THE BONUS REACTOR

Sample	Chemical Composition (wt %)								
	C	Cr	Ni	Fe	Mn	Si	S	Cu	Mo
No. 12 Supply									
45° elbow	0.037	18.8	9.83	69.3	1.80	0.47	0.019	0.11	
90° elbow	0.131	18.1	8.62	71.0	0.90	0.55	0.004	0.26	
Pipe	0.076	18.7	9.35	71.0	1.71	0.38	0.011	0.30	
Liner	0.056	18.4	9.33	68.3	1.47	0.34	0.008	0.13	
No. 17 Return									
90° elbow	0.137	18.2	8.43	71.2	0.93	0.54	0.003	0.27	
Pipe	0.076	18.3	8.91	68.3	1.67	0.38	0.010	0.29	
Liner	0.048	18.8	9.03	69.4	1.81	0.29	0.008	0.20	
No. 13 Header	0.063	18.0	10.09	69.8	1.73	*	0.012	0.11	0.203
No. 13 Set Screw	0.070	18.3	9.32	70.9	0.88	*	0.006	0.24	0.245

* Insufficient sample.

Additional random sections were made through all the welds and other portions of the piping assembly and examined metallographically. Two short transgranular cracks, about 6 and 9 mils deep, were found in the inner surface of the short section of pipe between the 45 and 90° elbows of No. 16 return. Both cracks, shown on Figures V-3 and V-4, were located near the pipe-to-45° elbow weldment. No additional cracks or defects were noted in the other sections examined. The inner surfaces of the elbows were pitted intergranularly to a maximum depth of about 1 mil. Typical inner surface regions of an elbow and a liner from No. 16 return are shown on Figure V-5. As can be seen, none of the specimens of pipe, elbow, or liner from No. 16 return showed any evidence of excessive carbides in the grain boundaries.

2. No. 13 Return

The section of piping removed from the No. 13 return line for examination at ORNL is shown on Figure V-6. The indication of a defect region detected by SwRI personnel at the reactor site with ultrasound equipment was confirmed at ORNL. This region is indicated on the figure; no other regions were found that gave indications of defects. Metallographic examination of sections made through the suspected defect region and three other sections through the same weldment yielded results similar to the suspected defect region in No. 16 return, that is, the defect indication was due to incomplete fusion of the pipe to the weld metal. Additional random sections were taken from each of the weld regions and examined metallographically. No unusual microstructural features were noted.

3. No. 13 Supply

The section of piping removed from the No. 13 supply line is shown on Figure V-7. An indication of a defect in this portion of piping was detected by SwRI personnel at the reactor site during ultrasonic inspection. The suspected defect was located in the piping adjacent to the flange-to-pipe weld; see the arrow on Figure V-7. The defect indication in this region was confirmed at ORNL; no other indications of defects were noted. Metallographic

examination of a longitudinal section taken from the suspected defect region disclosed the presence of an intergranular crack that originated at the inner surface of the pipe. Successive regrinding and repolishing showed that the crack was about 1/4 inch long and extended into the pipe to a maximum depth of 90 mils. The appearance of the crack and its location relative to the weld is shown on Figure V-8. Subsequent analysis of the pipe showed the carbon content to be 0.067 wt %.

Additional specimens were randomly sectioned from the 90° elbow and the associated piping and liner. Metallographic examination disclosed no unusual microstructural features.

4. No. 14 Return

The No. 14 return line was removed from the dryer preheater piping after the 45° elbow was found to contain 0.093 wt % C, as shown in Table V-1. The appearance of this portion of piping was similar to that of No. 16 return, shown on Figure V-3. Random sections were taken from both ends of the 90 and 45° elbows, the two pieces of pipe, and the associated liners. Metallographic examination of these sections revealed no unusual microstructural features. There was no evidence of sensitization in the high carbon elbow. However, the difference in the etching rates of the pipe specimens as compared to the 45° elbow specimens indicated that the latter were higher in carbon content.

