THE CRACKING OF PRESSURE TUBES IN THE PICKERING REACTOR

Small cracks in 17 of the 390 pressure tubes in Unit 3 of the 2056 MW (electrical) Pickering Generating Station and of 52 tubes in Unit 4, resulted in each of these units being out of service for many months. The cracks originated at areas of extremely high residual tensile stress produced by improper positioning of the rolling tool used during construction to join the pressure tube to its end-fitting. The mechanism of failure was delayed hydrogen cracking.

INTRODUCTION

The performance of the 2056 MW(e)* Pickering Generating Station has been extremely good; the station achieved net capacity factors of 83.4, 75.1, 62.7 and 87.3% during 1973, 74, 75 and 76 respectively. The relatively low capacity factors in 1974 and 1975 were caused by extended outages of the No. 3 and No. 4 units because of small cracks in some pressure tubes. Unit 3 was out of service from August 1974 to March 1975, and Unit 4 from May 1975 to March 1976, to replace leaking tubes. The defective pressure tubes were sent to CRNL where they were extensively examined and tested.

The Pressure Tube Reactor

The Pickering Generating Station consists of 4 reactors or units of 514 MW (e) each (Figure 1). The pressure tube is the pressure vessel in the CANDU (Canada Deuterium Uranium) nuclear power reactor; pressure tubes rather than one large pressure vessel contain the fuel and coolant. The power reactor basically consists of a calandria, a large tank containing the heavy water moderator, end shields, and an array of identical fuel channels which project through the end shields and calandria. The main components of a fuel channel are the pressure tube, the calandria tube, the central spacers and the end fittings. The capability to remove tubes from the reactor proved to be of great value during the investigation of cracks in the Pickering pressure tubes.

The pressure tubes of about 6 m (240 in.) length, 4.1 mm (0.162 in.) wall thickness, and 103 mm (4.07 in.) inside diameter contain the fuel and heavy water coolant at about 9.0 MPa (1300 psi) and 566 K (290°C). Cold-worked Zr.2.5 wt% Nb with a design stress of 158 MPa (23,000 psi) at 573 K (300°C) is the pressure tube material for current CANDU reactors. The pressure tubes in a CANDU-PHW (pressurized heavy water) reactor are horizontal and subject to internal pressure and to bending loads due to weight of fuel and coolant. The ends of the pressure tubes are rigidly joined to end-fittings of stainless steel by rolled joints (see Figures 1 and 2). The end fittings are firmly supported by the end shields. The tube is of simple geometry; there are no welds or appendages. The only discontinuity is at the tube joint to the end fitting.

Figure 2 shows the cross section of a rolled joint. Three grooves are machined in the end fitting bore. The pressure tube is inserted into the end fitting covering the grooves. A tube expander is introduced into the pressure tube through the end fitting (Figure 3). The tube is roll expanded into the end fitting. The tube wall thickness is reduced by 12 to 13% and the grooves in the end fitting are partially filled with tube material which locks the tube to the end fitting producing leak tightness and axial strength. Although the rolled joints themselves have behaved perfectly, improper rolling procedures during construction caused cracks close to the rolled joint in 17 pressure tubes of Unit 3 and in 60 tubes in Unit 4. However, before discussing the cracks in the tubes, the events leading to the discovery of the cracks will be reviewed.

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*Electrical capacity.

