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PM-2A REACTOR VESSEL TEST PROGRAM
FINAL REPORT

D.R. Mousseau, J.C. Pruden

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

IDAHO NUCLEAR CORPORATION
NATIONAL REACTOR TESTING STATION
IDAHO FALLS, IDAHO

U. S. ATOMIC ENERGY COMMISSION

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PM-2A REACTOR VESSEL TEST PROGRAM

FINAL REPORT

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A JOINTLY OWNED SUBSIDIARY OF
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ABSTRACT

The testing of the PM-2A Reactor Vessel was completed on November 18, 1966 following the deliberate brittle fracturing of the pressure vessel. Vessel failure occurred at 4475 psig and -20°F with a 1.75 inch deep by 11 inch long defect intentionally installed in the most highly irradiated portion of the vessel wall. The test was designed to study the brittle fracture characteristics of an irradiated pressure vessel and was completed in two phases. The first phase provided non-destructive data required for development of a test plan while the second phase consisted of testing to achieve brittle failure. This report summarizes the activities involved in the non-destructive testing, loop design, detector selection and application. The pressure testing phase is discussed in detail and data obtained during the final tests are presented.

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I. INTRODUCTION

A. PURPOSE

This report summarizes activities performed by Idaho Nuclear Corporation in fulfillment of Subcontract 73-14-1220 with the Bettis Atomic Power Laboratory to provide various services and to conduct a series of tests terminating in a brittle fracture of the PM-2A Vessel.^(1,2) All test activities described herein were performed in the Test Area North Building 607 Hot Cell at the U.S. Atomic Energy Commission's National Reactor Testing Station near Idaho Falls, Idaho.

The test was designed to study the brittle fracture characteristics of an irradiated reactor vessel and to obtain data that would provide a correlation between these characteristics and the predicted characteristics based on tests of conventional irradiated laboratory test specimens.

The work, as performed, was in three categories; disassembly of the reactor vessel skid; non-destructive testing of the vessel; and pressure testing of the vessel resulting in a brittle failure.

B. PAST HISTORY OF REACTOR

The PM-2A was the first nuclear power plant to use a modular package concept designed for air shipment and rapid installation at a remote location. The system was designed by the Army Corps of Engineers and built by ALCO Products Inc. of Schenectady, New York, in 1959 and early 1960. The design and fabrication was in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, 1956 Edition, Code Case 1234.⁽³⁾ The pressure vessel (Figure 1-1) is a cylindrical, stainless steel clad vessel of welded construction. A hemispherical head seals the bottom and a removable semi-elliptical top closure provides access to the interior. The removable head is secured by 18 studs and nuts and sealed by an octagonal, stainless steel ring gasket. The shell has penetrations for two 9 inch ID primary coolant nozzles, five 3 inch OD control rod drive nozzles, and a 1-1/4 inch decay heat removal line. The bottom head has one 1-1/4 inch penetration at the centerline for blowdown, draining, and the decay heat removal system return. Overall height of the vessel is approximately 10 feet 3 inches and the nominal ID is 37-1/2 inches. The cylindrical shell is fabricated from ring forgings of SA-350 gr. LF-3

carbon steel with a base metal wall thickness of 2-3/8 inches. The internal weld deposited clad is type 304 stainless steel with a minimum thickness of 3/16 inches.

The plant was designed as a pressurized-water type reactor operating at 1750 psig and 518°F with a rated reactor power of 10 megawatt (thermal) while producing a combined minimum net output of 1570 KW (electrical and one million BTU/hr of process heat in the form of 150 psig steam. In the spring of 1960, the entire plant was factory assembled, tested and disassembled before being shipped and installed as skid-mounted packages at Camp Century, the U.S. Army's under-ice research station in Greenland. From installation until shut-down in July, 1963, the plant supplied power, heat, and water for the entire Camp Century complex.

Disassembly and relocation efforts at Camp Century began in early 1964. After packaging and crating, the entire system was shipped from Greenland to the National Reactor Testing Station at Idaho Falls, Idaho, and was received there in October of 1964.⁽⁴⁾

II. REACTOR VESSEL DISASSEMBLY

A. DESCRIPTION OF DISASSEMBLY

As received at NRTS the reactor vessel skid contained the reactor vessel surrounded by the primary shield tank and shield rings, and five control rod drive assemblies. The top opening of the vessel was covered by a lead plug and temporary shielding brick. Attached to the top and sides of the shield tank was additional lead sheet and lead brick overlaid by wooden beams. Internally the reactor vessel contained the coolant flow helix and the core support structure, which consisted of the upper and lower grid plates, spacers, and baffles.

The reactor vessel skid was moved into the TAN 607 High Bay on November 23, 1964 (Figure 2-1). A radiation survey revealed a maximum field of 250 mR/hr around the skid. All crating, temporary transportation shielding fastened to the sides of the shield tank and most of the miscellaneous equipment mounted on the vessel skid was removed. The greater portion of this work was done using hand tools and direct-contact maintenance methods. Removal of the shielding increased the radiation level on the side of the shield tank to 1.3 R/hr at several locations. No surface contamination was detected.

Figure 2-2 indicates the results of a radiation survey made around the reactor vessel skid on November 25, 1964, after the transportation shielding was removed.

A broken stud was found in the vessel closure flange after removal of temporary shielding brick covering the top of the vessel. This stud was removed by manually welding a hexagonal extension to the exposed top of the stud and then extracting it with a large motor driven impact wrench.

The vessel closure head was received separately from the reactor vessel and as received was highly contaminated with Co^{60} and Mn^{54} activity. The head was successfully decontaminated using a four step process. The initial effort consisted of immersing the head in a tank of demineralized water, heated to 180-200°F, and wire brushing. Second, the head was immersed in a tank of 5% nitric acid for 10 minutes followed by a demineralized water rinse at 100°F and wire brushing. The third step was a two stage process in which alkaline permanganate and ammonium citrate solutions were used. The head was initially immersed in a tank of demineralized water heated to 180-200°F containing 12 gm/l of sodium hydroxide and 24 gm/l of potassium permanganate for four hours during which time the solution was mildly agitated. This was followed by immersion in a tank of demineralized water heated to 180-200°F containing 24 gm/l of ammonium citrate for two hours during which time the solution was again mildly agitated. This process was repeated three times. Residual surface contamination was removed by washing the head with Stoddard Solvent. Results of the decontamination work are summarized in Table I, Appendix A.

The vessel skid was transferred to the TAN Hot Shop for final disassembly on December 29, 1964. Most of the disassembly work performed from this point on was done by remote operation because of the high radiation fields involved.

A complete description of the TAN Hot Shop and contained equipment, most of which was used during the disassembly, is given in the Phillips Petroleum Co. report; "TAN Hot Shop and Satellite Facilities."⁽⁵⁾

The first items removed from the reactor vessel in the Hot Shop were the five control rod drive assemblies followed by the steel cover plate for the shield tank. Next were the eight cap screws which held

the core support structure to the bottom support ring plate. The core support structure was removed as a single unit and placed in storage (Figure 2-3). This cleared the reactor's internal barrel with the exception of the flow helix and bottom support ring plate.

The removal of the helix and support ring was accomplished by the use of manipulator-held impact-wrenches and air driven abrasive cutting disks. Because the work was on the inside of the vessel, it was necessary to view all operations through binoculars and a mirror held over the top opening. The core support ring was sectioned and removed from the vessel on February 8, 1965. Removal of this item completed the stripping of the vessel of all internal components.

In preparation for the non-destructive tests and to reduce radiation levels all accessible interior surfaces of the vessel were wire brushed and washed down with a mild detergent solution. The results of a radiation survey made after the cleaning procedure are shown in Figure 2-4.

Concurrent with the cleaning and decontamination operation, efforts were directed toward the removal of the primary shield tank and the shield rings. Various stages of this phase of the disassembly are illustrated in Figures 2-5, 2-6, 2-7, and 2-8. After the shield tank was completely removed, the vessel was lifted from the skid and a 7 HP air-driven abrasive-wheel was used to cut the stainless steel insulation canopy away from the vessel (Figures 2-9 and 2-10). During the week of August 23, 1965, the last of the insulation was removed from the vessel, thus, completing the disassembly phase of the program.

III. DESTRUCTIVE TEST PREPARATIONS

A. NON-DESTRUCTIVE TESTS

The following non-destructive tests were performed on the vessel to provide information for a detailed stress analysis; identification of any defects introduced into the vessel during fabrication or operation; and to obtain accurate knowledge of the integrated neutron flux actually seen by the vessel wall.

1. Liquid dye penetrant examination.
2. Ultrasonic examination of the vessel body and bottom hemispherical head, the closure area, and the inlet and the outlet nozzles.⁽⁶⁾

3. Dosimetry examination of the core zone. (6)
4. Out-of-roundness examination of the vessel shell.
5. Hardness determination of the outer surface of the vessel shell in the core zone.
6. Dimensional examination of the closure head.

1. Dye Penetrant Examination

- a. Examination Procedure

The Magnaflux Corporation Zyglo method of fluorescent dye penetrant testing was used in PM-2A inner surface examinations. A brief description of the procedure followed is given below.

Vessel surfaces tested were first cleared of contaminants such as scale, grease, oil, dirt, and water. Test areas were then brushed as necessary and scrubbed using a mild detergent solution, followed by a final water rinse. Air was circulated in the vessel and all surfaces allowed to dry before penetrant was applied. Type 2L-1C liquid penetrant was sprayed on the dry test areas at room temperature. A period of sixty (60) minutes penetration time was allowed after application during which time ultraviolet light (100 watt lamp) inspection of the surface confirmed that uniform penetrant coverage was obtained. Treated surfaces were then carefully water sprinkle-rinsed and the ultraviolet light was again employed to observe completeness of the rinse.

Type ZP-5 developer, mixed $3/4$ pounds per gallon of water, was sprayed over the test area. The excess developer was allowed to drain away to waste. Two hour developer drying time was required with air circulation at room temperatures. The test area was then darkened and fluorescent reflections from surface defects were observed under the ultraviolet light.

- b. Head and Vessel Examination

The liquid penetrant examination of the PM-2A closure head and vessel was performed using the fluorescent dye testing method. Any defects measuring $3/4$ inch or greater were to be reported. Also any concentration of defects numbering six or more in any $1-1/2$ by 6 inch rectangle or $3-1/4$ inch diameter circle were to be reported.

During examination of the head one linear defect and several weld porosity indications were found on the closure flange but none of reportable size or concentration.