D. CONCLUSIONS

Four sections of piping from the dryer preheater system of the BONUS reactor were examined for possible defects. Metallographic examination of suspected defect regions confirmed the high degree of reliability of the in-reactor ultrasonic inspection performed by SwRI personnel. All defects detected by SwRI personnel were confirmed by ultrasonic inspection by ORNL personnel under laboratory conditions. Two of the defect indications were the result of incomplete

fusion of the weldments, while a third was caused by the presence of a circumferential crack about 1/4 inch long and 90 mils deep. The only metallographically determined defects that had escaped ultrasonic detection were two microscopic cracks, one 9 mils deep and one 6 mils deep. The 90 mil crack was completely intergranular in nature, whereas both the 6 mil and 9 mil cracks were transgranular.

Carbon analyses of drillings taken from all 40 elbows in the dryer preheater piping system revealed that six elbows contained carbon in the range of Type 302 stainless steel (0.15 max) rather than the specified Type 304L stainless steel (0.03 max). Analyses of the setscrew and header samples showed them to be Type 304 stainless steel, as specified. Activation analysis of scrapings from the inner surface of one of the pipes showed the chloride-ion concentration to be less than $0.3 \mu\text{g}/\text{cm}^2$.

There was no evidence of sensitization in any of the specimens examined metallographically at ORNL, including the section of piping from one supply line that contained a 90-mil crack. The carbon content of the section of pipe that contained the crack was normal for Type 304 stainless steel.

approx. 1/2X

Figure V - 1. Appearance of the portion of piping removed from No. 16 return line. The arrow points out a defect indication recorded during ultrasonic inspection

approx. 3X

Figure V-2. Appearance of three longitudinal sections made through an elbow-to-pipe weld and the associated spacer ring and liner from No. 16 return. The upper photograph shows the defect detected in the elbow during the ultrasonic inspection (arrow). The other two photographs show the condition of the same weld at 60° (left) and 180° (right) from the defective region

Glyceria Regia Etch

Mag. 100X

Figure V-3. Appearance of two short transgranular cracks found in the inner surface of short section of piping adjacent to the 45° elbow from No. 16 return. The photograph shows the location of the cracks with respect to the weldment

Aqua Regia Etch

Mag. 250X

Figure V-4. Higher magnification of two transgranular cracks shown in Figure V-3. The top photomicrograph shows the crack closer to the weld

(a) 90° Elbow

R- 25591

(b) Liner
Glyceria Regia Etch

Figure V - 5. Appearance of typical inner surface regions of No. 16 return. The areas shown are typical of solution annealed Type 304 stainless steel

approx. 0.4X

Figure V-6. Appearance of the portion of the piping removed from the No. 13 return line. A defect indication was recorded during ultrasonic inspection of the piping in the region pointed out by the arrow

approx. 0.5X

Figure V-7. Appearance of the portion of the piping removed from the No. 13 supply line. A defect indication was recorded during ultrasonic inspection of the piping in the region pointed out by the arrow

Aqua Regia Etch

Mag. 50X

Figure V-8. Appearance of intergranular crack originating at the inner surface of pipe from No. 13 supply line. The photograph shows the location of the crack with respect to the weld

VI. REPAIR OF THE BONUS DRYER PREHEATER PIPING SYSTEM

A. SITE FABRICATION AND INSTALLATION OF BONUS PREHEATER PIPING REPLACEMENT SECTIONS

1. Introduction

The fabrication and installation of the eight BONUS preheater piping replacement sections were carried out during the period July 5 to July 30, 1965. The Department of Materials Engineering of Southwest Research Institute provided a welding technician and a welding engineer to assist Combustion Engineering and Puerto Rico Water Resources Authority (PRWRA) site personnel. Oak Ridge National Laboratory provided the Type 304L stainless steel components for the replacement piping and sent two welding technicians to the site to assist in the in-reactor welding. Mill test reports of the chemical and physical properties of the replacement material are retained at the BONUS site.

The following preheater pipes were removed from the BONUS dryer preheater system: No. 17 supply, No. 12 return, No. 13 supply, No. 13 return, No. 16 return, No. 10 return, No. 10 supply, and No. 14 return. As discussed previously, No. 17 supply and No. 12 return were the two preheater pipes which failed in service. No. 13 supply was removed because of an ultrasonic defect indication which subsequently proved to be an intergranular crack located adjacent to the connector weld. Ultrasonic testing of No. 16 return and No. 13 return likewise indicated defects, but metallographic investigations revealed these indications to be due to lack of fusion rather than cracking. ORNL, however, found two small transgranular cracks in No. 16 return which had not been detected ultrasonically. No. 10 return and No. 10 supply preheater pipes were removed on the basis of the high carbon content of the 90° elbows.

