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ZIRCALOY-2 PRESSURE TUBING

DECEMBER 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

Good Pract. New 63011 12/1/70

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10.0 OPERATIONAL STANDARDS AND SURVEILLANCE

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10.1 INTRODUCTION

Within the U.S., there are at least three water cooled reactors, operating at power producing temperatures, which use zirconium alloy pressure tubes in the core sections of the primary coolant circuit. In Canada, there are several similar reactors now operating or in advanced stages of construction. In the U.K., there is a steam generating reactor which also uses some Zircaloy-2 pressure tubes in the primary coolant system.

In these reactors, the number of pressure tubes in a single reactor range from eighty-five to nearly one thousand. In the construction of these nuclear reactors, both the type and scale of application of Zircaloy-2 pressure tubes were unprecedented with prior experience limited to special test loops in several operating reactors. The absence of a significant history of operating experience in both a nuclear and non-nuclear environment provided the incentive for undertaking pressure tube surveillance programs at several of these reactors. In most instances, the surveillance programs consist of periodic in-reactor inspections and destructive testing and evaluation of pressure tubes removed at specific increments of service.

This section will describe briefly the tube related operational standards and the surveillance programs in effect at the various reactors and the instrumentation used for in situ pressure tube inspections.

10.2 OPERATING STANDARDS

Operating standards which pertain to, or which limit, reactor operation because of the presence of zirconium alloy

pressure tubes are difficult to obtain for individual reactors. The Canadian experimental (NRX, NRU, NPD) and power reactors (CANDU-type) apparently have no written standards for reactor operation which relate directly to the pressure tubes;⁽¹⁾ nor do any Canadian or Hanford pressure tube reactors (PRTR and N-Reactor) have written specifications for items specifically investigated during tube inspections.^(1,2)

The PRTR and N-Reactor do have rather specific inspection programs which state the frequency of examination, normal sampling procedures to select tubes for examination, and criteria which require specific tubes to be examined because of non-normal operation history.⁽³⁻⁶⁾ This would include tubes which have experienced a stuck fuel element, a fuel rupture, a malfunction by temperature or flow trip, or a situation where a reasonable basis exists for suspecting that something detrimental may have happened to the tube.⁽⁵⁾

During inspection, the tubes are visually examined, with borescopes, for unusual items such as corrosion, fretting, blisters, or scratches and are checked for either inside diameter or circumferential dimensional changes. If anything unusual does appear, a technical analysis is made and a decision is made as to how to proceed.

There are no adopted criteria for tube removal. Such criteria have been written for the PRTR tubes, but have not yet been formally accepted.⁽⁷⁾

The PRTR⁽⁸⁾ and N-Reactor have operating standards, including startup and shutdown procedures, which relate to the pressure tubes. These standards are written to allow each tube situation to be considered individually. For example, the N-Reactor maintenance standards state "any incidence or occurrence

which may lead to the consideration of a pressure tube for replacement shall be referred to plant Engineering and Research and Engineering."

In general, operating pressure and temperature standards, coolant chemistry, and startup and shutdown procedures are limited more by the out-of-reactor primary piping and valves than by the Zircaloy-2 tubes.

10.3 IN-REACTOR SURVEILLANCE PROGRAMS

PRTR

There are 85 Zircaloy-2 pressure tubes in the PRTR core section of the primary coolant circuit. During normal reactor operation, most tubes contain fuel elements. That part of the pressure tube into which the fuel element is placed is nominally 3.25 in. in diameter on the inside. One end tapers to a nominal 1 1/2 in. ID. Actual dimensions of the pressure tube are shown in Figure 4.1, Section 4.2. The tubes are vertical and each is surrounded by a thermally insulating helium gas annulus which is enclosed in an aluminum tube. The arrangement of the pressure tube in the reactor core is shown in Figure 10.1. Fuel elements are charged and discharged from the pressure tube through the nozzle and nozzle cap assembly at the top end of the tube.

The design of the Zircaloy-2 pressure tubes was based on an allowable creep deformation of 1%. This deformation limit was selected because little stress rupture data were available; the strain limit was considered to be conservative in relation to the reduction in ductility due to radiation damage and this magnitude of deformation could be measured in situ by measuring the inside diameters of the Zircaloy-2 pressure tubes. Hence, this design criterion formed much of the basis for periodic inspections of pressure tubes in situ.

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FIGURE 10.1. PRTR Pressure Tube Assembly

Hydraulics investigation, with a prototypic pressure tube and fuel element, showed that minor fretting corrosion could occur and also that some ID surface scratching, from the insertion and removal of fuel elements, could be expected in the PRTR. Based on these observations, some means for visual examinations of the ID surface of the pressure tube was considered essential.

