EXPERIMENTS ON THE CONSEQUENCES OF BURSTING PRESSURE TUBES IN A SIMULATED POWER REACTOR ARRANGEMENT

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SUMMARY

The Canadian power reactors are of the pressure tube type. The pressure tube contains the fuel and coolant (pressurized heavy water or boiling light water), and hence is a pressure vessel. A power reactor basically consists of many identical fuel channel assemblies consisting of pressure tube, concentric calandria tube, end-fittings and spacers. The calandria tube is immersed in the cool moderator, and the central spacers maintain the annular gas-gap insulation between pressure and calandria tubes. The wall thickness of the calandria tube is chosen so that the tube will not collapse. Although a thickness/diameter ratio of only 1/100 is sufficient for this purpose, the tube is strong enough to act as containment in the event of loss of coolant from the pressure tube.

The rupture of a pressure tube is one of the highly unlikely accidents which has to be considered in the hazard analysis. The pressure tubes of zirconium alloys are not expected to rupture: should a tube be damaged in any way and a crack develop, the growing crack would penetrate the wall and leak pressurized coolant which would be detected in the gas annulus between pressure and calandria tubes. For safety evaluations, however, a pressure tube is assumed to fail with a rapid large discharge of coolant into the gas annulus so that the calandria tube would be subjected to high pressure.

This paper describes tests conducted to determine if the bursting of a pressure tube could cause failure of the calandria tube in a simulated power reactor arrangement.

It was found that the initial shock from the discharge of coolant through a gross defect in the pressure tube would not cause the calandria tube to fail. As the coolant discharges from the pressure tube, the pressure in the calandria tube due to the steam-water mixture rises and reaches a peak within the first half second after pressure tube rupture. Whether the calandria tube can contain the coolant or not is dependent on tube strength, and pressure build-up, which in turn is dependent on coolant conditions and the exhaust area from the annulus through the end-fitting and end-shield assemblies. The test results and analysis show that by increasing the exhaust area the designer can reduce the possibility of calandria tube rupture in the event of a pressure tube rupture, and thereby limit the damage in the reactor to just one fuel channel assembly.

Burst strength of irradiated and unirradiated calandria tubes of Zircaloy-2 was determined by a separate series of tests which are also described in this paper.
1. Introduction

The pressure tubes in the CANDU*-PHW (Pressurized Heavy Water) reactor contain the coolant at inlet and outlet conditions of 9.5 MPa (1380 psig) and 522 K (249°C), and 8.8 MPa (1280 psig) and 566 K (293°C) (1,2). Programs conducted on both irradiated and unirradiated pressure tubes of zirconium alloys (3,4,5) have shown that rupture of a pressure tube is very unlikely. At 573 K, the "critical crack length" (i.e. the length of a crack that is self-propagating at normal operating conditions) for zirconium-alloy tubes is about 10 cm (4 in.), and is almost independent of irradiation and hydrogen effects. Defects smaller than this size can be detected. Coolant would leak from the sub-critical crack and reveal its presence before the crack reached critical size, thus assuring leakage before gross failure. For safety evaluations, however, a tube is assumed to rupture with a rapid discharge of coolant into the gas annulus between the pressure tube and its coaxial calandria tube. The discharging coolant is assumed to rupture the calandria tube.

In tests on the consequences of pressure tube bursting in a simulated Nuclear Power Demonstration (NPD) fuel channel arrangement (6), the pressure build-up from discharging coolant could rupture the aluminum alloy calandria tube. In all CANDU reactors built after NPD, the calandria tubes are of Zircaloys-2 or Zircaloys-4 and are considerably stronger than aluminum tubes. In the present tests, artificial longitudinal defects were machined in the pressure tube (i.e. in the plane of maximum stress) to produce cracks much longer than the "critical crack length". The objectives of the program were to determine:

1) Whether a bursting pressure tube could cause rupture of a Zircaloy calandria tube;
2) What designers could do to decrease the possibility of calandria tube rupturing as a consequence of pressure tube rupture; and
3) The effect of neutron irradiation on the containment capabilities of the calandria tube.

2. Test Apparatus

2.1 General Arrangement of a Fuel Channel

Fig. 1 is a sketch of a fuel channel in a CANDU-PHW reactor such as Douglas Point. In the Pickering reactors the calandria tubes are joined to the end shield and the annulus are sealed by bellows (of relatively low blowout strength) on the outside of the end shield. Information on the tube sizes and coolant conditions in CANDU power reactors are given in Table 1. The volume of coolant in a pressure tube is about 0.02 m$^3$ (0.7 ft$^3$) and about equal to the volume in the gas annulus. In a power reactor, the fuel channel is connected to inlet and outlet headers by feeder pipes of 4 to 7 cm (1.5 to 2.9 in.) diameter and with an L/D ratio (length/diameter) from 170 to 440.