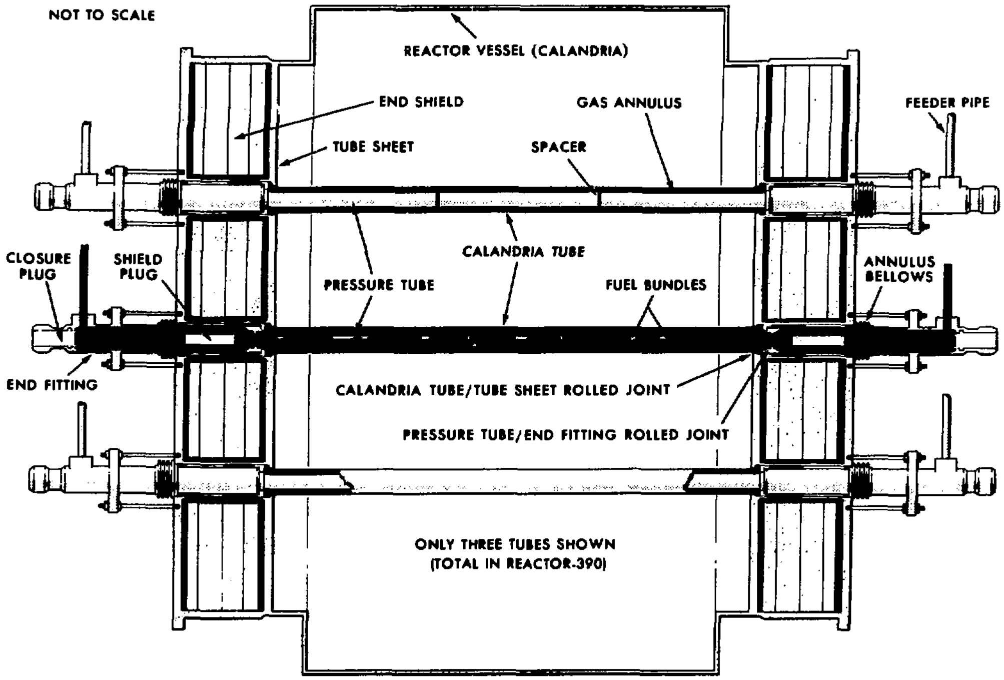

Figure 1 – Simplified diagram of Pickering reactor.

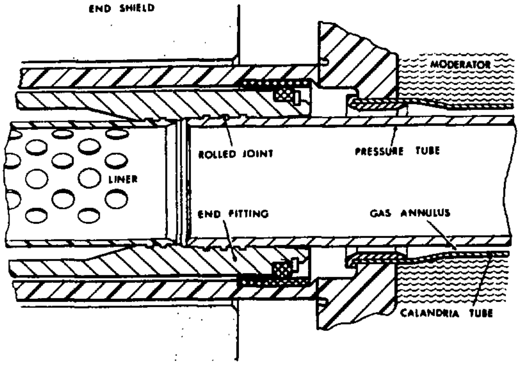

Figure 2 – Rolled joint arrangement in Pickering reactor.

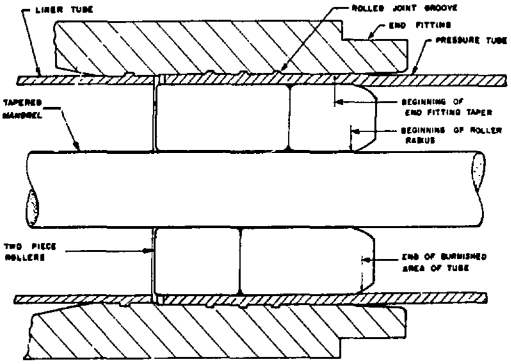

Figure 3 – Cross section of a rolled joint during roll expanding.

Leak and Crack Detection

On August 10, 1974, when Unit 3 was being returned to service after a scheduled maintenance outage, routine checks revealed heavy water leaks into the system which circulates dry nitrogen gas through the annulus between the pressure and calandria tubes. The leaking heavy water was fully recovered from the gas circulating system, and at no time was there any hazard to operator or to the public. Chemical analysis identified the water as coolant from the primary heat transport system and not moderator water, thus indicating the leak was in the fuel channel. At this time, it was realized that the pressure tube and end fittings from the leaking fuel channel would have to be removed.(1)

By August 17, the leaking channel had been positively identified and preparations were made for its replacement. The channel was defueled and isolated by blanking off the coolant feeders. Repair procedures were finalized and crews were trained on a mock-up. The fuel channel was removed in 30 hours,(1) and a new channel was installed in 8 hours. After the first channel was replaced, a procedure to dry the annular gas space was initiated. After this procedure had been used for several days, a continued high collection rate from the annulus gas system led to the unpleasant conclusion that there must be another leak. During the next few weeks two more leaking channels were identified and replaced. Leaks were found by an "acoustic emission" technique. A probe was placed in turn on the end fitting of each pressure tube. With the reactor pressurized, leaking channels could be discriminated from non-leaking ones by a characteristic increase in the signal amplitude in certain frequency ranges.