The Zircaloy-2 pressure tube in the PRTR is essentially "hung" from the top flange end (see Figure 10.1). Lateral displacement at the lower end is restricted by the shield plug and inlet jumper. Except for these end restraints, there were no other lateral restraints and bowing of either the aluminum shroud of Zircaloy-2 pressure tubes could occur. If there were sufficient bowing of either tube (less than 0.3 in. lateral displacement), the aluminum and Zircaloy-2 tubes would contact. Heat transfer considerations indicated that boiling at the moderator side of the aluminum tube could occur. Boiling at the OD surface of the aluminum shroud tube could promote intergranular corrosion and ultimately heavy water leakage from the moderator. Such an incident posed no nuclear hazard but from an operational and economic viewpoint, it was most undesirable. Preliminary investigations suggested that eddy current techniques could provide an instrument which would measure the position of the Zircaloy-2 pressure tube within the aluminum shroud tube.

Based on all of these requirements, the examinations and measurements to be made on the pressure tubes in-situ were as follows:

- Visually examine the ID surface of the pressure tube for evidence of mechanical damage, localized fretting corrosion film buildup.

- Measure the inside diameter and/or wall thickness to determine uniform creep deformation and locate areas of local wall thinning.
- Measure the displacement of the axis of the Zircaloy-2 pressure tube from the axis of the aluminum shroud tube as an indication of the eccentricity of the gas annulus between the ID of the aluminum shroud tube and the OD of the Zircaloy-2 pressure tube.
- Measure the zirconium-95 isotope radioactivity in the effluent primary system cooling water as an indicator of unusual corrosion conditions.
- Detect general and/or local hydriding of the Zircaloy-2 pressure tubes.

The initial in-reactor monitoring schedule was based on inspecting one-half of the pressure tubes twice within the initial year of operation. Under this schedule, two tubes from each of three alternate sextants were inspected at the end of each 10-day operating period with repeat inspection after three and before seven consecutive operating periods. Any tube in which a fuel element rupture occurred would be visually inspected prior to reactor startup.

The overall monitoring program also provided for the evaluation of certain pressure tubes by destructive testing after incremental periods of PRTR services. The initial removal and destructive testing and evaluation schedule provided for the removal of two tubes each year for about the first 2 years of operation. This removal rate was subsequently reduced to one per year and now stands at 40 to 200 MW of incremental service exposure, usually 100 MW.

Of the five inspections proposed, only three (visual and ID and gas annulus measurements) were undertaken under the initial schedule and concurrent with PRTR startup. All inspection instruments were incorporated into a single probe which could

be inserted into the process tube in a manner similar to fuel element charge-discharge. Shortly after PRTR startup, visual inspections were augmented with the addition of a remotely operable dial indicator for the purpose of measuring the depth of scratches and fretting corrosion marks.

Early in 1962, inspections indicated a trend of increasing occurrences and severity of local fretting corrosion at points of contact between fuel elements and the ID surface of the pressure tube.⁽⁹⁾ A full reactor inspection was made in June of 1962 and several of the more severely fretted tubes were removed for destructive testing and evaluation.⁽¹⁰⁾ Subsequent to this, the inspection schedule was changed to provide for the inspection of each tube at least once each year. At the same time, experiments were done which showed that the severity of fretting corrosion could be substantially reduced by enlarging the area of each point of contact between the fuel element and the ID surface of the Zircaloy-2 pressure tube.

The schedule of inspecting each tube at least each year continued for almost two more years. During this period very little severe fretting attack occurred although the rate of incidence probably did not change. Evidently, the increase in surface area of the fuel elements supports did effectively reduce the severity of fretting.⁽¹¹⁾ As a consequence, the inspection schedule was revised to provide for inspection of 80% of the pressure tubes each year and all process tubes are examined in each 2 year period.⁽¹²⁾ Current inspection results suggest that further decreases in the required inspections could be considered.⁽¹³⁾

In conjunction with the pressure tube inspections, an effort was made to monitor the radioactivity of the effluent of pressure tubes for the zirconium concentration as a method

for detecting significant fretting corrosion.⁽¹⁴⁾ Water samples that were obtained are concentrated and analyzed by emission spectroscopy. This method is sensitive to zirconium concentration as low as 0.1 ppb. Such analyses lose D_2O but they were generally found to correlate with other general observations of fretting corrosion activity in suggesting that in the PRTR the fretting attack was intermittent rather than continuous. With the rapid bulk mixing of D_2O coolant, this technique is incapable of pinpointing pressure tube by pressure tube where fretting was and was not occurring. Other schemes considered were:

- Continuous bypass of a small portion of the coolant stream into a continuous analyzer where the zirconium content is determined by colorimetric procedure. As yet this scheme is unreliable in concentration ranges of 0 to 10 ppb and depends on the physical state of the corrosion product (e.g. ionic, colloidal, particulate, etc.)
- Continuous bypass of a small portion of the coolant stream into a radioactivity analyzer to detect the concentration of the zirconium-95 isotope.