2. Removal of Defective Preheater Piping

Seven of the eight preheater pipes removed from the BONUS system were cut with a standard pipe cutter. The preheater return pipes were cut close to the header, leaving a 2 inch stub attached to the header. The preheater supply pipes, with the exception of No. 10 supply, were cut in the horizontal run in the nipple below the first 90° elbow. The 90° elbow of No. 10 supply had to be removed from the underside of the header. A fillet weld attaching this elbow to the header was ground off with a small pneumatic grinder.

Figures VI-1 through VI-4 show various views of the stub remaining after No. 12 return preheater pipe was cut and removed from the vessel. These photographs illustrate the limited accessibility of the parts for the cutting operation and the subsequent installation of the replacement pipe section. Figures VI-5 through VI-7 show the location of the cut made to remove No. 17 supply pipe. All supply preheater pipes, except No. 10 supply, were cut at a similar location.

3. Welding Procedure Qualification

The procedure specification for welding the preheater piping, designated as BONUS No. 1, was prepared by the Department of Materials Engineering of Southwest Research Institute. The procedure is essentially the same as PACECO welding procedure WP101 and calls for the use of a backing ring for all circumferential butt joints. The procedure qualification test weldment was prepared at the site and forwarded to SwRI where the tensile and bend tests required for qualification were performed. In accordance with the requirements of Paragraph Q-10b of Section IX of the ASME Boiler and Pressure Vessel Code, qualification of the base metal-filler metal combination of this procedure for butt welds automatically qualified the procedure for the line-to-backing ring fillet welds of the preheater piping.

The in-reactor installation of the No. 10 supply replacement pipe involved a dissimilar fillet weld between the Inconel 600 section of the header and the Type 304L stainless steel replacement pipe. The necessary dissimilar metal welding procedure was qualified at ORNL.

4. Welder Performance Qualification Tests

The limited accessibility of the in-reactor weld spots made it necessary to employ pipe welders who had been qualified beforehand for mirror-welding techniques in the fixed horizontal (5G) position. Figure VI-8 illustrates the limited space available for welding the No. 14 return replacement pipe.

The special requirements set up by SwRI for the welder qualification tests were beyond code requirements and were intended to prove the welder's ability to produce sound welds under the conditions existing within the reactor vessel. It was required that the test pipe weldment be made 28 inches above the floor in the fixed horizontal position with 2.5 inches clearance between a wall and the backside of the pipe. A mirror was used to view the backside of the weld. Figures VI-1 to VI-4 illustrate that these conditions closely simulate the actual space available for making the in-reactor welds of the return preheater pipes.

Two welders of the PRWRA were qualified at the site for welding the stainless steel preheater piping in accordance with the conditions described in the foregoing. The two welders furnished by ORNL were similarly qualified at ORNL and one of them qualified for both the stainless steel and the dissimilar metal welding procedures.

5. Bench Fabrication of Preheater Piping Replacements

Detailed sketches were made of each of the eight preheater piping sections which were to be fabricated at the site. Dimensions were obtained from the sections removed from the reactor whenever possible. The initial step in the fabrication of a replacement pipe was the welding of the lower section of the Marman connector to the vertical section of 1-1/2 inch pipe above the first 90° elbow. (In the following, the 1-1/2 inch pipe and elbows will be referred to as the outside components of the piping.)

The first 90° elbow and the additional outside components, with the exception of the final pipe spool piece to be welded to the stub in the reactor vessel, were machined to the dimensions indicated in the working sketches prepared at the site. The connector and the other outside components were then assembled, without tacking, for a trial fitup within the reactor vessel. In carrying out these trial fitups, it was found that proper gasket placement had to be assured before the Marman connector joint was torqued to the prescribed 15 ft-lb level. Failure to seat the two mating parts of the Marman connector could introduce an error of up to 1/8 inch into the indicated vertical length of the replacement pipes which would have to be corrected before the final in-reactor weld joint could be fitted up for welding.