During August and early September when the first leaking channels were being replaced, the cause of the leakage was still not known, but one of the strong points of the Canadian nuclear power program was already emerging, i.e. the ability to organize itself and react when troubles occur. Before the first channel was removed, the radiation safety, security, transport, and numerous other service groups from Atomic Energy of Canada Limited and Ontario Hydro, who were familiar with the transportation of highly radioactive components, were being organized. They prepared detailed plans and obtained clearances to move the components which had radiation fields of about 1500 R/h by special transport in heavy shielded flasks to the Chalk River Nuclear Laboratories (CRNL) where numerous facilities exist for handling radioactive components.

By September 10, pressure tests in the 'bays' (water-filled trenches) had confirmed the leak to be in the pressure tube near the end fitting at the coolant inlet end of the channel. At this point Canadian industry became deeply involved; a team from Canadian General Electric with extensive experience in the design and development of rolled joints for CANDU reactors, was called to help with the investigation. At first, it was suspected that the rolled joint had loosened and begun to leak. However, after extensive ultrasonic testing and dimensioning of the joint had been completed, the stainless steel end fitting was cut away from the pressure tube and three cracks in the tube were revealed. The cracks had been hidden from view by the overhanging portion of the end fitting (Figures 4 and 5). These cracks were all located just beyond an unexpected ridge on the outside of the pressure tube. The origin of the ridge appeared to be associated with the rolling procedure used. Dimensional checks on the rolled joint had revealed that the rollers used during fabrication must have extended beyond the parallel part of the end fitting.

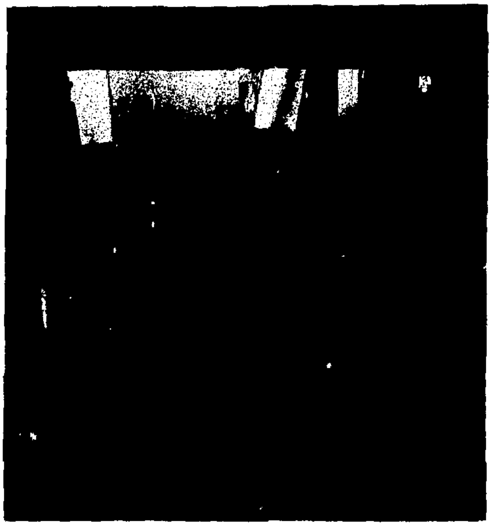

Figure 4 – Section of pressure tube containing crack being examined in a shielded cave.

The Crack Investigation

Figure 5 shows some of the important features of the crack and joint, and Figure 6 is a view of a typical crack. During October the examination of the fuel channels removed from Pickering Unit 3 revealed the following:

a) Dimensional measurements in the tube and rolled joint showed that the rolling tool had been inserted about 13 mm (0.5 in.) too far into the tube at the 'West' end during the rolling operation. This condition is termed 'over-extended' rolling. The rolling tool had thus been expanding the tube for about 10 to 15 mm (0.4 to 0.6 in.) beyond the hub (the parallel bore of the end fitting), and in a region where the tube has little support. (See position of taper and roll in a poor joint, Figure 5.) The joints at the 'East' end of the reactor were not as over-extended as those at the 'West' end.

b) The cracks were about 13 to 20 mm (0.5 to 0.8 in.) long and were just inboard of the rolled joints, where the tube is flared out during the roll forming process. The crack initiation point was close to the innermost point of contact of the rollers (Figure 5). The cracks had either propagated through the tube wall or had propagated almost through the wall with only a thin web on the outside remaining.

c) The surface of the cracks showed that propagation was from the inner wall of the tube and was in distinct bands (Figure 6). Each band was oxidized a different amount. The first heavily oxidized gray bands suggested the crack had been exposed to the coolant for a long time. The second black bands showed some oxidation, and the last bands showed very light oxidation suggesting very little exposure to coolant at temperature.

d) Electron fractography of the oxidized crack surface showed characteristics found in zirconium alloys that had failed by delayed hydrogen embrittlement.(2, 3)

e) Radial hydrides (i.e. zirconium hydride platelets in the radial-longitudinal plane) existed in the same circumferential plane as the cracks (Figure 5). The orientation of zirconium hydrides within the pressure tube is normally circumferential. Circumferential hydrides will reorient when cooled under high tensile stress.

f) The hydrogen (plus deuterium) concentration (about 15-20 ppm), the oxide layer on the inner and outer walls of the tube, and the tensile strength and ductility of the tubes were as expected from previous experience.

g) There was little radiation damage in the region of the cracks.