The internal clad surfaces and the closure parting surfaces of the vessel were visually examined with the aid of a manipulator controlled ultraviolet light and mirror. Observations were made from a shielded personnel enclosure equipped with a viewing window and suspended over the vessel from the Hot Shop facilities overhead crane as shown in Figure 3-1. No surface defects of reportable size or concentration were found.

2. Ultrasonic Testing

a. Head Examination

The ultrasonic examination of the PM-2A closure head was performed using a contact 45-degree shear wave technique.⁽⁶⁾ Reference defects of known dimensions were measured and the resulting data used to indicate the test defect measurements. The reference used for head defect measurement comparisons was a 3/16 inch, No. 1 stencil identification stamping (0.020 inch), on the crown of the head. No defect indications were measured on the head surface which exceeded the reference indication. One defect found in the bolt flange cladding (UD) indicated a depth of 1/4 inch based on the extent of the response.

b. Vessel Examination

The ultrasonic examination of the PM-2A Vessel was conducted by filling the vessel with water to act as a coupler between the crystal of the ultrasonic test equipment and the test metal. Four matched test crystal elements of 2-1/2 mc frequency were available and three were used to test scan the vessel. Both radial, longitudinal, and shear wave ultrasonic examinations were conducted. The search crystals were mounted on a fixture (Figure 3-2) located inside the water filled vessel and were rotated twice over the 360-degree circumference of the vessel at 3/4 inch vertical increments. A back reflection signal, a reflected signal from any defect from the longitudinal inspection, a metal-water interface reflection, and a reflected signal from any defect from the shear wave inspection were plotted on continuously recording charts. The ultrasonic scanning unit

assembly is shown in Figure 3-3.

A 2-1/2 inch thick reference block, containing three 1/8 inch diameter flat bottom holes of varying known depth and two slotted defects (1/4 and 1/2 inch long), was used for calibration and comparison with readings from vessel defects.

The entire vessel, with the exception of an inaccessible 9-1/4 inch length of shell in the core support area, was ultrasonically examined. Test equipment was calibrated so that reflecting defects as small as 0.012 square inch could be detected in uniformly clad shell and head metal. Tests produced no reflections of 0.049 square inch area or larger. No radial defects were found deeper than 1/4 inch in either longitudinal or shear wave scannings.⁽⁶⁾

3. Dosimetry

The dosimetry of the PM-2A Vessel was determined by examination with a High Intensity Radiation Survey Probe (HIRSP). The Mn^{54} activity on the vessel wall was measured and from these measurements the integrated fast flux was calculated. Activity measurements at six vessel wall locations were taken and compared to the intensity of a standard specimen of known activity. The resulting comparison ratios were applied to determine dosimetry data over the full length of the vessel. Results compared favorably with dosimetry calculations determined using the multigroup neutron diffusion computer code, P3MG.

Results of the measurements indicated maximum intensity occurred close to the core mid-height plane and the azimuthal gradient was relatively small. The vessel metal at the core mid-plane has received a measured maximum neutron dose of $1.4 \times 10^{19} \text{ n/cm}^2 > 1 \text{ Mev.}$ ⁽⁶⁾

4. Vessel Out-of-Roundness Examinations

Out-of-roundness measurements were made on the vessel interior using the specially designed fixture and recorder assembly shown in Figure 3-4. Measurements were taken from the top flange to four elevations within the vessel, three in the core region and one in the 28 inch diameter closure plane area. Core region measurements taken 12, 24, and 34 inches below the closure flange indicated that the vessel is truly "out-of-round" in this area and has a diameter greater than the nominal 37-1/2 inches. A composite out-of-roundness diagram is shown in Figure 3-5.

The following procedure was used to prepare the device for the test. A diameter of 37-1/2 inches was selected to be the zero or null point for the measuring device as the vessel manufacturer's drawings indicated this was the vessel inside diameter. To set the device at the required diameter it was necessary to measure from the outside edge of the machined base plate back to the stylus tip. As this measurement was made inside the Hot Shop with hand held tools it was estimated the accuracy was $\pm 1/32$ inch relative to the desired diameter. After the stylus was set at the selected diameter the recorder pens were made to indicate zero deflection. The recorder was then calibrated for deviations above or below zero by use of a micrometer attached to the stylus. Reproducibility of any given deviation, using the micrometer, was found to be equal to or less than ± 0.02 inch. Vertical measurements from the top of the vessel closure flange to the various data planes are subject to an error of $\pm 1/8$ inch.

5. Hardness Determination

Hardness determinations were made on the vessel outside surface with a Branson Instrument Co., Sonar model 100 hardness tester, modified for remote operation. Calibration of the instrument was checked after every group of five test points. Four separate hardness readings were obtained at each test point and to assure valid data the test was run twice. The results from the procedure were eight hardness values at each test point. Complete test results are shown in Figure 3-6 and Figure 3-7. The hardness test-probe assembly is shown in Figure 3-8.

The data does not compare favorably with data obtained by the Naval Research Laboratory from irradiated specimens of the sister forging.⁽⁶⁾ This is believed caused by a change in surface condition when the test areas were buffed and ground during preparation for the test. The data were not used to assess PM-2A Reactor Vessel mechanical properties but were used to confirm peak neutron dose location.

6. Head Dimensional Measurements

Dimensions of the PM-2A Reactor head were determined by mounting the head on the rotary table of a jig borer and reading desired measurements from dial indicators. Measurements were estimated to be accurate to ± 0.005 inch (Figure 3-9).

IV. TEST LOOP AND DATA EQUIPMENT

A. TEST LOOP DESIGN

The PM-2A Test Loop was designed from the concept of obtaining maximum flexibility from four separate functions required in an integrated, closed cycle, hydraulic system. Functions required were fluid circulation, heating and cooling of the vessel, and pressurization of the vessel for test purposes. Due to the highly radioactive nature of the vessel, all process functions were monitored and operated remotely from a control panel in the Hot Shop Gallery, adjacent to the Hot Shop, where the loop and vessel were located.

In addition to being designed for the various functions, and remotely controlled, the system was required to meet the following temperature and pressure criteria.⁽⁷⁾

1. Provide for control of the PM-2A Reactor Vessel wall temperature over the range of -20°F to 272°F .
2. Limit the transverse thermal gradient through the vessel wall in the region of the core to $\pm 5^{\circ}\text{F}$.
3. Limit the longitudinal temperature differential from the vessel head to the lower dome to $\pm 50^{\circ}\text{F}$.
4. Limit the longitudinal thermal gradient across the core region to $\pm 10^{\circ}\text{F}$.
5. Provide for a maximum heating rate not to exceed 100°F per hour.
6. Provide for control of the vessel internal pressure whenever the vessel is isolated from the loop, over a range of 0 to 5000 psig at any desired temperature between -20°F and 272°F (Figure 6-2).

The test loop design was premised upon the intention of reducing the vessel pressure between each test temperature. This enabled the process loop to be designed so that commercially available standard equipment could be utilized for heating, cooling, and circulating the test fluid. These components would then be isolated from the vessel for the pressure test and the only high pressure components would be the charging pump and isolation valves.

The IBM 7040 computer, using a unidirectional, transient state, heat transfer computer code (HEAT I), was used to calculate vessel wall temperature gradients as a function of time. This was done to insure that the maximum heating or cooling rate of the designed loop would not cause the thermal gradient criteria to be exceeded.

Thermocouples were provided for temperature control at various points in the loop and on the vessel and were attached at locations designated as TE on Figure 4-1.

B. LOOP DESCRIPTION

The test loop equipment consisted of the PM-2A Reactor Vessel, an oil cooler and refrigeration unit, a resistance heater, a pressurizing pump, circulating pump, temperature and pressure monitoring equipment, loop piping, and fluid transfer and storage facilities (Figure 4-2).

Under normal operating conditions, 100 gpm of hydraulic fluid was circulated through the test loop at pressures up to 200 psig. The fluid was discharged from a rotary gear circulating pump, and flowed through a section of loop piping to a 60 KW immersion type electrical resistance heater. The heater was capable of heating the loop fluid, reactor vessel and component piping from 70°F to 272°F in five hours. Heat input to the system was controlled by means of a saturable core reactor.

Upon leaving the heater, the fluid passed through the shell side of a shell and tube heat exchanger where it was cooled by Freon-22 refrigerant. A single water cooled condenser unit was utilized to supply the necessary cooling capacity for the refrigeration system. Condenser cooling water flow was controlled by a compressor discharge pressure operated regulating valve. The primary refrigeration compressor unit provided the heat removal capacity for cooling the loop fluid, reactor vessel, and component piping from 125°F to 40°F in three hours. The secondary unit supplied the refrigeration capacity for cooling the loop fluid, reactor vessel and component piping from 40°F to -20°F in 13 hours (Figure 4-3).

Upon leaving the heat exchanger the loop fluid flowed through the PM-2A Reactor Vessel where it served as the heat transfer media for heating or cooling the vessel.

A closed, cylindrical filler piece was located concentrically in the reactor vessel for the purpose of providing uniform circumferential fluid flow within the vessel. This arrangement insured equal flow area in the annulus between the vessel and filler piece and hence uniform fluid flow, while essentially doubling the fluid velocity at the internal wall of the test vessel.

The circulating heat transfer fluid entered the bottom of the reactor vessel through the 1-1/4 inch diameter drain nozzle and subsequently flowed through the annulus formed by the filler piece and the vessel wall. The fluid was withdrawn from within the reactor vessel by means of an outlet line that extended from the inside of the head to the 1-1/4 inch decay heat removal nozzle. This internal outlet line was supported by the filler piece within the vessel and was a slip-fit inside the 1-1/4 inch outlet nozzle.

A 3/8 inch diameter tube was extended from the inside surface of the vessel head through one of the 9 inch ID vessel nozzles for the purpose of removing entrapped air and gaseous decomposition products from within the vessel.

Double-block valves were provided at the reactor vessel inlet and outlet lines and on the reactor vent line to allow isolation and pressurization of the reactor vessel at the desired temperature. A 3/8 inch high pressure line and valve, which could be opened by a manipulator, was provided around the main isolation valves in the event of the failure of these valves to open while under pressure. The 9 inch ID nozzles were sealed by means of blind flanges.

After leaving the reactor vessel the fluid flowed through the coils of an air cooled, finned heat exchanger which was capable of cooling the loop fluid, reactor vessel and component piping from 272° to 120°F in six hours.