Once the trial fitups indicated that the vertical and horizontal runs of the replacement pipe had the proper length and orientation, the outside components were temporarily tack welded together. The next steps were intended to control the amount of anticipated shrinkage during the completion of each of the circumferential welds. Three lines were scribed across each of the tacked joints of the outside components at 120° intervals. Every line was

identified and punch-marked at intervals of roughly 1 inch across the joint. The distance between punch marks was then measured with Vernier calipers. When the as-tacked dimensions had been recorded, the tacks were broken and the outside components separated. The liners for each component were cut to the proper length, welded to the backup ring and inserted in the outside components, which were then reassembled. The three scribed lines were used as guides to obtain proper alignment.

In order to compensate for shrinkage, each of the circumferential joints was opened up to increase the width across the punch marks by 80 mils over the as-tacked dimensions. This 80 mil shrinkage factor had been obtained by welding a number of trial joints and measuring shrinkage. A dimensional check across the joint was carried out after completion of the root pass, the first filler pass, and the final weld pass. In most instances, it was found that by application of the shrinkage factor, the as-tacked dimensions across a joint could be reproduced in the final weldment to within 10 to 15 mils.

Upon completion of the intermediate bench welding operation, the semi-completed replacement pipe was installed in the reactor with the Marman connector properly torqued down, and the final dimensions of the spool piece which would join the preheater pipe to the stub were obtained. The spool piece was then welded to the replacement pipe to complete bench fabrication.

B. IN-REACTOR WELDING OPERATIONS

Figure VI-9 shows the area within the BONUS reactor vessel in which the preheater piping fitup and replacement operations were carried out. Every effort was made by CEND site personnel to facilitate the in-reactor welding from the standpoint of safety and physical comfort of the craftsmen involved. Two large air conditioning units were installed above the reactor vessel and ducts were fabricated from polyethylene sheet to introduce cool air into the vessel. The air conditioning units and ducts are shown on Figure VI-10.

Contamination of the welders and other mechanics working within the vessel was minimized by covering all of the superheater piping and headers with polyethylene sheet, as shown on Figure VI-11. This plastic sheeting also prevented objects accidentally dropped by workmen from falling to the bottom of the reactor. Strict control of all objects and tools lowered into the working area was exercised. Nylon lanyards similar to those shown on Figure VI-14 were attached to all objects and tools before they were lowered to the working area within the reactor vessel. The end of these lanyards contained a loop which could either be tied to the workman's wrist or secured to some fixed object adjacent to the working area.

The in-reactor welds of the eight replacement preheater pipes were made by teams of two welders. The cramped position of the welder manipulating the welding torch made it impossible for him to operate the remote amperage control switch. As shown on Figure VI-12, the second welder operated the remote amperage control switch and increased or decreased the welding amperage as instructed by the torch operator. The welders working within the vessel were rotated as often as possible to minimize fatigue and exposure to radiation. The exposure received by the welders and mechanic during each entry into the vessel was monitored, and health physics personnel maintained an up-to-date record of the total exposure received by each welder during the entire operation. The 300 mr weekly exposure level imposed on site personnel by the health physics department was not exceeded by any of the welders nor did it affect their availability for in-vessel work.

The replacement of the No. 10 supply preheater pipe presented the most difficult problems of fitup and preparation of the header for welding. As the 90° elbow welded to the underside of the No. 10A small superheated steam header, Figure VI-13, was found to contain high carbon, it was necessary to remove the elbow and all traces of the elbow-to-header weld metal. Removal was carried out by grinding, and precautions were taken to collect all grinding dust so as to minimize contamination of the mechanics performing the grinding and to keep the reactor as clean as possible. The final operation in installing the No. 10 supply preheater pipe consisted of welding the saddle stub shown on Figure VI-14 to the underside of the header. The inside of the header was purged with argon to prevent oxidation of the root of this fillet weld, which was made using Inco 82 filler metal, since an Inconel section of the header was within the area of the weld. Figures VI-15 and VI-16 show one of the ORNL welders, who had qualified beforehand for making Inconel-to-stainless steel dissimilar welds, in position to make this weld.

C. REPAIR OF PINHOLE IN NO. 13 HEADER

A pinhole leak had been discovered in the No. 13 header during the air leakage test which revealed the cracks in No. 12 return and No. 17 supply preheater pipes. An overall view of the header is shown on Figure VI-17. The location of the pinhole is indicated by the pointer on Figure VI-18.