Further work needs to be done on both schemes before the feasibility of "on-line monitoring" can be determined.

Inspection of the pressure tubes in the PRTR on the scale undertaken was fully as unprecedented as was the use of Zircaloy-2 pressure tubes in the core section of the primary coolant circuit. For nearly the first 4 years of the in-reactor inspection program, all efforts were done by research and development personnel not directly involved in the operation of the reactor. For the past several years, all inspection efforts were done by reactor operating personnel with some consultation from R&D personnel.

On the whole, the in-reactor monitoring effort proved worthwhile in the PRTR. Visual examinations proved to be an

invaluable tool in detecting the extent and magnitude of the fretting corrosion problem and also proved to be quite useful in the effort undertaken to alleviate the problem. Visual examinations detected blister type defects on the ID surfaces of three pressure tubes which had gone undetected through thorough preinstallation inspections. Visual examinations were indispensable in handling the fuel element-pressure tube failure in 1965.⁽¹⁵⁾

About 3 years after the start of the reactor monitoring program, both ID and gas gap measurements were discontinued. Inside diameter measurements disclosed only a little creep deformation. Independent R&D programs on Zircaloy-2 tubing showed that little or no creep deformation was to be expected at stress and temperature conditions present in the PRTR. Hence, there was no further need for ID measurements. With regard to gas gap measurements, little or no permanent warpage of either the pressure or shroud tube was observed with the exception of one or two process channels. One must recall, however, that measurements were obtained with the reactor in a shutdown condition and at or near room temperature. Hence, these measurements may not truly represent conditions when the reactor is operating. In consideration of these two factors, routine gas gap measurements were discontinued.

In the matter of hydride detection, a really suitable instrument has not yet been developed. Examinations of pressure tubes removed from service have disclosed some local hydriding at areas where fretting corruptions occurred. Destructive testing, however, shows that the extent of hydriding so far does not appear to have adversely affected mechanical properties of the tubing to any significant degree. For the present there are no plans to include hydride detection in the routine in-reactor inspection schedules.

As initially conceived, the in-reactor inspection program was rather ambitious. There was no need for ID measurements on a statistically large number of pressure tubes. Measurements on several tubes would have been adequate. Gas gap measurements were not entirely adequate in that they may not truly represent actual operating conditions. They did, however, provide a degree of assurance. As yet there is no really satisfactory substitute other than the installation of some contrivance that physically precludes contact between the pressure and shroud tubes.

One of the greatest difficulties was combining all inspection and measuring instrumentation into a single inspection probe. Separating the instrumentation for each of the inspection functions would have greatly simplified construction and subsequent maintenance of equipment. Separation would also allow much greater freedom in scheduling inspections and make it easier to incorporate changes that experience showed to be useful and desirable.

Visual examinations were made with a borescope coupled to a standard closed circuit television camera. This system produces a two dimensional "view" of the inner surface of the pressure tube. With experienced personnel, this system provides a quick scan of the inner surface of the tube. When the tube surface is not heavily filmed, fretting corrosion "marks" can be readily seen and identified with appropriate lighting. Unidentifiable objects on the inner surface of the tube could be viewed directly through the borescope by means of a "right angle eyepiece." For inexperienced operators, the television system is less than adequate. With the television system there is no color to aid in "scene" identification. Optical resolution and clarity is less than with a borescope alone. A television camera responds most readily to the brightest part of the scene in view, hence dark parts of the scene may not be seen at all.

For an inexperienced operator a standard borescope also presents some significant difficulties. Here again, the view is not truly three dimensional. Axial distances invariably appear to be significantly less than actual. Under certain conditions the image may be reversed and/or inverted thus making it difficult to establish a frame of reference. Despite these difficulties, visual inspections are still considered to be the most useful of currently available inspections methods.

N-Reactor

The N-Reactor utilized about 1000 Zircaloy-2 pressure tubes in the core section of the primary coolant circuit. The pressure tubes are placed horizontally within a stack of graphite and are approximately 50 ft in length. Fuel elements are inserted from one end of the pressure tube and removed from the opposite end. The tube is uniformly 2.70 in. ID with a wall thickness of 0.270 in.

As was the case with the PRTR, N-Reactor pressure tubes were designed primarily on the basis of allowable creep deformation. Based on the few years of prior PRTR experience and additional laboratory data for both irradiated and nonirradiated Zircaloy-2, the allowable creep deformation selected was 1%.