An 800 gallon storage tank was provided to facilitate the filling and draining of the loop. A strainer was located in the tank outlet to prevent foreign particles from damaging the pumps or blocking the valves in the loop. A strainer bypass system was available in the event the strainer became clogged and inoperative.

An 80 gallon auxiliary storage tank, pressurized by 25 psig nitrogen gas, was utilized to supply fluid to the pressurizing pump whenever a pressurization test was made at -20°F . The pump required fluid at ambient temperature, or above, for proper operation. The pressurizing pump had the ability to pressurize the vessel to 5000 psig in less than 3 minutes utilizing loop fluid as the pressurizing medium.

The loop equipment is described in detail in Appendix B. A $1\frac{1}{4}$ inch thick steel missile shield was placed over the vessel whenever a pressure test was being performed to prevent possible vessel fragments from striking the overhead manipulators or glass windows in the Hot Shop. Figure 4-2 illustrates the interior layout of the Hot Shop during the test program.

Insulation utilized on the loop was standard 2 inch fiberglass pipe insulation. A polyurethane foam, "Urefroth", was sprayed on the vessel and nozzles to a thickness of 4 to 6 inches after all thermocouples and strain gages had been attached to the vessel surface. Figures 4-4 and 4-5 illustrate the vessel with insulation covering it and in a condition ready for testing.

C. LOOP INSTRUMENTATION AND CONTROLS

The PM-2A process control panel was located in the Hot Shop Control Gallery, adjacent to the location of the loop and vessel in the Hot Shop. Figure 4-6 illustrates the panel in actual usage. The panels left to right are:

1. TV monitor of loop and vessel.
2. Temperature recording instruments for loop and vessel.
3. Saturable core reactor control and temperature recording instrument.
4. Loop control and pressure monitoring panel.
5. Refrigeration control and temperature recording instrument.

An alarm annunciator panel with 21 light locations was located above the control panels with an audible and visual alarm provided for each alarm function. The alarm acknowledge switch had to be depressed to silence the audible alarm; however, the visual alarm light would not go off until corrective action had been taken to alleviate the indicated problem.

A number of interlocks and controls were designed into the PM-2A test loop for the purpose of safeguarding the loop operation from operator error and equipment malfunction and to insure safe action and simultaneous operation of coordinated parts.

V. DATA ACQUISITION EQUIPMENT, DETECTORS AND DETECTOR APPLICATION

A. DATA ACQUISITION EQUIPMENT

In order to fulfill the purpose of the test program it was necessary to obtain strain data from the vessel during the pressurization stages. Investigation of the various transducers available for measurement of strain levels determined that resistance type strain gages were the most suitable for this particular application.

Bakelite-encapsulated foil-gages were selected after exhaustive testing of various strain gages and cements. Sixty-nine locations on the inside and outside of the vessel were selected to provide representative strain level information. Forty-eight of the gages were linear, single element units and twenty-one were three-element rosettes for a total of 111 data channels.

The data acquisition equipment provided for the strain gages consisted of a digital scanner system with a paper tape printer, magnetic tape recorders, and an X-Y plotter (Figure 5-1).

The digital system sequentially scanned, measured, and recorded DC voltages from strain gages and linear motion transducers and was designed to process a maximum of 200 such 3-wire sources.

A CIMRON Corporation Model 765 data acquisition system was used and consisted of the following components.

1. digital voltmeter
2. DC preamplifier
3. 600 wire scanner
4. Hewlett-Packard digital recorder (paper tape printer)

In addition, strain gage excitation was obtained from 30, 5-volt DC, 200 milliamp, solid-state power supplies (Figure 5-2). Four individual strain gages were supplied from each power supply.

Strain gage bridge completion resistors and balancing potentiometers were housed in plug-in modules. These circuits were constructed so that there were four bridges in each of twenty-nine modules. The bridge resistors were $120 \text{ ohm} \pm 0.5\%$ and the circuit was completed by a remotely located $120 \text{ ohm} \pm 0.5\%$ strain gage (Figure 5-3 and 5-4). Each bridge circuit had a coarse and fine adjustment which made it possible to adjust the strain gage output, at zero vessel pressure, to $\pm 2 \times 10^{-6}$ volt or an indicated strain of less than one microinch per inch. A continuity check button was also included in each circuit and which, when pressed, would give an immediate indication of whether or not the circuit was operative.

The scanner-voltmeter-printer system read and recorded 4 digits of data from each bridge circuit or channel. The scanner stopped on each channel long enough for the voltmeter to seek a null or balance and the printer to print its line of characters; if a null was not found within a preset time, the value of the voltage at the end of the time was printed along with a character indicating "forced print" (printed tape format, Figure 5-5). The time required for a single print-out of the 111 channels was about 3-1/2 minutes.

The digital data system was designed so that it would not introduce errors of more than 1 part in 1000. This is less than one tenth of the error expected from the primary transducers, so the data errors introduced by the acquisition system produced negligible difference in the magnitude of the total data error.

Two 14 channel tape recorders were also used to record data during the PM-2A tests. One tape recorder was used for strain gages and the other for records of data from pressure transducers, accelerometers, and piezoelectric shear strain detectors.

In addition to the channels recorded on the tape recorder, strain gage outputs from 15 other selected channels were displayed on a large oscilloscope screen as a live histogram bar graph showing the progress of the tests. No permanent analog record was made of these outputs.

The first test indicated that the calibration of the primary system pressure transducer was not wholly reliable, so for subsequent tests an X-Y recording was made of the output of a highly accurate ($\pm 1/4\%$) pressure transducer which measured the vessel internal pressure and was installed in one of the blind flanges.

B. DETECTORS

Instrumentation installed on the PM-2A Reactor Vessel originally consisted of strain gages, thermocouples, and motion transducers. Later accelerometers, piezoelectric crystals, and a crack-opening-displacement measuring device were added.

The Idaho Nuclear group installed the original instrumentation. The Safety Test Engineering Project (STEP) organization of Phillips Petroleum Company installed the accelerometers and piezoelectric crystals. The Phillips experiment was an effort to determine if it were possible to detect impending fracture by sensing the pre-rupture surface wave that is believed to exist in brittle failure situations.

Southwest Research Institute built, installed, and recorded data from the crack-opening-displacement module.⁽⁸⁾ Its purpose was to detect changes in the defect width during vessel pressurization.

The strain gages were all bakelite-encapsulated foil-gages and consisted of two types: linear (single-element) gages and rosette gages (three superimposed elements). These were installed on the reactor vessel at locations shown on Figure 5-6 and Figure 5-7. Accuracy of location during installation was $\pm 1/4$ inch.

Iron-constantan thermocouples were installed at locations indicated by "TE" on Figure 5-6 and Figure 5-7.

Two linear motion transducers were positioned at the top and bottom heads of the reactor vessel and were adjusted in position so the probes were nearly perpendicular to the surface of the top and bottom head at the points of contact. Data obtained during testing indicated that expansion or contraction in the directions parallel to the axes of the motion transducer probes was probably less than 0.003 inch, which was just within the sensitivity region of the instruments used. No attempt was made to obtain motion transducer data after Test 2.

The crack-opening-displacement (COD) module was first installed between Test 4 and Test 5 and data was taken during all succeeding pressurizations. The COD module consisted of three ultrasonic crystals mounted in a bridge which spanned the defect. The bridge was held in place by means of an electromagnet. Two of the crystals were used to determine the amount of crack opening or displacement and the third was

used to determine that the seal chambers remained full of coupling fluid. The device was capable of measuring crack displacement with an accuracy of ± 0.001 inch.

C. DETECTOR SELECTION AND INSTALLATION TECHNIQUES

The highly radioactive nature of the vessel made it necessary to select strain gages and thermocouples which were capable of being applied by remotely controlled operations. They also had to be capable of functioning accurately over a wide operating temperature range while in a radioactive environment.

Weldable strain gages were ruled out because of the difficulty of application to the varied curvatures of the vessel using remotely controlled procedures. Bakelite-encapsulated foil-type gages were then investigated and this led to the development of a magnetically held, pressure application tool. This tool consisted of three high strength permanent magnets and a pressure pad connected to a spring loaded shaft (Figure 5-8). In use the spring loaded shaft and pad were cocked and held until the tool was correctly positioned and the magnets applied. A trigger was then depressed which released the shaft and moved the strain gage about $3/16$ inch into contact with the vessel surface.

A series of tests were made to select the best combination of cement and strain gage for this application. The strain gage selected was a Baldwin-Lima-Hamilton SR-4 FAB bakelite-encapsulated foil-gage. This gage is temperature compensated over most of the range of interest (i.e. -20°F to 272°F); but since the strain gage bridges were zeroed or balanced just prior to each pressure run, this was a secondary consideration. One disadvantage of these gages was that they tended to drift if high strains were applied for long periods of time. This was not regarded as a hindrance since the test pressures were only to be held for approximately ten minutes.

Several epoxy-type cements were tested in conjunction with the BLH gage. It was necessary to select a high temperature cement which would withstand the 272°F maximum operating temperature and yet possessed a reasonable cure time and temperature.

There were four cements which appeared to be satisfactory after tests made upon sample tensile test coupons. These coupons were mounted in the Hot Shop and the strain gages installed remotely with the manipulator

and pressure pad tool. Many of the coupons tested showed correlation within five percent up to strains of more than 10,000 microinches/inch. The final selection of cement was based on the minimum observed variance between several different gages mounted on a small steel cylinder metallurgically similar to PM-2A vessel shell and tested at 300°F. The cement which performed best under these conditions was "EpoxyLite 810" epoxy.

The thermocouples used were fiberglass insulated iron constantan. The thermocouple junction was made by spark welding the twisted pair of wires and then encapsulating them in an epoxy matrix with the tip of the junction protruding from the bottom. The encapsulated thermocouple was then attached to the vessel surface using the same tools and methods as were used for strain gages. There were a total of 12 thermocouples on the vessel surface and four thermocouples peened into the core filler piece (flow bafflement). These provided fluid vessel differential temperature measurements, vessel wall temperatures, and fluid temperatures inside the vessel.