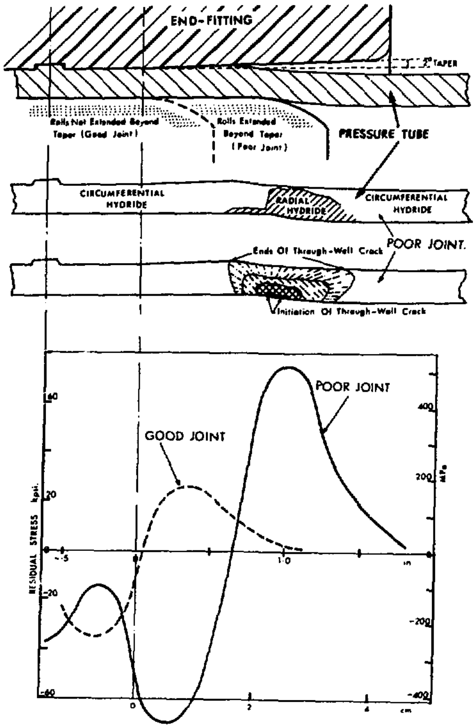

Figure 5 – Pickering rolled joint showing:

(a) relative position of rolling tool during installation.

(b) position of radial hydrides and cracks in a poor (over-extended) joint, and

(c) residual stress distribution on the inner wall of a good and poor joint.

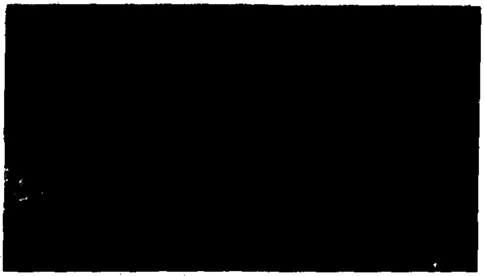

Figure 6 – View of cracked surface showing bands of zirconium oxide.

Rolled Joint Investigation

As soon as the 'over-extended' rolling was identified as a probable factor in the cracking of the tubes, experimental stress analysis was initiated. By the end of October, initial results indicated very high residual tensile stresses on the inner wall at the same point as the initation of the cracks. It was then confirmed that over-extended rolling was the major contributor to the cracking problem.

Possible reasons to explain the consistent over-extension of joints were explored. Examination of tools and procedures used for roll forming showed that wear of the tool, cumulative tolerances and stretch of the tool during rolling could account for some incorrect or over-extended rolling of the joints in the Pickering reactor. However, the major problem appeared to be that the danger of over-extension had never been foreseen and the rolling tool positioning procedures used on each reactor did not specifically prevent it. Another weakness was the lack of any dimensional check on rolling tool position as a quality assurance control after fabrication. Quality control and records on all other aspects of the joint were excellent.

Experimental stress analysis made in support of the investigation into the cracking of the tubes showed that:

a) over-extended rolling produces high residual tensile stresses which are generally dependent on clearances between pressure tube and hub, tube wall thickness variation, and rolling tool position. Residual tensile stresses in the transverse direction greater than 600 MPa (87,000 psi) can be produced on the inner wall. There are longitudinal and transverse (hoop) stresses due to bending loads during flaring and rolling, and transverse stresses due to an increase in tube diameter. There are compressive (hoop) stresses on the outer wall opposite the crack initiation point. After one pressure-temperature cycle (at coolant conditions) the stresses drop about 20%. During the first 1000 hours of operation the stresses drop another 15 to 20%; after 1000 hours the stresses continue to decrease but very slowly.

b) the position of the cracks, radial hydrides, and peak residual transverse tensile stresses, all coincided (Figure 5).

c) properly rolled joints have residual transverse tensile stresses on the inner wall of about 145 to 300 MPa (20,000 to 48,000 psi), and the zone of residual stress is closer to the end fitting.