Based to a large extent on PRTR in-reactor monitoring experience, the N-Reactor monitoring effort was designed to provide for:⁽¹⁶⁾

- Visual inspection of the ID surface of the pressure tubes at periodic intervals. A minimum of 2% and up to as high as 5% of the tubes are to be routinely inspected per year under normal reactor operating conditions. Inspections of specific tubes are made whenever a fuel element rupture occurs near the pressure tube wall, or if there were stuck

fuel elements in the tube, or if prolonged hot coolant or severe local power cycling was found to occur in the specific pressure tube.

- Inside diameter measurements of about 2% of the pressure tubes each year under normal reactor operation. Based on visual examinations, ID measurements may also be obtained for specific pressure tubes subjected to any of the aforementioned abnormal operating conditions.
- Routine measurements with eddy current instrumentation for the detection of severe general or localized hydriding (e.g., 1000 ppm H_2).

Under normal reactor operation, the monitoring efforts also requires the removal of two pressure tubes each year for postirradiation examination. A specific tube will be candidate for removal if:

- A fuel element rupture occurs in contact with the ID surface of pressure tube.
- Severe physical damage occurs so as to produce a gouge, scratch, etc., which is 0.025 in. or greater in depth.
- Evidence of severe (1000 ppm or more H_2) local hydriding.
- There is general or local deformation in excess of 2%.

Current in-reactor inspections have been limited to visual examinations. The visual examinations are made by both closed circuit television and direct viewing with an optical borescope. To date, inspections disclosed nominal amounts of fretting corrosion and scratching from fuel element insertion and removal.

Thus far, two pressure tubes have been removed for post-irradiation testing and evaluation. This work is classified and, therefore, it is not reported here.

AECL Reactors

All of the Canadian power reactors utilize pressure tubes. For the reactors already constructed and operating, all used

Zircaloy-2 pressure tubes. Reactors in the design stage and under construction may use Zircaloy-2 or Zr-2.5 wt% Nb alloy pressure tubes. In the NRX and NRU, the pressure tubes are in vertical position. In most, if not all of the power reactors, the pressure tubes will be in a horizontal position.

The current in-reactor surveillance program is limited to the test loops in NRX and NRU.⁽¹⁾ Current schedules call for inspection of the 3-loop tubes in NRU every 2 to 4 months. The single loop tube in NRX is inspected every 4 months. In the NPD, one tube was inspected in 1963,^(1,17) and the same tube was inspected again in 1965. It is anticipated that the same tube and perhaps more will be inspected about every 2 years. These inspections are done by technical personnel at Chalk River Nuclear Laboratory (CRNL). For the power reactors, the utility operator is expected to be responsible for whatever surveillance program he feels to be necessary. CRNL would supply no more than technical consultation.

One of the primary reasons CRNL undertook the in-reactor surveillance effort was to measure in-reactor creep on pressure tubes. Design stresses for the pressure tubes in NPD and other Canadian reactors are appreciably higher than was the case with PRTR and N-Reactor in the U.S. With precision ID measuring equipment, neutron flux effect on in-reactor creep has been observed. As a consequence, the AECL program has been modified to provide for ID measurement on pressure tubes in NRU and NRX test loops which operate at hoop stresses ranging from about 16,000 to 25,000 psi.

All factors considered, the current AECL in-reactor surveillance program is more orientated toward the acquisition of research data than as a reactor operating aid.

Postirradiation evaluation of pressure tubes removed from operating reactors has not yet gotten underway. Two tubes, however, have been removed from the NPD.

The inspections which are done in the NRX and NRU loops are:

- Surface defect and roughness gaging. Instrumentation provides a measure of scratch depth, pits and other surface defects.
- Visual examination of the ID surface by direct viewing through a borescope. Inasmuch as substantial time (several hours) is required, borescoping is not done unless surface defect gaging indicates a need for visual examination.
- ID measurements to detect creep deformation.
- Wall thickness measurements. As yet no wall thickness measurements have been obtained from pressure tubes in-reactor.
- Measurement of bowing of the pressure tube by optical sighting of a target as it is moved along the length of the pressure tube.

The surveillance program has, so far, disclosed little or no fretting corrosion or scratching of the inner surface of the pressure tubes in NRX, NRU, and NPD. Diameter gaging discloses small ($\sim 0.1\%$) but discrete increases in pressure tube ID in the in-core section of the pressure tube. Plotted curves of the increase in pressure tube ID along the length of the tube through the reactor core show the same shape as do curves of neutron flux intensity through the reactor core. Bow measurements indicate that there are no significant problems with bowing.