The actual installation of strain and temperature detectors on the outside of the PM-2A Vessel was accomplished as follows:

The Hot Shop manipulator operators were trained in the technique of surface preparation and strain gage positioning by having them install strain gages on tensile test coupons. The manipulator was used to perform all the operations necessary to prepare the surface for the strain gage: first, the surface was ground to a 180 grit finish using a small rotary sander. This required the use of three or four different grit disks; 100, 180, 180, or on the vessel itself, 40, 100, 180, 180. The area thus prepared was about 4-6 inches in diameter. Immediately after grinding, the surface was cleaned with reagent grade trichlorethylene. A manipulator held, saturated gauze pad, was pressed gently against the area to be cleaned and moved up and down several times. Approximately six trichlorethylene pads were used in succession, or until all traces of dirt were removed. Then the metal was etched with a mild acid type metal conditioner. This was done by soaking a pad with conditioner and using the manipulator to squeeze the pad against the area where the strain gage was to be applied. The next step was to neutralize the conditioner with ammonium hydroxide applied in the same manner.

Finally, the surface was dried by pressing a clean, dry pad against it and rubbing slightly. Strain gages were installed within an hour after the surface was thus prepared to avoid oxidation damage to the surface. Areas for the thermocouples were similarly prepared except the conditioner and neutralizing steps were omitted.

While the surface was being prepared, the strain gage (or thermocouple) assembly was being mounted on the pressure application tool.

The strain gage assembly consisted of the foil strain gage with its built-in leads, sheathing for the leads, a terminal strip onto which the leads were soldered with high temperature silver solder, and three wires leading ultimately to the data system (Figures 5-9 and 5-10). After mounting the strain gage assembly was checked for integrity.

The pressure pad was made ready by cocking, cleaning, and applying a disk of 1/8 inch thick silicon gum rubber with ~~tapemaker's~~ cement. The strain gage and terminal strip, with wires attached, was applied against the silicon gum. Thus in place, on the pressure pad, the strain gage was roughened with 400 grit emery paper, and thoroughly cleaned with cotton swabs saturated in trichlorethylene.

The epoxy was spread on the surface of the strain gage and terminal strip with a small spatula; then the manipulator operator positioned the application tool so the magnets centered the gage over the area where it was to be applied. When the device was in place, the manipulator released the carrier handle and squeezed the trigger. The spring loaded shaft then pressed the strain gage against the vessel surface with about 20 pounds force.

In order to speed the cure of the adhesive and free the application tool for further use, the vessel was filled with water and heated with a steam hose and sparge nozzle. In this manner the outside vessel wall temperature was raised to about 130°F and the epoxy cured within 24 hours.

The lead wires of the transducer assemblies were coiled and hung on aluminum hooks that were taped to the side of the vessel with double backed tape (Figure 5-11).

The exterior strain gages were waterproofed with a synthetic varnish which protected against frost, water, oil, and many chemicals, as well as providing a general protective coating for the gage installation.

The lead wires coiled on the aluminum hooks were removed by the manipulator and strung to a terminal panel where the transducer leads were connected to wires from the data system or the control panel. When all the detectors had been applied and checked for location, orientation, electrical continuity, and circuit resistance, the vessel was covered with insulation.

Photographs showing strain gages and thermocouples as installed on the outside of the vessel can be seen as Figures 5-12, 5-13, 5-14, and 5-15.

Installation of the three rosette gages inside the vessel behind the notch was made in the same manner as the external gages with the exception that a special fixture was used to accurately locate the gages behind the defect and the magnets were replaced with convex shaped blocks to which high-strength double backed tape was attached. A wire clamp was fitted over the nine 3-conductor wires and fastened to the side of the vessel with epoxy. The terminal strips, wire clamps and wire insulation used on the inside of the vessel were fiberglass. Penetration through the vessel was made at the 9 inch diameter outlet pipe blind flange using "Conax" fittings.

VI. DESTRUCTIVE TESTING

A. TEST SEQUENCE AND DEFECT MACHINING

The temperature-pressure points selected for the tests (Figure 6-1) were determined by Bettis Atomic Power Laboratory after a review of all applicable brittle fracture data, the non-destructive test data, and the completion of a stress analysis of the vessel. The testing sequence was designed to delineate, within the system capabilities, the temperature-pressure limitations of defects of varying known size. The upper test temperature boundary was defined as the Charpy energy fix transition temperature plus 60°F and was designated as the reference transition temperature (RTT). The sequence was such that stress levels increased for each consecutive test point so as to insure that the vessel failure, when it occurred, could not have occurred at some combination of lower pressure and higher temperature.

The vessel was first tested under conditions which the stress analysis had indicated would not, in all probability, cause failure and then into

progressively more severe conditions. The severity of each consecutive test was increased by introducing a series of larger and larger artificial defects in the outside vessel wall by the use of an electrostatic discharge machining (EDM) device.

The stress analysis had indicated that the most highly irradiated section of the vessel barrel would not be subject to failure, in the undefected condition, before failure of other sections of the vessel such as the nozzles and head.⁽⁶⁾ Thus, the installed defects were designed to insure that failure would occur, at a predetermined location, in the most highly irradiated section of the vessel barrel at pressures less than that required to cause failure in other sections of the vessel.

The defect geometry was to be a 30-degree "vee" shaped slot with radiused ends. Installed in the apex of the vee was an additional hairline defect which was to be a minimum of 0.030 inch deep by 0.002 inch wide and run the length of the defect (Figure 6-2). This small slot was to serve as a stress riser and fracture initiator. The installed defects were intended to simulate the stress concentrating effects of a naturally occurring defect and to provide a defect of known size and geometry which would be analytic within the frame of reference of fracture mechanics.

Several methods of cutting an artificial defect were investigated by Bettis and included mechanical machining, electrochemical machining, and electrostatic discharge machining (EDM).⁽⁷⁾ The EDM method was decided upon because it was found to be the only method which would consistently produce the required hairline defect. The other methods also presented some problems for remotely controlled operations.

The EDM device (Figure 6-3) used in the program consisted of the cutting head which held the electrode, a small work tank which kept the electrode submerged in dielectric, a dielectric storage tank and pump, and a servo-drive pump for the cutting head. All of these items were constructed as a unit and mounted on a dolly which made it possible to move the device away from the vessel during testing (Figure 6-4). The power supplies and control console were located outside the test cell.

The machining operation was conducted in two steps. First, a vee shaped carbon electrode of the desired size (Figure 6-5 and 6-6) was mounted in the cutting head and the device moved into cutting position on the side of the vessel. The work tank was filled with dielectric and the defect was then machined to the required depth. Second, the carbon electrode was removed and replaced by a 0.001 inch thick tungsten foil electrode in a special holder (Figure 6-7). The foil was used to machine the hairline slot at the apex of the vee shaped defect.

One complete defect was machined in a section of a mock-up ring forging to verify the existence and dimensions of the small slot as produced under actual operating conditions. It was found that the width of the defect was not the desired 0.002 inch but varied from a minimum of 0.006 inch to a maximum of 0.014 inch. A similar condition was found for the depth. The required depth was 0.030 inch but actual measurements indicated a minimum depth of 0.008 inch and a maximum of 0.032 inch. Figure 6-8 is a set of microphotographs of transverse cross-sections taken from the sample defect and serves to illustrate the variance in the width and depth of the slot at the base of the 30 degree vee. The greatest depth and least width was obtained near the center of the cut while each end tended to become wider and more shallow. These variations were attributed to excessive electrode flutter and vibration and could not be corrected.

The vessel was tested with the following defects machined into the wall at the center of the core zone. Each defect was cut at the same location as the one preceeding, so that only one defect was present during each test sequence.

Test 1	no defect
Test 2	3/8 inch deep x 3 inches long
Test 3	1/2 inch deep x 5 inches long
Test 4	5/8 inch deep x 7-1/2 inches long
Test 5	1-3/32 inch deep x 8-1/2 inches long
Test 6	1-1/4 inch deep x 9-1/2 inches long
Test 7 & 8	1-3/4 inch deep x 11 inches long

Test 1 through 4 were conducted over the temperature-pressure sequence, shown in Figure 6-1, through point 14. Test 5 was made only through point 13 because the defect had been machined to a greater depth than specified. A depth of 7/8 inch was requested but the actual final depth was found to be 1-3/32 inches.

Calculations which were based on an assumed fracture toughness for the irradiated vessel material and a known defect geometry had indicated that vessel failure was possible during Test 6.⁽⁶⁾ The test sequence, however, was completed through point 15 with no vessel damage indicated or observed. A decision was then made which led to an attempt to increase the acuity of the defect by inducing a low-cycle fatigue crack at the apex of the defect by cycling the vessel at 72°F from 0 psig to 5000 psig. Tests on sample specimens made by Bettis indicated that the fracture toughness of samples defected by fatigue cracking was some 40% to 60 % lower than that for EDM defected samples.⁽⁷⁾ It was presumed that the difference was caused by a lack of acuity or sharpness in the EDM slot. A total of 250 fatigue cycles were applied with intermediate tests, at 5250 psig and -20°F, made at the end of 50, 150, and 250 cycles. The crack-opening-displacement module, which ultrasonically scanned the sides and bottom of the defect, was used to determine if the cycling procedure produced a fatigue crack. No indications were received which indicated crack growth.

For Test 7, in order to avoid any possible effects which could possibly have resulted in increased fracture toughness, the usual temperature-pressure sequence was omitted and the vessel was pressurized at point 15 (-20°F, 5250 psig) only. After the pressurization the vessel was still intact and another attempt was made to produce a fatigue crack at the apex of the defect by cycling the vessel at 72°F and from 0 psig to 5000 psig. A total of 500 cycles was applied with intermediate tests at point 15 after 100, 300, and 500 cycles. No evidence of fatigue crack growth was obtained. At this point the cycling procedure was discontinued as additional cycling could possibly have caused fatigue failure at several points remote from the defect, such as vessel penetrations, vessel head, head bolts, or gasketed joints.

Further tests, made by Bettis, on means of sharpening the root of the defect resulted in the test sequence for Test 8. It was found that single, intergranular stress corrosion cracks could be introduced at the apex of the defect by injecting a 1:1 aqueous solution of hydrochloric acid and then pressurizing the vessel to stress the vessel wall.

For the first part of Test 8 the vessel was pressurized to 4000 psig at 72°F and the acid solution injected into the defect. This condition was held for one hour after which time the acid was flushed from the defect and the vessel cooled to -20°F and pressurized to 5250 psig. No vessel damage was indicated or observed. The acid injection was repeated a second time at 72°F but the vessel internal pressure was increased to 5000 psig. During this second acid application the crack-opening-displacement module indicated that the defect opening was greater than it had been on previous tests. The normal displacement of 0.013 to 0.015 inch increased to approximately 0.022 inch. After one hour the acid was flushed from the defect and the vessel was cooled to -20°F.