A strain-gauging technique was selected for determining the residual stress distribution because it was a technique which was known and could be applied on a mass production basis. It could also be used in the shielded caves at CRNL on the joints removed from the Pickering reactor. The measurements at CRNL on joints with cracks showed a transverse (hoop) tensile stress on the inner wall of about 345 MPa (50,000 psi) and a transverse compressive stress on the outer wall of about 140 MPa (20,000 psi). There were also residual stresses in the axial directions. The rolled joints at the coolant inlet end of the channel had operated for 14,000 hours at 522 K (249°C). Results from stress-relaxion tests on specimens from cold-worked Zr-2.5 wt% Nb tube could explain the difference in stresses measured in rolled joints simulating Unit 3 joints as installed, and the irradiated joints removed from Unit 3.

Conclusions from the Crack and Joint Investigations

The basic cause of the cracks was the high residual tensile stresses combined with periods of cold coolant and tubes. It appears the hydrogen normally found in pressure tubes (about 10 ppm) migrated to areas of high residual stress on the inner wall where the stress intensity factor at some discontinuity or small defect was high enough to initiate cracking. Crack propagation was by fracture of hydrides which are brittle when cold. The cracks progressed outward as far as the compressive zone under the hub at the rolled joint and inward as far as the zone of zero residual stress in the pressure tube (Figure 5). Once initiated, the cracks proceeded through the tube wall by the repeated formation and fracture of the hydrides at the tip of the crack when the heat transport system was cold.(2, 3) When the system was hot, the hydrogen was in solution and crack growth did not proceed.

Reactor Inspections and Fuel Channel Replacement

The original searches carried out on Pickering Unit 3 were aimed at detecting tubes with through-wall cracks, allowing leakage. It was believed that many other tubes may have contained small cracks which were not through-wall cracks, which would eventually propagate and leak. Inspection for such cracks required development of an ultrasonic technique. Initially, this technique could only be applied to a channel which had already been drained and defuelled, a requirement that greatly limited the number of tubes that could be inspected. A later development allowed one to install the equipment into any channel without draining or defuelling. Seventy joints were examined. Surprisingly, no cracks were found. This greatly increased confidence that *the cracking problem was limited to a few tubes.*

While those involved with ultrasonic techniques were fully occupied with the Pickering problems, a group of eddy current specialists were enlisted to help on the Bruce 2 reactor which was under construction. During November, techniques were being studied in the laboratories at CRNL for the detection of small cracks using eddy currents. On December 1, a decision was made to inspect all the tubes in the Bruce Unit 2 reactor. These tubes had been over-extended rolled. Eddy current probes were designed, fabricated and proof tested, and a mobile home was equipped as a data recording centre. The equipment and a nine man team were sent to the Bruce reactor, and with help from station personnel, all 480 channels were inspected. The program was completed on December 19th. No cracks were found. The results indicated that the *rolling operation had not initiated cracking.*

The ultrasonic and eddy current results gave further confirmation that retubing of a limited number of tubes and not of the whole reactor would be required.

By January, inspections established that only 14 pressure tubes were leaking and had to be replaced. Two shielded cabinets were fabricated and mounted on the fuelling machine bridge. The cabinets could be moved remotely to the desired channel. The personnel inside the cabinets worked through ports and doors and were subject to low radiation levels. During January and February 1975, the 14 pressure tubes were replaced, and by the end of March the reactor returned to service.

Safety Considerations

Pickering Unit 3 was not returned to service without extensive testing to confirm that the reactor could be operated safely. The ultrasonic inspection of 70 tubes showed no cracks in those tubes. These results were very encouraging but undetected cracks could still exist in other pressure tubes. One of the safety criteria is that 'pressure tubes will leak before they break'. This was proven by the Pickering cracks; the leakage was detected before the cracks grew to a critical length, i.e. the length of a crack which would propagate rapidly in an unstable manner at normal operating temperatures and pressure. Some of the cracked tubes from Pickering were tested in the shielded cells at CRNL and at the Whiteshell laboratories. Thermal, pressure and fatigue cycles were able to grow the cracks beyond the zone of high residual stress, but only at rates comparable to crack growth rates produced in standard tube tests (about 0.5 μm (2 x 10^{-6} in.) per cycle). Sections of Pickering tubes were given artificial defects and burst to determine the critical crack length. The length was greater than 70 mm (2.7 in.) and the same as the length established by earlier experimental work on irradiated pressure tubes. For an undetected crack to propagate in reactor outside the residual stress zone (of about 20 mm (0.8 in.) length) to critical crack length would require a great many thermal and fatigue cycles.