10.4 EQUIPMENT

Instrumentation for operational surveillance of pressure tube type reactors has primarily been designed for use in the pressure tubes in situ and when the reactor is in shutdown status. As yet there is little "on-line" instrumentation for monitoring behavior during reactor operation. The only known instance of "on-line" monitoring is the measurement of vibration of pressure tubes in the PRTR by means of standard commercial accelerometers attached to the inlet jumpers of the primary coolant circuit.

The inspections of pressure tubes made during a normal or special reactor outage generally consisted of:

- Visual inspection of the ID surface and/or measurement of surface defects, fretting corrosion, scratch depth and the like.
- Dimensional measurements, ID, wall thickness, and gas gap (PRTR only).
- Hydride detection, local and/or general.

Within the U.S., the main inspection method was and still is, visual inspection and surface defect measurements. In Canada, the greatest emphasis is placed on ID measurements and surface defect measurements; relatively little emphasis is currently placed on visual inspection. These differences probably reflect the differences in operating experience at the various reactors.

Visual Inspection Equipment

The system initially designed for the PRTR used an optical borescope through which the ID surface of the tube could be viewed directly or remotely by means of a closed circuit TV camera and monitor.⁽¹⁸⁾ The closed circuit television (CCTV) system provides a means for rapidly scanning the ID surface of the pressure tube and further provides for simultaneous viewing

by two or more operators. The view presented on the CCTV monitor has no color. Lighting of the surface of the tube under inspection must be carefully done to avoid glare since the CCTV camera responds to the most intense light emanating from the object in view. Hence, under certain conditions, a critical part of the view may be "washed" out because it is too bright or too dark in comparison with some other part of the view. In short, a TV camera falls far short of the ability of the eye to accomodate rather wide differences in light intensity within an area in view. To make the adjustments in lighting and CCTV adjustments requires considerable skill on the part of the operator. Optical resolution of a standard commercial CCTV camera is appreciably less than for most optical borescopes.

Both the CCTV camera and the more or less standard monocular borescope present essentially a "two dimensional" view of the area within view of the borescope's objective lens. Distances parallel to the axis of the objective lens are "foreshortened" and difficult to estimate even by a well experienced operator. Under certain conditions, the image seen by an operator in the eyepiece of the borescope may be reversed and/or inverted. Under such conditions, inspections of the ID surface of a round or symmetrical tube makes it difficult to establish a "frame of reference" for locating and identifying surface defects.

Despite the difficulties and shortcomings of visual inspection equipment, visual inspection is still the most important in the PRTR. At present, the use of the CCTV has been discontinued because of operator inexperience and excessive maintenance. Borescope examinations are still continuing at the rate of about 80% or about 60 pressure tubes per year.

The visual inspection system designed for the N-Reactor uses a special high optical resolution CCTV which can be

inserted into the pressure tube.^(19,20) This CCTV system can optically resolve two 0.003 in. diameter wires spaced as close as 0.010 in. The optical system is equipped with a moveable mirror. This mirror, when at 45 degrees to the axis of the CCTV camera, provides a normal and enlarged view of the pressure tube wall. Surface defects, when viewed normally and obliquely, are more easily identified by even relatively inexperienced personnel.

The above CCTV system still has appreciably less optical resolving power than do monocular borescopes. Hence, at N-Reactor, the CCTV system is used primarily for general scanning of the ID surfaces of the pressure tube. A video tape recorder is also available to provide a permanent record of the ID surface condition of the pressure tube. Detailed examinations of selected areas within the tube are done with a monocular borescope.

CRNL personnel use a monocular borescope exclusively for visual examinations of the ID surface of pressure tubes.⁽²¹⁾ Relatively few visual inspections are made in the AECL in-reactor monitoring program. The overall monitoring effort to date is largely limited to one tube in NRX, three in NRU and one in NPD. Previous visual examinations revealed only nominal surface damage from fretting, and surface scratching by fuel element supports. A device similar in principal to a phonograph needle is used to "scan" the entire surface of the ID of these pressure tubes and measure the depth and contour of surface defects, scratches, and the like. Successive "scans" of the tubes inspected can be compared and only in those instances, where significant "roughness" (e.g., 5 mil deep gouges, scratches, etc.) or significant changes are noted, is the tube then visually inspected with the borescope.

In spite of all the shortcomings of both CCTV systems and borescopes for visual examination, visual examinations of pressure tubes continues. For the PRTR and the N-Reactor, optical systems have become the primary inspection tool. Based on such experience, it appears that optical inspection systems might well be reviewed with the aim of achieving significant improvements in them. As yet, there has been no effort to develop a binocular borescope which would provide a good three dimensional field of view. At present, CCTV systems do not provide adequate optical resolution, color, or simplicity in operation and maintenance. Any further effort with CCTV systems is probably not warranted until significant breakthroughs in the television industry come about.