On November 18, 1966, the vessel was pressurized and a brittle fracture type failure was obtained at 4475 psig and -20°F.

B. DISCUSSION AND DESCRIPTION OF VESSEL FAILURE

The vessel failure appears to be a typical brittle fracture. The rupture is a single, straight crack through the defect longitudinal centerline proceeding upward to the closure flange and downward through the center girth weld to a point 18-1/4 inches below the defect. At this point the break bifurcated with one of the fracture lines stopping in the cylindrical portion of the shell and the other proceeding down into the lower head (Figures 6-9, 6-10, 6-11, and 6-12). With the exception of the fracture area the vessel remained intact and no fragmentation occurred.

The internal flow baffle was also ruptured, but in a ductile manner, during the pressure release (Figures 6-13 and 6-14).

C. DATA ANALYSIS, REDUCTION, AND REPORTING

All data obtained from the strain gages, by the data acquisition system, were in the form of millivolts rather than direct strain readings. Three sets of millivolt readings were obtained from each strain gage at each temperature-pressure point in the test sequence. These readings

were then examined for anomalies, manually averaged and submitted to the NRTS Computer Center for final processing. The IBM 7040 computer was programmed to multiply the millivolt input data by factors determined from gage characteristics and lead wire resistance and produce a table of calculated strain in microinches/inch. The algebraic sign of the calculated strains indicated the type of strain; a positive sign indicated tensile strain and a negative sign indicated compressive strain. The data from the rosette gages was operated on by a program which resolved the component strains into a maximum calculated tensile strain and the angle at which that strain occurred.⁽⁹⁾⁽¹⁰⁾ The strain angle was defined in terms of the standard circular coordinate system; i.e., looking at the developed surface of the vessel zero degrees was the horizontal reference axis extending to the right. Positive angles were counter-clockwise and negative angles were clockwise from the zero degree reference axis. The angles for the inside rosette gages were defined for an observer looking through the vessel wall and so had the same reference axis.

A complete tabulation of all input data and computer calculated strains and angles were transmitted to Bettis Atomic Power Laboratory at the conclusion of each test sequence.

D. DISCUSSION AND DESCRIPTION OF STRAIN DATA OBTAINED DURING THE TESTS

The strain data received from the gages on the vessel barrel, nozzles, and closure head were generally linear and exhibited good correlation from test to test (Figures 6-15 and 6-16). In addition, approximately 90 per cent of the strain gages installed produced usable information throughout the program.

Gages in the defect area produced fairly linear data for any given test but were not repeatable from test to test. This lack of repeatability was due to the fact that the defect size was different for each test and required the relocation of the gages to new positions. Although every effort was made to position the gages as accurately as possible, there were variations of $\pm 1/4$ inch in the location of the gage grid centers. For strain gradients such as those that existed at the upper and lower ends of the defect this amount of mislocation would have introduced considerable variation in the indicated strain.

Examination of the data received from the gages in the defect area indicated a general buckling effect which became more pronounced as the defect was machined longer and deeper for each succeeding test. The evidence of this effect was obtained from the circumferential elements of the two rosette gages mounted at the sides of the defect which indicated increasing compressive strain and from the inside gages which indicated decreasing circumferential tensile strain. The indicated circumferential strain at the upper and lower ends of the defect became generally larger with increasing defect size and the strain at the top was less than the strain at the bottom.

Figure 6-17 is a drawing of the defect area gages and a table of the strains indicated by those gages at 4000 psig and -20°F during Test 7 and Test 8. As the defect size was not changed between Tests 7 and 8, the strain gages are the same for both tests and the tabulated data indicates the results of the acid application which was made during Test 8. The most pronounced changes were found in the readings of the inside gages. In comparison to Test 7 the Test 8 readings, after the first acid application, were approximately 450 microinches/inch larger. The table is based upon the 4000 psig pressure to provide a comparison between the last set of data taken before the vessel rupture and prior runs at similar conditions.

Other areas of interest on the vessel exhibited the following indicated strains at 5000 psig and were essentially repeatable from test to test.

Top Head: The center of the head recorded the highest strain on the vessel, with the exception of the defect area, and indicated approximately 1200 microinches/inch. The linear gages mounted near the closure flange indicated strains on the order of 625 microinches/inch while those gages mounted six inches higher on the head indicated only 500 microinches/inch. Rosette gages on the knuckle radius recorded predominantly negative (compressive) strains but the magnitude was less than 100 microinches/inch.

Nozzles: At the flange end the indicated strains were approximately 850 microinches/inch and varied from 600 to 900 microinches/inch at the vessel connection.

Vessel Body: The general circumferential strain was 1000 to 1100 microinches/inch. Gages on the vessel near the large nozzle penetrations recorded circumferential strains near 870 microinches/inch and longitudinal strains of approximately 700 microinches/inch.

Bottom Weldment: Three of the four rosette gages mounted in this area recorded maximum strains between 625 and 850 microinches/inch. The other, near the control rod access nozzles, indicates a maximum strain of 400 microinches/inch.

Bottom Head: The strain field on the bottom head was complicated by the pressure of the decay heat system inlet nozzle and the three linear gages near the nozzle indicated strains of 130, 335, and 620 microinches/inch.

These strain levels indicate that in all probability no point on the vessel was stressed beyond the yield point and bears out the stress analysis prediction that it would have been possible to test the vessel, in the undefected condition, at pressures higher than those actually used.

Complete tabulations of the maximum computed strain and angle of the strain for all of the gages are shown in Appendix A. The tables are the results of the computer runs for Test 6, point 10 (4000 psig, 272°F), Test 6, point 15 (5250 psig, -20°F), Test 7, (4000 psig, -20°F and 5250 psig, -20°F), Test 8.1 (4000 psig, -20°F and 5250 psig, -20°F) and Test 8.2 (4000 psig, -20°F). A blank in the data tables indicates that the gage was not working or, in the case of a rosette gage, that one or more of the three elements was inoperative. The data presented for the 4000 psig, -20°F points are not averages but only the results of a single "read and print" cycle by the data acquisition system. The data for the other points are averages of three data acquisition cycles.

VII. CONCLUSION

The pressure testing phase of the PM-2A Reactor Vessel Test Program was completed with the rupture of the vessel. Postdestruct sample acquisition and specimen testing is being directed by the U.S. Naval Research Laboratory (NRL) and consists of obtaining specimens for tensile

tests, drop weight tests, charpy V-notch, and wedge-opening-loading (WOL) fracture toughness tests. In addition, the fracture surfaces are to be characterized by macro- and microscopic examinations and will involve (1) estimation of the per cent of ductile fracture from the fracture appearance, (2) microstructure determination of the adjacent material to determine composition, grain size, and inclusion frequency or soundness, and (3) overall macroexamination of the fracture appearance and effect of the HCl treatment. These postdestruct tests will be made to obtain a more exact definition of the properties of the irradiated vessel material, which in turn will allow refinement of the mathematical analysis of the brittle fracture and predicted failure point.

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PM-2A REACTOR VESSEL

Fig. 1-1

Fig. 2-1 Vessel and Skid As-Received at NRTS

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Fig. 2-3 Core Support Structure Removal

NOTES:

- 1 - Readings Are $\gamma + \beta$ R / hr.
- 2 - Date May 18, 1965.
- 3 - Location NRTS - TAN Hot Shop.
- 4 - All Core Support Structure Removed.
All Vessel Inner Surfaces Wire Brushed
And Water Flushed
- 5 - Transportation Shielding Remaining On
Skid Is Shown In Cross Hatching.

Fig. 2-4 Radiation Survey After Internal Decontamination

Fig. 2-5 Reactor Vessel Disassembly - Shield Tank Removal

Fig. 2-6 Reactor Vessel Disassembly - Shield Tank Removal

Fig. 2-7 Reactor Vessel Disassembly - Inner Shield Tank Removal

Fig. 2-8 Reactor Vessel Disassembly

Fig. 2-9 Insulation Canopy Removal from Vessel Barrel

Fig. 2-10 Insulation Canopy Removal from Lower Head

Fig. 3-1 Dye Penetrant Examination

Fig. 3-2 Ultrasonic Scanning Unit - Search Crystals

Fig. 3-3 Ultrasonic Scanning Unit Assembly

Fig. 3-4 "Out-of-Roundness" Gage

Fig. 3-5 "Out-of-Roundness" Test - Composite Results Diagram

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HARDNESS TEST RESULTS					
Point No.	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Average
1	26.0	24.5	22.0	25.0	24.4
2	28.0	26.5	30.5	25.0	27.5
3	29.0	27.0	29.0	27.5	28.1
4	26.5	24.5	26.5	26.0	25.9
5	25.0	27.0	28.5	28.5	27.2
6	29.5	29.5	29.0	31.5	29.9
7	31.5	30.0	31.5	31.5	31.1
8	25.0	27.0	30.0	27.0	27.2
9	28.0	26.5	26.0	27.0	26.9
10	24.5	27.0	27.0	28.0	26.6
11	29.5	27.0	27.0	26.0	27.4
12	29.5	26.0	27.5	30.5	28.4
13	29.5	30.5	29.5	30.0	29.9
14	31.0	26.0	30.5	28.0	28.9
15	29.0	30.0	28.0	31.5	29.6
16	27.5	32.0	29.5	31.0	30.0
17	29.5	30.0	28.0	29.5	29.3
18	26.5	27.0	26.5	25.5	26.4
19	26.5	24.5	27.5	25.0	25.9
20	27.0	29.0	28.5	29.0	28.4
21	29.0	28.0	28.0	28.5	28.4
22	27.5	27.0	32.5	32.5	29.9
23	30.5	30.0	30.5	31.5	30.6
24	29.5	31.0	31.5	30.0	30.5
25	31.5	31.0	33.0	31.5	31.8
26	31.5	33.0	32.0	31.0	31.9
27	29.0	31.5	30.0	30.5	30.3
28	29.0	26.5	28.5	27.0	27.8
29	26.5	29.5	26.0	30.0	28.0
30	28.5	26.5	28.0	29.0	28.0
31	28.0	31.0	32.5	30.0	30.4
32	31.0	32.5	29.0	32.0	31.1
33	30.5	32.5	31.5	29.0	30.9
34	24.5	24.5	30.0	30.0	27.3
35	30.0	34.0	27.0	28.0	29.7
36	30.0	30.0	35.0	33.0	32.0
37	31.0	31.0	32.0	33.0	31.7
38	32.0	32.0	30.0	27.0	30.3
39	31.0	27.0	29.0	33.0	30.0
40	32.0	26.0	30.0	27.0	28.7
41	31.0	29.0	27.0	32.0	29.7

NOTES:
1 - Points 35 Thru 41 Are Equally Spaced And Are 31.5" Below Top Of Vessel.
2 - All Hardness Data Is Given In Rockwell "C".