Burst tests on three joints with cracks showed the strength to be greater than 620 MPa (90,000 psi) at 247°C (520 K), i.e. the same or greater than the joint strength as installed. The existence of cracks in the vicinity of the rolled joints does not affect the capability of the pressure tubes to withstand failures due to other causes. The crack is protected by the hub of the end fitting and is located within the end shield tube sheet (Figure 2). Should undetected cracks exist in some pressure tubes they would not constitute a hazard to the safe operation of the reactor.

Pickering Unit 4

On May 10, 1975, during startup of Pickering Unit 4 after a planned outage, water was found in the annulus gas system. On May 12 an acoustic emission scan identified 2 leaking channels. The channels were removed and shipped to CRNL where examinations revealed cracks identical to those in Unit 3. An extensive ultrasonic program was initiated; during June and July over 300 joints were inspected. Signals which were interpreted as cracks ranging from about 2 to 1mm (0.1 to 0.7 in.) in length were recorded in 58 tubes. The existence of many cracks of various sizes was quite different to the situation in Unit 3 where only large cracks of 13 to 20 mm (0.5 to 0.8 in.) in length were found.

During the period July 1975 to January 1976, 50 fuel channels were removed from Unit 4, and shipped to CRNL. The replacement of the 52 channels was completed in early 1976 and Unit 4 was returned to service on March 25th. There was one benefit, however, from this program; the large quantity of tubes and rolled joints provided the research and experimental teams at CRNL with a good supply of test specimens; of particular value was the broad range of crack size.

Crack Investigation on Joints from Unit 4

All joints (i.e., the ones with cracks and the ones at the other end of the channel without cracks) were again examined using ultrasonic and eddy current methods as soon as they arrived at CRNL. This work along with the opening up of a number of cracks in the shielded cells, established the correlations between inspection signal and crack size. It was learned that some of the signals which were initially interpreted as small cracks, were in effect either small surface discontinuities or extremely small cracks. As a result of these findings, 8 channels which had given ultrasonic signals were left in the reactor since propagation from such small defects if they were cracks would be slow. Such cracks could be monitored or removed at a later date. Crack propagation rates were determined by installing joints with small cracks in test loops and putting them through many cycles simulating the shutdown and startup sequences of the Pickering reactors.

The return of Unit 4 to service did not mean the end of the investigation. Although we were confident the reactors would operate safely, there was still much to be done to define the 'threshold stress' at which delayed hydrogen cracking could initiate and propagate such that an adequate margin (or safety factor) between design and operating conditions and the 'threshold stress' could be established.

Of major importance was the development work going on in Canadian industry (Canadian General Electric, Hawker Siddeley and Ontario Hydro). Strain-gauge investigations on experimental joints along with extensive dimensioning or 'profiling' of the flare area had established a correlation between residual hoop stresses and the amount of flaring or straining of the tube which occurs during rolling. Some of the residual hoop stresses are due to the springing of the tube to a larger diameter and some are due to bending effects by the rolls as they rotate around the tube. The greater the clearance and the more the amount of over-extension (which allows expansion into the tapered area of the hub and has much the same effect as greater clearance), the greater the residual hoop stresses on the inner wall of the tube. Furthermore it was established that with increasing clearance the flare area (not the joint itself) could be rolled askew; hence more springing or flaring occurred on one side than the other. Residual stresses of over 690 MPa (100,000 psi) were measured.

Although the residual stresses in the joints removed from Units 3 and 4 had relaxed due to operation, profiling of a large number of joints and strain gauging of a few selected joints in the shielded facilities confirmed that the cracks in general originated where the initial residual stresses (i.e. as rolled) were approaching 690 MPa. No cracks were found in regions where the original residual stresses were less than 550 MPa (80,000 psi). Work continues to define this threshold more accurately.