The area of the pinhole was inspected both ultrasonically and by the dye penetrant technique in an attempt to establish the extent of the defect. Both nondestructive inspections indicated that this was a point-type defect.

The location of the pinhole was found to coincide with the location of one of the three set screws used to center the liner within the header. These set screws were set even with the outside surface of the header, seal welded, and ground smooth. The pinhole coincided with the edge of one of the seal welds.

The defect was repaired by replacing the set screw with a 3/8 inch diameter stainless steel plug that was seal welded to the header. The completed weld was inspected both visually and by the dye penetrant technique.

D. REPAIR OF DRILL HOLES IN PREHEATER PIPING ELBOWS

As described in Section I-C, samples for chemical analysis were obtained from all elbows of the fixed sections of the preheater piping to verify that no other Type 302 stainless steel elbows existed in this part of the system. The samples were obtained by drilling several shallow holes into each elbow.

A welding procedure for repairing the 75 drill holes was qualified by both destructive and nondestructive examination of similar welds. Drill holes identical to the sampling holes made in the BONUS preheater piping elbows were drilled into a spare Type 304L elbow and were welded at the site using the tungsten inert gas process and Type 308 ELC filler wire. The completed welds were inspected visually and by the dye penetrant technique and found to be free of defects. The elbow was forwarded to SwRI and sectioned for metallographical examination. The welds were examined metallographically at magnification 100 and were found to be free of fissures or other defects.

Prior to welding, the surface of the elbows around the drill holes was filed to remove all traces of oxide. The drill holes were then filled, using the tungsten inert gas process and Type 308 ELC filler metal. All of the completed drill hole welds were inspected both visually and by the dye penetrant technique and were found to be free of defects.

E. QUALITY CONTROL OF BONUS PREHEATER PIPING WELDING

The procedure specification for welding the preheater piping, designated as BONUS No. 1, required that the root pass and the completed circumferential welds be inspected both visually and by the dye penetrant technique. The overall inspection included assurance that proper material control and cleanliness of the components was maintained, that fitups were in conformance with the welding

procedure, that the interpass temperature required by the welding procedure was observed, that all visual and dye penetrant tests were carried out as specified, and that the final fitup of the pipe sections within the reactor vessel minimized misalignment upon completion of weldment. Inspection record sheets were made up for each section of preheater piping. A schematic of each of the preheater piping sections fabricated at the site is shown on Figure VI-19.

Figure VI-1. Top view of BONUS preheater return pipe No. 12 after cutting. Accessibility for welding indicated by yardstick

Figure VI-2. Oblique view of BONUS preheater return pipe No. 12 after cutting

Figure VI-3. Horizontal view of BONUS preheater return pipe No. 12 after cutting

Figure VI-4. Horizontal view of BONUS preheater return pipe No. 12 after cutting

Figure VI-5. Top view of BONUS preheater supply pipe No. 17 after cutting. Accessibility for welding indicated by yardstick

Figure VI-6. Oblique view of BONUS preheater supply pipe No. 17 after cutting

Figure VI-7. Horizontal view of BONUS preheater supply pipe No. 17 after cutting

Figure VI-8. Limited access available for making the No. 14 return in-reactor weld

Figure VI-9. Top view of area within BONUS reactor vessel where preheater piping replacement operation was carried out

Figure VI-10. Air conditioning units and ducting installed above the BONUS reactor vessel

Figure VI-11. Polyethylene sheet used to minimize personnel contact with super-heater headers and connectors

Figure VI-12. Typical two-man welding operation during installation of the BONUS preheater replacement pipes. The man on the right is operating the remote foot control pedal for the welder shown at the left

Figure VI-13. Number 10A superheater outlet nozzle with No. 10 return preheater pipe already welded in place. No. 10 supply preheater pipe was welded to the underside of this nozzle

Figure VI-14. Completed Type 304L replacement preheater pipes ready for installation in the BONUS preheater system

Figure VI-15. Welder in position for welding back side of No. 10 supply pipe fillet weld

Figure VI-16. Welder preparing to weld the front side of No. 10 supply fillet weld. Note purging arrangement

Figure VI-17. Top view showing location of pinhole in BONUS header No. 13. Accessibility for welding is indicated by yardstick

Figure VI-18. Pointer indicating location of pinhole in BONUS header No. 13

Figure VI-19. Schematic of replacement piping sections for the BONUS preheater

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