APPROVED			CHECKED	REV. BY	DATE	NO.	REVISION
DESIGNED	BY	DATE					
DRAWN	Jensen	2-11-67					
CHECKED							
APPROVED							
IDaho Nuclear Corporation IDAHO FALLS, IDAHO							
Fig. 3-7							
PM-2A REACTOR VESSEL							
HARDNESS TEST RESULTS							
TEST NUMBER 2							
INDEX CODE & DRAWING NUMBER							
D 034060740400340336							
PROJECT NO.							

TOLERANCES UNLESS OTHERWISE SPECIFIED:
FRACTIONS ± DECIMALS ± ANGLES ±
BREAK ALL SHARP EDGES UNLESS OTHERWISE SPECIFIED.
FINISH 11/16 UNLESS OTHERWISE SPECIFIED.
UNLESS SHOWN THIS DRAWING.

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Fig. 3-8 Hardness Test Probe Assembly

Fig. 3-9 Closure Head Mounted on Jig Bore Machine

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Fig. 4-2 Test Equipment - NRTS Hot Shop

Fig. 4-3 Process Loop

Fig. 4-4 Reactor Vessel - Test Configuration

Fig. 4-5 Reactor Vessel - Test Configuration with Defect Area Insulation Plug Removed

Fig. 4-6 Process Control Panel

Fig. 5-1 Data Acquisition System

Fig. 5-2 Strain Gage Data Acquisition System

Fig. 5-4 Strain Gage Bridge Module

Channel Identification	Mode ¹ Forced Print 2	Data	Algebraic Sign Decimal Location ³
0 9 6 2	-	1 8 4 3	- 3
0 9 7 2		0 2 0 9	- 3
0 9 8 2		0 1 3 1	- 3
0 9 9 2		0 0 1 0	- 3
1 0 0 2	-	1 3 2 8	3
1 0 1 2		1 6 5 0	3
1 0 2 2	-	5 2 8 7	3
1 0 3 2	-	1 0 1 8	2

- 1 - "Mode" Prints 2 For Millivolts, 0 For Volts.
- 2 - "Forced Print" Makes A Mark If No Null Was Found Within A Preset Time.
- 3 - Digit Indicates The Number Of Decimal Places From The Right In The Data.

Fig. 5-5 Printed Tape Format

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Fig. 5-8 Strain Gage Application Tool

Fig. 5-9 Strain Gage Wiring Diagram

Fig. 5-10 Thermocouple Wiring Diagram

Fig. 5-11 Strain Gage Application

Fig. 5-12 Vessel with Instrumentation Applied

Fig. 5-13 Vessel with Instrumentation Applied

Fig. 5-14 Vessel with Instrumentation Applied - Top View

Fig. 5-15 Defect Area Instrumentation

Fig. 6-1 Testing Sequence

Fig. 6-2 Defect Geometry

Fig. 6-3 EDM Device

Fig. 6-4 EDM Device - Overall View

Fig. 6-5 Carbon Electrode for $\frac{3}{8}$ in. Deep by 3 in. Long Defect

Fig. 6-6 Carbon Electrode for 1-3/4 in. Deep by 11 in. Long Defect

Fig. 6-7 Tungsten Foil Electrode for 3 in. Long Defect

Section A-A

Section B-B

Section C-C

Fig. 6-3 Sample Defect Cross-Sections at 100X

Fig. 6-9 Vessel After Rupture

Fig. 6-10 Vessel After Rupture

Fig. 6-11 Defect Area After Rupture

Fig. 6-12 Vessel Rupture Measurements

Fig. 6-13 Ruptured Flow Baffle

Fig. 6-14 Ruptured Flow Baffle Close-up

Fig. 6-15 Data Plot - Strain Gage #22

Fig. 6-16 Data Plot - Strain Gage #26

	Test 7.1	Test 8.1	Test 8.2
60A	0.0	315	0.0
60B	0.0	248	0.0
60C	509	0.0	0.0
60*	—	—	—
61A	530	561	572
61B	514	514	483
61C	430	383	0.0
61*	542 $\angle$ -72.9°	572 $\angle$ -77.1°	—
63A	-436	-317	-274
63B	138	554	638
63C	-64	138	193
63*	181 $\angle$ +12.9°	658 $\angle$ +9.7°	676 $\angle$ +9.4°
64A	99	231	274
64B	300	1206	1525
64C	-364	-290	-258
64*	368 $\angle$ -14.1°	1232 $\angle$ +5.9°	716 $\angle$ -11.1°
65A	-439	-296	-258
65B	95	539	651
65C	-228	-56	-9
65*	107 $\angle$ +6.9°	494 $\angle$ +5.2°	661 $\angle$ +4.5°
66	690	710	713
67	882	1101	802
68A	1104	—	—
68B	1580	—	—
68C	2271	2360	3960 (?)
68*	2286 $\angle$ 5.2°	—	—
69A	778	817	623
69B	230	251	241
69C	-292	-347	284
69*	778 $\angle$ -89.3°	820 $\angle$ -87.0°	634 $\angle$ +83.7°
70A	752	777	782
70B	304	406	414
70C	-279	-292	-292
70*	773 $\angle$ -82.0°	803 $\angle$ -81.5°	808 $\angle$ -81.3°
71A	820	847	863
71B	877	927	941
71C	1256	1390	1462
71*	1313 $\angle$ 18.4°	1502 $\angle$ 18.0°	1528 $\angle$ 18.3°

Data In μ /in Strain

* = Computed Maximum Strain And Angle.
 — = Bad Gage
 0.0 = No Data This Run (electronics troubles)

Fig. 6-17 Indicated Strains in the Defect Area at 4000 psig and -20°F

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APPENDIX A

TEST DATA

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TABLE I
RESULTS OF DECONTAMINATION EFFORTS ON PM-2A CLOSURE HEAD

	Inner Clad Surface of Closure Head*			Seal Face of Closure Head Flange*			Beveled Surface of Insulation Canopy*		
	$\gamma + \beta$ R/hr	γ R/hr	cts/min	$\gamma + \beta$ R/hr	γ R/hr	cts/min	$\gamma + \beta$ R/hr	γ R/hr	cts/min
Initial Reading Before Decon.	25.0	7.5	2.14×10^5	-	-	2.8×10^3	-	-	-
After Demin. Water Wash	12.0	7.0	2.03×10^3	3.0	3.0	9.6×10^3	2.5	2.5	7.25×10^2
After Nitric Acid Wash	12.0	5.0	1.6×10^3	3.0	3.0	-	1.7	1.7	4.0×10^3
After Alkaline Permanganate and Ammonium Citrate Process	5.0	5.0	4.2×10^3	1.5	1.5	5×10^3	0.5	0.5	1.0×10^3
After Solvent Wash	5.0	5.0	1.15×10^2	1.5	1.5	5.5×10^2	0.5	0.5	5.5×10^2

* Gamma and Beta readings are R/hr at surface contact.

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TEST # 6

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
1	476	0.0	677	0.0
2	471	0.0	675	0.0
3	479	0.0	672	0.0
4	422	0.0	589	0.0
5	358	0.0	490	0.0
6	376	0.0	543	0.0
7	----	-----	12	11.7
8	74	18.5	35	16.5
9	13	- 0.3	31	- 4.6
10	----	-----	----	-----
11	470	-83.1	661	7.3
12	483	-91.6	654	-90.4
13	919	9.8	1226	25.1
14	----	-----	----	-----
15	----	-----	----	-----
16	----	-----	----	-----
17	----	-----	----	-----
18	619	0.0	820	0.0
19	713	0.0	926	0.0
20	741	0.0	980	0.0
21	826	0.0	1070	0.0

TEST # 6

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
22	868	0.0	1093	0.0
23	843	0.0	1063	0.0
24	800	0.0	1018	0.0
25	853	0.0	1087	0.0
26	861	0.0	1097	0.0
27	790	0.0	1010	0.0
28	850	0.0	1176	0.0
29	757	0.0	957	0.0
30	816	0.0	1040	0.0
31	826	0.0	1069	0.0
32	808	0.0	1006	0.0
33	845	0.0	1081	0.0
34	796	0.0	1023	0.0
35	GAGE NOT INSTALLED			
36	537	90.0	713	90.0
37	718	0.0	923	0.0
38	547	90.0	699	90.0
39	688	0.0	899	0.0
40	----	-----	----	-----
41	732	0.0	946	0.0
42	693	90.0	889	90.0

TEST # 6

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
43	297	0.0	410	0.0
44	306	90.0	403	90.0
45	715	0.0	908	0.0
46	GAGE NOT INSTALLED			
47	429	0.0	565	0.0
48	754	0.0	930	0.0
49	489	0.0	689	0.0
50	524	0.0	716	0.0
51	489	0.0	615	0.0
52	403	0.0	563	0.0
53	153	0.0	365	0.0
54	57	0.0	178	0.0
55	485	0.0	663	0.0
56	599	- 2.6	758	- 3.3
57	487	6.6	661	7.3
58	238	40.8	480	31.8
59	659	7.1	874	7.0
60	236	- 2.3	668	-100.2
61	661	- 0.6	860	- 2.7
62	----	-----	----	-----
63	224	5.0	306	7.4

TEST # 16

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
64	-----	-----	-----	-----
65	185	2.5	273	2.7
66	618	-0.0	797	0.0
67	888	0.0	1136	0.0
68	-----	-----	-----	-----
69	964	54.4	1255	54.5
70	536	-87.9	887	-70.0
71	1658	9.3	2153	9.2

TEST # 7

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
1	493	0.0	681	0.0
2	498	0.0	689	0.0
3	494	0.0	687	0.0
4	431	0.0	597	0.0
5	362	0.0	503	0.0
6	392	0.0	549	0.0
7	10	9.1	12	9.0
8	68	14.4	45	8.7
9	25	- 1.4	35	- 1.7
10	----	-----	----	-----
11	470	-83.1	624	-83.1
12	502	-91.0	664	-90.8
13	942	18.9	1236	20.0
14	----	-----	----	-----
15	----	-----	----	-----
16	----	-----	----	-----
17	----	-----	----	-----
18	615	0.0	838	0.0
19	695	0.0	941	0.0
20	731	0.0	980	0.0
21	801	0.0	1071	0.0