When the first cracks were opened up and the oxide bands were observed, it was realized that the bands were probably associated with the periods when the reactor was shut down and cooled.

A number of cracks from the Unit 4 joints were cut out and subjected to further operation in water simulating reactor coolant conditions, in autoclaves and in loop facilities in the NRX research reactor to establish the oxide bands as a time scale. The results of these investigations showed that the 14 bands (the three bands evident in Figure 6 are associated with the change in colour of the oxide: sub-bands are not easily seen in the figure) were directly related to the 14 major shutdowns of Unit 4, and the extent of crack growth could be related to shutdown time and temperature.(4)

Also, the results on oxidation rates confirmed that oxide thickness in each band was related to operating time at temperature between shutdowns and that no crack growth occurred in Units 3 or 4 during operation. Of most importance is the conclusion from this work that crack initiation occurred early in the life of the tube, probably after the first time the coolant system was at operating temperature and pressure. In all joints examined there was no evidence that cracks initiated at a later date when residual stresses were lower because of stress relaxation at operating temperature. This again confirms that extremely high residual stresses were required to initiate cracking, and a small amount of stress relaxation dropped the residual stresses below the 'threshold' level.

Fabrication and inspection records were kept at Pickering on every pressure tube and rolled joint, and these were examined in detail during the crack investigation. One of the advantages of the pressure tube as a pressure vessel is that a ring can be cut off each end of the tube and kept as an 'archive' specimen. These records and archive specimens proved extremely valuable. Through a combined effort of the non-destructive testing and materials experts, a correlation was established between the resistivity of the archive ring, the oxygen content, and the susceptibility of tubes to cracking. Particular batches of tubes had high resistivity which was related to high oxygen content and generally high strength. A tube with high tensile strength can retain generally higher residual stresses. Most tubes with cracks were tubes with high resistivity.

The work described here has been primarily concerned with the work done on the tubes and cracks removed from Pickering. Needless to say, there has been an extensive complementary program to improve rolling procedures to reduce residual stresses and to define parameters related to delayed hydrogen cracking in both small test specimens and tube (joint) specimens.

An important step in avoiding delayed hydrogen cracking is to reduce the residual hoop stresses during the rolling process. By avoiding 'over-extended' rolling, residual stresses are reduced by one-half. Two further methods of improvement have been proven. One is by reducing the clearance between pressure tube and the hub of the end fitting to close to zero (heating the hub and cooling the tube to produce a shrink fit). The other is to leave the initial clearances unchanged and then stress relieve by heating the flared area after rolling. With these improvements residual stresses can be reduced to about 100 MPa (14,500 psi) or less. A number of improvements have also been incorporated in assuring good and uniform quality during fabrication of the tubes to further reduce the material susceptibility to delayed hydrogen cracking.

SUMMARY

The cracks in the cold-worked Zr-2.5 wt% Nb pressure tubes of Pickering Units 3 and 4 were a consequence of improper positioning of the rolling tool used to join the pressure tubes to the end fitting during construction. The 'over-extended' rolling produced high residual tensile stresses. The basic cause of the cracks in a relatively small number of tubes was the high residual tensile stresses in combination with periods with the coolant and tubes cold. Crack propagation was by fracture of hydrides which are brittle when cold. When the heat transport system was hot, the hydrogen was in solution and the crack growth did not proceed.

The crack problem did demonstrate one advantage of the pressure tube as a pressure vessel. The defective tubes were small enough to be removed from reactor, thoroughly examined to identify the cause of the cracking and thoroughly tested to prove safety. Non-destructive techniques were quickly adapted for inspections of tubes in Pickering. The resources of Canadian industry along with those of Ontario Hydro and Atomic Energy of Canada Limited were coordinated to define the stress state of correctly rolled and over-extended rolled joints, the corrective procedures required for existing joints, and new procedures to be applied to all future rolled joint operations.

Unexpected problems will occur in any program as extensive as CANDU nuclear power; the capability to identify and solve problems quickly is essential to the program. The coordinated program conducted by experts representing operator, fabricator, designer and developer, effectively found engineering solutions to the crack problem in Pickering Unit 3 and 4.

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