Surface Defect Measuring Instrumentation

A modified standard dial gage is used for measuring surface defects such as local tube wall erosion by fretting corrosion, gouges, and scratches in the PRTR.⁽¹⁸⁾ The dial gage is mounted on the borescope within the normal field of vision through the borescope. The dial gage is mounted on a moveable piston which is actuated by air. When actuated, the dial gage moves toward the tube wall until a curved "shoe" fitted to the stem of the dial gage makes contact with the tube wall. The contact point of the dial gage extends through the "shoe" until it contacts the "bottom" of the surface depression, scratch, etc. When repeated at a point on the tube wall adjacent to the defect, the dial indicator gives a different reading and the difference denotes the depth of the scratch, gouge, or other surface defect. This device has worked satisfactorily for measuring fretting corrosion erosion, gouges, and open "blister" defects on the ID surface. The dimensions of the contact point preclude depth measurements of scratches 10 mils or less in width.

The device used in the N-Reactor equipment^(18,19) is very similar to that used in the PRTR. In this case, actuation of the dial gage is through an electric motor driven cam rather than by air.

The device developed by CRNL is quite similar in principle to a phonograph needle.⁽²¹⁾ Actually three "needles" are used to cover the expected range of defect magnitudes. The gage is spiraled along the tube so as to provide a complete surface scan of the ID surface of the tube. Defect measurements are recorded on a strip chart. Reportedly, this gage has worked satisfactorily for the past several years.

Dimensional Gaging Instrumentation

The inside diameters of the pressure tubes in the PRTR were measured at two mutually perpendicular axes along the full length of the 3.25 in. bore by means of two LVDT systems.⁽⁷⁾ The LVDT gages are calibrated and checked before and after measuring each tube. Subsequent measurements were to be made at the same perpendicular axes for comparison purposes. Any diameter changes would provide the measure of creep deformation that had occurred between measurements intervals. In theory, this scheme appeared to be good. It was difficult, however, to obtain subsequent measurements in exactly the same planes of the original measurements. If the pressure tubes had been perfectly round, there would be no difficulties. But since all tubes are randomly out-of-round to some degree or other along their length, some measurement error was introduced. This error was estimated to be about 0.1%. After about 3 years of measurements no deformation significantly greater than the error measurement was observed. (Subsequent diameter measurements obtained with a Pi tape on tubes removed from the PRTR showed approximate diameter increases of between 0.1 and 0.2%.) In-reactor diameter measurements have been discontinued for the past several years. Future diameter measurements are expected to be obtained only from tubes removed from the reactor and by means of a Pi tape. Pi taping can be done in the storage basin with little effort and expense.

The ID gage for N-Reactor pressure tubes is identical with the LVDT system initially used in the PRTR.⁽¹⁷⁾ To date no measurements have been made.

The gage developed by CRNL is of the LVDT type similar to that used in the PRTR but with provision for measuring three equally spaced diameters.⁽²¹⁾ The LVDT gages are calibrated and checked before and after each tube is measured. These measurements are combined to provide an average diameter at specific distances along the length of the tube. These techniques have been useful in detecting flux influenced pressure tube creep in the test loops at NRX and NRU reactors. Measurements of the inside diameters of the pressure tubes in the NRX and NRU test loops are continuing.

Gas Gap Measuring Gage for the PRTR

The PRTR uses flowing helium within the annulus between the OD of the Zircaloy-2 pressure tubes and the ID of the aluminum calandria tube as a heat transfer barrier between the hot primary coolant system and the cold D₂O moderator system. Sufficient bowing of either the Zircaloy-2 or aluminum tubes to cause contact of the two tubes could cause boiling in the moderator. Using four eddy current coils spaced at 90 degree intervals, the eccentricity of the gas annulus could be measured.^(18, 22-24) The eddy current coils are held in contact with the ID surface of the Zircaloy-2 pressure tube. Using an appropriate exciting frequency, the coil can detect the distance it is away from the aluminum calandria tube. The device must be calibrated and checked before and after measuring each tube. Relatively little bowing was observed. The gage as built could only be used when the reactor was shutdown; hence, no information under actual operation was obtainable. This gage is no longer used but has been maintained on a standby basis.

Hydride Detection Instrumentation

To date, a really usable hydride detection instrument has not been developed. Both eddy currents and ultrasonic can be made to respond to the presence of large concentrations of zirconium hydride. However, both types of instruments respond to other changes in metallurgical structure (e.g., grain size, orientations, etc.). For this reason, it is quite difficult to interpret any signal obtained from either type of instrument.