TEST # 7

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
22	815	0.0	1086	0.0
23	798	0.0	1068	0.0
24	761	0.0	1013	0.0
25	1082	0.0	1082	0.0
26	824	0.0	1098	0.0
27	756	0.0	1009	0.0
28	1174	0.0	1174	0.0
29	719	0.0	956	0.0
30	772	0.0	1025	0.0
31	1052	0.0	1052	0.0
32	759	0.0	1007	0.0
33	811	0.0	1080	0.0
34	767	0.0	1021	0.0
35	GAGE NOT INSTALLED			
36	527	90.0	707	90.0
37	688	0.0	923	0.0
38	523	90.0	701	90.0
39	676	0.0	899	0.0
40	632	0.0	844	0.0
41	703	0.0	944	0.0
42	658	90.0	878	90.0

TEST # 7

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
43	299	0.0	408	0.0
44	296	90.0	396	90.0
45	673	0.0	895	0.0
46	GAGE NOT INSTALLED			
47	390	0.0	574	0.0
48	699	0.0	935	0.0
49	516	0.0	696	0.0
50	530	0.0	718	0.0
51	468	0.0	620	0.0
52	419	0.0	569	0.0
53	290	0.0	361	0.0
54	146	0.0	175	0.0
55	496	0.0	665	0.0
56	569	- 2.8	762	- 2.7
57	493	7.1	664	7.4
58	372	28.4	488	29.7
59	656	7.0	878	6.9
60	----	-----	----	-----
61	542	-72.9	772	-76.8
62	----	-----	----	-----
63	179	12.7	66	13.3

TEST # 7

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch
Angle in Degrees

Gage No.	4000 psi, 272°F		5250 psi, -20°F	
	Strain	Angle	Strain	Angle
64	356	-14.1	413	-14.2
65	107	6.9	- 24	8.4
66	689	0.0	- 943	0.0
67	881	0.0	1176	0.0
68	2286	5.2	----	-----
69	779	89.3	1041	89.3
70	775	-82.0	1033	-81.9
71	1313	18.4	1804	32.6

TEST # 8

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	TEST 8.1				TEST 8.2	
	4000 ps, -20° F		5250 psi, -20° F		4000 psi, -20° F	
	Strain	Angle	Strain	Angle	Strain	Angle
1	474	0.0	656	0.0	474	0.0
2	486	0.0	671	0.0	489	0.0
3	486	0.0	674	0.0	489	0.0
4	421	0.0	581	0.0	422	0.0
5	352	0.0	489	0.0	339	0.0
6	384	0.0	534	0.0	387	0.0
7	- 2	8.6	3	8.8	3	12.8
8	26	- 1.8	35	4.0	- 9	-19.1
9	----	-----	----	-----	----	-----
10	----	-----	----	-----	----	-----
11	452	-82.7	600	-83.2	476	-83.2
12	481	-90.0	646	-91.3	490	-90.7
13	897	16.0	1194	18.3	918	29.2
14	----	-----	----	-----	----	-----
15	----	-----	----	-----	----	-----
16	----	-----	----	-----	----	-----
17	----	-----	----	-----	----	-----
18	603	0.0	817	0.0	603	0.0
19	695	0.0	933	0.0	686	0.0
20	722	0.0	960	0.0	723	0.0

TEST # 8

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	TEST 8.1				TEST 8.2	
	4000 psi, -20° F		5250 psi, -20° F		4000 psi, -20° F	
	Strain	Angle	Strain	Angle	Strain	Angle
21	791	0.0	1048	0.0	793	0.0
22	812	0.0	1078	0.0	813	0.0
23	774	0.0	1022	0.0	839	0.0
24	744	0.0	984	0.0	806	0.0
25	804	0.0	1065	0.0	799	0.0
26	815	0.0	1082	0.0	817	0.0
27	751	0.0	999	0.0	751	0.0
28	873	0.0	1158	0.0	876	0.0
29	713	0.0	944	0.0	714	0.0
30	761	0.0	1011	0.0	763	0.0
31	780	0.0	1034	0.0	784	0.0
32	755	0.0	1001	0.0	752	0.0
33	804	0.0	1067	0.0	807	0.0
34	760	0.0	1008	0.0	764	0.0
35	NOT INSTALLED					
36	521	90.0	695	90.0	525	90.0
37	679	0.0	906	0.0	681	0.0
38	519	90.0	691	90.0	518	90.0
39	668	0.0	887	0.0	670	0.0
40	624	0.0	830	0.0	624	0.0
41	693	0.0	925	0.0	693	0.0

TEST # 8

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	TEST 8.1				TEST 8.2	
	4000 ps, -20°F		5250 psi, -20°F		4000 psi, -20°F	
	Strain	Angle	Strain	Angle	Strain	Angle
42	649	90.0	863	90.0	650	90.0
43	291	0.0	397	0.0	294	0.0
44	292	90.0	387	90.0	292	90.0
45	664	0.0	882	0.0	667	0.0
46	GAGE NOT INSTALLED					
47	420	0.0	565	0.0	420	0.0
48	686	0.0	915	0.0	689	0.0
49	511	0.0	686	0.0	511	0.0
50	526	0.0	708	0.0	526	0.0
51	457	0.0	612	0.0	456	0.0
52	413	0.0	558	0.0	414	0.0
53	263	0.0	322	0.0	265	0.0
54	161	0.0	186	0.0	168	0.0
55	485	0.0	648	0.0	486	0.0
56	561	- 2.8	747	- 2.7	560	- 2.9
57	485	6.7	647	6.8	485	6.8
58	360	31.2	471	31.7	302	22.0
59	646	7.0	861	6.9	649	7.2
60	----	-----	----	-----	----	-----
61	572	-77.1	768	-77.4	----	-----
62	----	-----	----	-----	----	-----

TEST # 8

STRAIN GAGE DATA

Maximum Computed Strain and Computed Angle

Strain in Microinches/inch

Angle in Degrees

Gage No.	TEST 8.1				TEST 8.2	
	4000 ps, -20°F		5250 psi, -20°F		4000 psi, -20°F	
	Strain	Angle	Strain	Angle	Strain	Angle
63	593	9.7	902	9.3	678	9.5
64	1232	6.0	1526	- 6.6	1517	- 5.0
65	550	4.7	853	4.5	662	4.5
66	709	0.0	951	0.0	712	0.0
67	1102	0.0	1465	0.0	801	0.0
68	----	-----	-----	-----	-----	-----
69	818	90.8	1084	89.8	635	96.3
70	803	-81.5	1067	-81.4	809	-81.3
71	1502	18.0	2019	20.6	1528	18.3

APPENDIX B
DETAILED LOOP EQUIPMENT
DESCRIPTION

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CIRCULATING PUMP

Quantity	One
Item No.	PM-2A-P-1
Type	Herringbone Gear Rotary Pump
Manufacturer	Worthington Pump Co.
Model	3-GAR (Mfg. bulletin 2066-BIA)
Capacity	100 gpm
Speed	1150 rpm
Pressure	
Suction	4.3 psig
Discharge	180 psig max.
Motor Size	30 hp
Type	drip-proof
Power	440V 3-phase 60 cycle
Pump Eff.	85% max.
NPSH req.	none
Physical Dimensions	
Flange to flange	15"
Drive shaft to back	20-15/16"
Height	12"

PRESSURIZING PUMP

Quantity	One
Item No.	PM-2A-P-2
Type	Vertical reciprocating plunger
Manufacturer	Kobe, Inc. Huntington Park, Calif.
Model	P/N 3-34606, 2E Triplex
Capacity	
Max.	4.6 gpm
Min.	0.54 gpm
Pressure	
Suction	180 psig (max.)
Discharge	5000 psig
NPSH req.	25 psig
Physical Dimensions	
Pump base length	78"
Pump base width	19-3/4"
Overall height	43"

VARIDRIVE

Quantity	One
Actuator	Air (3-15 psi)
Motor Size	15 hp U.S. Motors Varidrive
Type	drip proof
Power	440V 3-phase 60 cycle
Speed range	2000 to 236 rpm
Control	Variable remote manual

ELECTRICAL RESISTANCE HEATER

Quantity	One
Item No.	PM-2A-H-1
Manufacturer	Industrial Engineering & Equipment Co., St. Louis, Missouri
Heater rating	60 kW
Shell side fluid	oil
Material	
Elements	copper
Sheath	steel flat blades
Insulation	2" rock wool
Temperature	
Heating range	-30 to 375°F
Heat flux	18 watts/sq. in.
Design pressure	180 psig
Design temperature	375°F
Physical Dimensions	13 1/2" o.d. by 52" long

FLUID HEATER TEMPERATURE CONTROL SYSTEM

The heat output of the three Y-connected heater elements is controlled by varying the 3-phase input power to the heater elements. The voltage is varied by operating saturable core reactors ahead of and in series with each heater element. Each reactor core is magnetized by passing a controlled dc current through the core secondary winding. The degree of magnetization varies (non-linearly) with the dc current applied. Increased magnetization reduces reactor core impedance and results in higher voltage at the heater. A G.E. Reactrol unit supplies the dc current. The current is an amplified signal relayed by the Reactrol from a temperature recorder-controller sensing loop fluid temperature.

Reactrol dc voltage	50-200 (output)
Reactrol dc current	0.3-1.2 amps to reactor core
Heater ac voltage	243 V
Saturable core reactor rating	
No. furnished	3
Voltage	277 V ac
Power	25 KVA (each)

TEST LOOP PIPING

All piping on the low pressure side of the test loop is fabricated of schedule 40 ASTM-A106-Gr-A seamless carbon steel with 150 lb slip-on raised face flanges. All piping from the discharge of the pressurizing pump to the reactor vessel is designated high pressure piping and is fabricated of double extra strong ASTM-A106-Gr-B, seamless carbon steel with 6000 lb socket weld and butt weld fittings.

TEST LOOP VALVES

Valves used in the PM-2A Test Loop fall into three catagories which are described below:

1. Vessel Isolation Valves

Quantity	Four
Item No.	FCV-1, FCV-2, FCV-8, and FCV-9
Type	Self-draining, lubricated plug valve with air operated spring return operator
Pressure drop (max.)	7 psi @ 100 gpm and -30°F
Design pressure	5500 psig
Design temperature	375°F
Materials	A216 Gr WCB cast steel
End connections	2" 2500# ASA raised face flanges

2. Vessel Bleed Valves

Quantity	Two
Item No.	FCV-10 and FCV-11
Type	Self-draining, lubricated plug with air operated spring return operator
Design pressure	5500 psig
Design temperature	375°F
Materials	A216 Gr WCB cast steel

End connections	3/4" 2500# raised face flanges
3. <u>Low Pressure Valves</u>	
Material	Carbon steel
Fittings	150 lb raised face flanges
Design temperature	375°F
Design pressure	150 psi

GASKETS

Gaskets used throughout the PM-2A Test Loop are standard style CG compression gauge "Flexitallic" gaskets. These gaskets are available in all ASA standard sizes and are manufactured with type 304 stainless steel and Canadian asbestos filler. Gauge rings are 3/32" thick carbon steel. Gaskets used in the low pressure side of the test loop are rated at 150#. Gaskets used on the high pressure side of the test loop are rated at 2500#.

OIL COOLER AND REFRIGERATION SYSTEM

The oil cooler and refrigeration system consists of an air-cooled heat exchanger for high temperature cooling (375 to 125°F) and of refrigeration equipment for intermediate temperature cooling (125 to 40°F) and low temperature cooling (40 to -30°F). The air-cooled exchanger and refrigeration units are completely instrumented and packaged on a 10' x 6' steel skid for attachment to the loop system. Principal components of the packaged system are as follows:

1. Air Cooled Exchanger

The air-cooled exchanger is an industrial type finned-tube air cooler. It is sized to cool 100 gpm of system fluid in the range of 375 to 125°F. At 125°F fluid temperature instrumentation automatically switches the cooling operation from the air-cooled heat exchanger to the refrigeration units.

Quantity	One
Item No.	PM-2A-HX-3
Manufacturer	Young Radiator Co., Racine, Wis.
Model	MWC #75-B-36-ARY-8-4
Core type	#AX96
Capacity	150,000 Btu/hr @ 125°F exit oil temp. and 95°F entrance air

Face area	12 ft ²	
Materials		
Tubes	copper	
Fins	aluminum	
Temperature (°F)	<u>Inlet</u>	<u>Exit</u>
Air	95	111
Oil	155.25	150
Air requirement	10,000 SCFM	
Fan design	4 aerodynamic pitch blades	
	36" diameter throat	
	clockwise rotation	
	roll-formed fan ring	
Fan motor	2 hp	
Motor type	drip-proof	
Pressure drop (tubes)	10 psi max.	
Design pressure	100 psig	
Design temperature	375°F	

2. Oil-Freon Exchanger

The oil is cooled in the 125 to -30°F temperature range in a single circuit shell-and-tube heat exchanger.

Quantity	One	
Item No.	PM-2A-HX-1	
Manufacturer	Vilter Mfg. Co., Milwaukee, Wis.	
Model	DE 1616	
Tubeside	Freon 22	
Shellside	System oil	
Materials		
Tubes	3/4" o.d. seamless copper ASME spec. SB-111	
Shells	Seamless steel ASTM spec. SA-133B	
Insulation (shell)	3" fiberglass insulation with sheet metal jacket	
Temperatures (°F)	<u>Intermediate Temp. Cooling</u>	<u>Low Temperature Cooling</u>
Tubeside	30	-40
Shell inlet	46.1	-28.5
Exit	40	-30
Capacity	150,000 Btu/hr	
Pressure (design)		
Tubes	225 psig	
Shells	150 psig	

3. Primary Compressor

The primary cooling compressor is of reciprocating, single stage, semi-hermetic design for operation when oil is being cooled in the temperature range of 125 to 40°F.

Quantity	One
Item No.	PM-2A-C-2
Manufacturer	Copeland Refrigeration Corp. Sidney, Ohio
Model	#9RS1
Capacity	150,000 Btu/hr @ 30°F suction
Pressures	
Suction	57.7 psig (4900')
Discharge	200.4 psig (4900')
Motor horsepower	15
Temperatures	
Suction	30°F
Discharge	100°F
Motor type	drip-proof
Electrical power	440V 3-phase 60 cycle
Refrigerant	Freon 22

4. Secondary Compressor

The secondary compressor is a six cylinder, reciprocating, internally compounded, two stage compressor. It operates when oil is being cooled in the temperature range of 40 to -30°F.

Quantity	One
Item No.	PM-2A-C-1
Manufacturer	Vilter Mfg. Co., Milwaukee, Wis.
Model	F2250446 - 426 B
Capacity	112,860 Btu/hr @ -40°F suction
Pressure	
Suction	3.11 psig (4900')
Discharge	200.4 psig (4900')
Temperatures	
Suction	-40°F
Discharge	100°F
Motor size	40 hp
Motor type	drip-proof
Electrical power	440V 3-phase 60 cycles
Refrigerant	Freon 22

5. Refrigerant Condenser

The refrigerant condenser is a single-stage water cooled unit designed to handle refrigerant flow from either the intermediate or the low-temperature compressors.

Quantity	One	
Manufacturer	Vilter Mfg. Co., Milwaukee, Wis.	
Capacity	150,000 Btu/hr@100°F condensing temperature	
Tubeside	Freon 22	
Shellside	Cooling water	
Material		
Shells	Steel	
Tubes	Copper	
Temperatures (°F)	Inlet	Outlet
Tube	100	100
Shell	60	67
Pressures (design)		
Tubes	200 psig	
Shell	150 psig	
Dimensions		
Length	7'	
Diameter	8"	

6. Refrigerant Receiver

The receiver is sized to hold 300 lb of refrigerant at 100°F and 200 psig.

7. Refrigerant Oil Separators

Quantity	Two	
Manufacturer	Temprite Prod. Corp., Birmingham, Mich.	
Model	225 (primary compressor) 226 (secondary compressor)	
Oil required	16 oz (#225) 29 oz (#226)	
Shell material	Steel	
Pressure	300 psig max.	

8. Instrumentation

A completely automatic temperature control system is provided to maintain the fluid leaving the oil-Freon heat exchanger at the controller set point to $\pm 5^{\circ}\text{F}$. The major components of this system are as follows:

Temperature Recorder-Controller - Temperature recorder-controller TRC-2 is a strip-chart, thermocouple-sensing, electronic recorder-controller with a range of -100 to +400°F. A 7" chart is provided in the control gallery for ease of read-out over the wide operating range. An immersion well with thermocouple is linked from the Hot Shop to the control gallery instrument by 200' of Type T thermocouple wire.

Sequencing Controllers - Two sequencing temperature controllers TIC-1 and TIC-2 are provided on the cooling system equipment package. Temperature controller TIC-1 functions at 125°F and makes the following changes during a cool-down:

- a. Diverts the output control signal of temperature recorder-controller TRC-2 from the fan motor starter on air-cooled heat exchanger PM-2A-HX-3 to solenoid valve FCV-21 which controls freon to the refrigerated heat exchanger PM 2A-HX-1.
- b. Cycles motorized valves FCV-3 and FCV-4 and motorized valves FCV-7 and FCV-16 so that loop fluid by-passes the air-cooled head exchanger and flows through the refrigerated heat exchanger.
- c. Cycles solenoid valves FCV-20 and FCV-27 in the suction lines to the freon compressors PM-2A-C-1 and PM-2A-C-2. The intermediate temperature valve FCV-27 is opened and the low temperature valve FCV-20 is closed.

Temperature controller TIC-2 functions at 40°F and makes the following changes during a cool-down:

- a. Diverts the output control signal of the temperature recorder-controller TRC-2 from the intermediate temperature, freon-control solenoid valve FCV-21 to the low temperature, freon-control valve FCV-22.
- b. Cycles solenoid valves FCV-20 and FCV-27 in the suction lines of freon compressors PM-2A-C-1 and PM-2A-C-2. The intermediate temperature valve FCV-27 is closed and the low temperature valve FCV-20 is opened. Since the compressors are controlled by suction pressure they will automatically start or stop in response to the suction valve position.

The sequencing controllers are interlocked to prevent improper sequencing so all the operator need do is set the recorder-controller to the desired temperature and turn on the "cooling-temperature control" switch.

HYDRAULIC FLUID STORAGE TANK

Tank

Quantity	One
Item No.	PM-2A-T-1
Type	Horizontal cylindrical with flat head
Capacity	940 gallons
Size	4' dia. x 10' long
Material	Type 304 stainless steel
Design temperature	375°F
Design pressure	Atmospheric

Filter

Quantity	One
Type	Pleated wire mesh cartridge filter
Design pressure drop	3 psi @ 160 gpm and 40°F fluid

AUXILIARY STORAGE TANK

Quantity	One
Item No.	PM-2A-T-2
Type	Vertical cylinder
Capacity	80 gallon
Dimensions	18" dia. x 6' high
Material	A-212 carbon steel
Insulation	None
Design temperature	100°F
Design pressure	50 psig

RELIEF VALVES

Relief valves are provided on the reactor vessel and on loop components which could be over-pressured. General specification pertaining to the valves are as follows:

Material	A-216 Gr. WCB carbon steel body with stainless steel internals
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End connections	Raised face flange
Max. service temp.	375°F
Min. service temp.	-40°F

LOOP FLUID

A fire resistant hydraulic fluid, Stauffer Chemical Co. "Base Stock 704" was selected as the loop fluid. This fluid, which is a trimethylolpropane triester, meets the following requirements.

1. The fluid remains in the liquid phase over the entire operating temperature range of -30 to 375°F.
2. The fluid exerts a negligible vapor pressure when at the maximum operating temperature.
3. The fluid possesses satisfactory physical properties for use as a heat transfer media for heating the reactor vessel.

Physical properties of the fluid are tabulated below, and the density, viscosity, thermal conductivity and specific heat of the fluid are indicated as a function of temperature in Figures I through IV.

FLUID PROPERTIES

<u>Laboratory Test</u>	<u>Base Stock 704</u>
Autoignition, °F	800
Evaporation loss, 6-1/2 hrs. @400°F, ASTM D972, Wt. %	6
Fire point, COC, ASTM D92, °F	520
Flash point, COC, ASTM D92, °F	460
Foam, mL, ASTM D892, After 5 min.	Trace
Pour point, ASTM D97, °F	-90
Specific gravity, 60/60 °F	0.963
Viscosity index, ASTM D567	+126

Figure I

Figure II

Figure III

Figure IV