An ultrastable eddy current device that could detect hydride concentrations as low as 250 ppm was demonstrated in the laboratory.⁽²⁵⁾ This device was used in the K reactors at Hanford, with rather indifferent success.^(26,27) A prototype ultrasonic device was built for use in N-Reactor, but was never used because of mechanical problems.⁽²⁸⁾

Tubes removed from the PRTR are examined metallographically for reasons other than hydride detection. As a result, adequate data were obtained without the use of an in-reactor gage.

CRNL has done little or no work toward the development of a hydride detection gage.

Over the past several years, laboratory investigations have included the effects of hydriding on the general mechanical properties. While entirely adequate knowledge concerning the effect of hydriding on pressure tube properties is not yet available, work is proceeding in that direction. Hence, the incentive for a hydride detection instrument has lessened to some extent.

Wall Thickness Measurements

Although wall thickness measuring prototypes were developed for PRTR pressure tubes and the pressure tubes in NRX and NRU, wall thickness measuring gages have not been used on pressure tubes in situ. The generally good performance of Zircaloy-2

pressure tubes and the conservatism existing in the design of the tubes now in the various reactors seems to eliminate any need for wall thickness measurements.

Ultrasonic methods requiring good coupling between the transducer and the tube wall were used in the prototype gages. For this reason, measurements are most easily obtained when the tube is full of water. This is in sharp contrast to all the other inspections which require that the tube be empty and dry. Potential D₂O losses also discouraged use of ultrasonic wall thickness measuring gages.

10.5 SURVEILLANCE AND TUBE REMOVAL CRITERIA GRID

A surveillance criteria and tube removal criteria grid have been prepared covering the operational standards and surveillance for the PRTR and N-Reactor.^(3-6,29) A column called "Comments and Priorities" is included that gives an evaluation of existing specifications and shows where additional specifications are needed. The specifications are rated as follows:

- I. Areas where ASTM specifications and other existing specifications and operating or maintenance standards are adequate.
- II. Areas where existing ASTM specifications and operating or maintenance standards should be modified.
- III. Areas where no specifications operating or maintenance standards exist and are needed.

Items, believed necessary to assure quality of pressure tubes are classified I, II or III as defined above. Also, priorities are listed for the R&D efforts needed to modify or establish, where absent, specifications, operating and/or maintenance standards for pressure tubes in heavy water reactors. These priorities are defined as follows:

- A. Areas which have a major effect on tube life, reliability or operating and maintenance procedures, which are not backed up by common commercial practice or other specifications.

- B. Areas which have a major effect on tube life, reliability or operating and maintenance procedures but which are backed up substantially by other specifications, operating or maintenance standards.
- C. Areas which have a minor effect on tube life, reliability or operating and maintenance procedures and for which adequate technology exists.

TABLE 10.1. Surveillance and Tube Removal Criteria

Surveillance Criteria

A. Operating Incidents

Item	PRTR	N-Reactor	Comments and Priorities
1) Rupture of a fuel element	BNWL-MA-1. Visual inspection in situ if fuel element inspection in storage basin shows evidence of contact with tube. If tube examination shows evidence of damage, tube is removed, inspected and proof tested before returning to service.	(Tentative) Visual inspection in situ if there is evidence that ruptured fuel element contacted tube surface. Contact is assumed if: 1) 5 times greater than normal force is required to discharge fuel element. 2) If rupture occurred in an outer fuel element.	II-A. An NDT test for hydriding would be desirable. More data and experience are desirable to establish actual service limiting damage.
2) Excessive temperature excursion of a pressure tube	BNWL-MA-1. If temperature of tube exceeds 600 °F, it must be removed, inspected and proof tested before returning to service if undamaged.	(Tentative) In situ inspection required if tube has been subjected to prolonged hot channel service. Temperature and time unspecified.	II-A. BNWL-MA-1 appears to be unnecessarily stringent. For N-Reactor there are no provisions for spotting a "hot" coolant channel by operating personnel.
3) Loss of flow in a pressure tube	Pressure drop limits are set to scram the reactor. Fuel elements examined to determine cause of flow loss.	Pressure drop limits are set to scram reactor. Fuel elements examined to determine cause of flow loss.	I. Principally a problem in operating procedure.
4) Continued high concentration levels of Zr corrosion product in primary coolant	No operating standards	No operating standards	II-B. Appreciable efforts are needed to establish a monitoring method and concentration levels of Zr corrosion product in the primary coolant which can reliably signal the need for fuel element and pressure tube inspections.
5) Prolonged vibrations of one or more pressure tubes	No operating standards	No operating standards	III-B. Some work has been done under PRP Program to correlate vibration frequency and amplitude with fretting. Work also needs to be done to ascertain the effects of superimposing pressure cycling and bending from flexural vibrations on fatigue crack growth rates.

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TABLE 10.1. Surveillance Criteria (contd)

B. Inspection Equipment

Item	PRTR	N-Reactor	Comments and Priorities
1) Visual	Borescope + CCTV and direct view - Monocular CVTR closed circuit TV	Borescope and/or CCTV Monocular	II-B. Development of binocular may be quite desirable. BNW has technology and personnel. Holography may also be applicable
2) Flaw detection (Surface and internal)	None used other than visual for surface flaws	None used other than visual for surface flaws	III-A. Need to develop instruments which are easily and reliably used by semi-skilled operators. Basic technology is available.
3) Hydride detection (materials evaluation efforts have not progressed to point where "go-no-go" limit can be set.)	None used now	None used - an eddy current device is available	III-A. Reliable and simple-to-use equipment is not yet available. Development work has stopped. Neutron radiography reported as a potential detection method.
4) Dimensional measurements	Routine measurements discontinued. Pi taping done on a convenience basis on tubes removed from the reactor.	ID measurements obtained for 2 to 5% of pressure tubes in the reactor	I. Technology is available. Design of equipment probably needs to be tailored to each reactor.

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TABLE 10.1. Surveillance Criteria (contd)

C. Inspection Schedules and Frequency

Item	PRTR	N-Reactor	Comments and Priorities
1) Visual	80% of the 85 pressure tubes inspected once per year. Special tests require inspection at specified intervals. "Operating incidents" require inspection.	Minimum of 2% and up to 5% of the 1,000 pressure tubes in the core. Operating incidents require inspections.	I. For PRTR inspection frequency probably exceeds needs. For N-Reactor, there is not enough experience to assess adequacy of current schedules.
2) Flaw detection	Surface flaw detection is incorporated with visual inspection. NDT methods not used.	Surface flaw detection is incorporated with visual inspections. NDT methods not used.	II-A. Visual methods are not adequate to detect fine type cracks.
3) Hydride detection	Not scheduled. Operation depends on examination and destructive testing of tubes permanently removed from reactor.	Not scheduled. Same as for PRTR. An NDT instrument is available for use.	II-A. Periodic tube removal and destructive examination is unsuitable for commercial reactors in most cases.
4) Zr corrosion product. Content of primary coolant	Sampling discontinued. Cost too great and technique is inadequate to detect corrosion products	Not scheduled	III-B. Feasibility of on line monitoring should be undertaken.

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TABLE 10.1. Tube Removal Criteria

Item	PRTR	N-Reactor	Comments and Priorities
1) Overtemperature	Tube removed for out-of-reactor inspection if tube temperature exceeds 600 °F.	Action is based on a review by Plant Engineering and by Research and Engineering Groups	II-C. PRTR standards appear to be overly conservative. Limit for inspection may be more realistic than one for mandatory removal.
2) Dimensions (Creep, straightness)	No operating standards which specify limit of dimensional changes for mandatory removal.	Tentative deformation limit is a 2% increase in the tube ID	II-A. In-reactor creep and stress rupture data is needed to establish a realistic deformation limit and to establish appropriate working stress levels and minimize in-reactor inspections. Straightness requirements should be determined by designer.
3) Flaw Size (Surface and internal which may enhance probability of "brittle" failure)	No operating standard for internal flaws. Tentative standards based on a safety factor of 4 are: 1) failure - flaw length, 1 in. - flaw depth, 1/8 in. 2) leakage - flaw length, 1/4 in. - flaw depth, 1/8 in.	No standard	II-A. For PRTR, the tentative flaw size specification is based on unirradiated tests. Irradiated data is required to assess the effects of: 1) neutron exposure 2) hydriding 3) combined reactor service environment on the fracture toughness of pressure tubes.

TABLE 10.1. Tube Removal Criteria (contd)

<u>Item</u>	<u>PRTR</u>	<u>N-Reactor</u>	<u>Comments and Priorities</u>
4) Neutron exposure (cumulative)	No standard	No standard	III. There is no information which as yet can suggest whether or not a neutron exposure limit exists.
5) Hydrogen uptake from corrosion or other sources	No standard	Tentative limit of 1,000 ppm locally. Unspecified as to how measured.	II. As yet there is no reliably usable instrument for measuring, hence limit is somewhat unrealistic. Effects of hydriding on fracture toughness and other pertinent mechanical properties needs further investigation before a reasonable limit is established. Hydrogen uptake from corrosion can be estimated. From a fuel failure or other source, the extent of hydriding cannot easily or reliably be estimated.

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