2.2 Full Scale Test Arrangement

In the test arrangement (Fig. 2) all materials were unirradiated. A mild steel tube with an artificial defect to reduce its burst strength was used instead of a zirconium alloy pressure tube. The calandria tube of Zircaloys-2 was fabricated from seam welded sheet, rolling the weld bead flat, and then annealing for 0.5 h at 1023 K. The tube was 10.8 cm (4.24 in.) I.D. by 0.127 cm (0.050 in.) wall thickness. The pressure tube was filled with fuel bundles. Two coiled springs were wrapped around the pressure tube to maintain the concentric annular gas gap between hot pressure tube and cool calandria tube.

* CANada Deuterium Uranium
Light water was used in the coolant circuit. The water was heated with electric immersion heaters mounted in a vertical standpipe (Fig. 2). L/D and D for the feeder pipes were 300 and 4 cm (1.5 in.). There was about 180 kg (400 lbs) of water in the coolant system. Flow was by natural convection thus the coolant velocity in the system was low. Inlet and outlet temperatures were about 555 and 545 K.

The test arrangement was instrumented with thermocouples to measure the temperatures of the coolant, gas annulus and calandria tube, and with transducers to measure the pressure of the coolant and gas annulus. A high speed camera photographed the outside of the calandria tube adjacent to the defect in the pressure tube. No instrument was placed close to the rupture area.

The tube was defected by milling a longitudinal flat area of from 15 to 20 cm (6 to 8 in.) in length, on the outside surface near its centre, to reduce the tube wall thickness to about 1 mm (0.040 in.). Gas pressure increased the system pressure until the defected area burst.

2.3 Burst Test Rig

The tube burst rig (Fig. 3a) was designed to test active Zircaloy-2 calandria tube specimens 45 cm (18 in.) long. Each test specimen was clamped in position on the perforated pipe assembly which was mounted over the reservoir. The reservoir was filled with water and heated externally. Additional pressure was then applied by a pump to rupture the disc. The water flashed to a steam-water mixture as it discharged through the rupture disc, orifice and perforated pipe, and pressurized the test specimen. The pressure developed in the test section depended upon the relative volumes of the reservoir and specimen, and the original water temperature in the reservoir. Burst pressure was determined by repeating the test using increasing reservoir temperatures, until the specimen burst. Pressures up to 11 MPa/m² (1600 psi) could be obtained by discharging water heated in the reservoir to 610 K.

A series of experiments was also conducted on a similar apparatus to that of Fig. 3a but with a larger reservoir as shown in Fig. 3b. The objectives were to:

a) Determine the reduction in peak pressure which would result if the steam-water mixture in the test specimen was allowed to escape through an exhaust nozzle or orifice of different sizes; and

b) Determine the difference in burst strength with and without water (simulating moderator) on the outside of the tube. Burst tests on the apparatus of Fig. 3b could not be performed on irradiated specimens with water on the outside.

The irradiated tubes received about $2 \times 10^{24}$ n/m² (>1 MeV) at 340 K in the NRU experimental reactor. All calandria tube specimens were of annealed Zircaloy-2 10.8 cm (4.24 in.) I.D. by 0.127 cm (0.050 in.) wall thickness. The Ultimate Tensile Strength of the unirradiated tube in the transverse direction at room temperature is 440 MPa (64,000 psi).

3. Observations and Results

3.1 Full Scale Tests

In the full scale tests none of the Zircaloy calandria tubes failed; the coolant from the ruptured pressure tube escaped through the openings at the ends of the fuel channel.

The high speed films showed a slight jarring of the calandria tube with relatively little movement when the pressure tube ruptured. A few small bubbles (or voids) were
observed on the tube surface and there was slight fogging of the water. The bubbles and fog dissipated quickly and a period of relative calm followed before the calandria tube oscillated slightly. After 1 to 2 s surface boiling of the moderator water along the calandria tube began. The steam bubbles expanded, moved upwards around the outside of the tube, floated free and collapsed.

The pressures measured by the transducers are shown in Fig. 4. As soon as the pressure tube ruptured the pressure in the coolant system and pressure tube dropped immediately to a value close to saturation pressure of the hottest water in the system. The pressure in the gas annulus increased rapidly and reached a maximum after about 0.05 to 0.15 s. There was a large pressure gradient along the gas annulus; the pressure at the ends was about one-half the pressure near the burst area at the centre of the channel. The results from the eight tests conducted all showed similar behaviours. Results in Fig. 4 are representative of the tests with maximum coolant temperatures around 560 K. As the discharge continued the coolant system emptied, and system and annulus pressures dropped to approximately atmospheric pressure in about 10 s. The pressure ratio between annulus and system pressure did not change significantly during the blowdown.

Examination of the ruptured pressure tube showed that it had cracked the desired length but had opened more than intended in some cases when the crack became transverse (Fig. 5). An accurate estimate of the exhaust area was not possible; the fuel elements in all tests were pushed into the opening and in some cases rested against the calandria tube. The edges of the rupture area of the pressure tube scraped and pushed against the calandria tube and caused some deformation, usually ovality or local bulging. The increase in mean diameter of the calandria tube was less than 0.2% indicating slight local yielding.

The spring spacers made shallow indentations in the calandria tube when the pressure tube burst, and were then blown out of the open annulus. The indentations were from 0.02 to 0.06 cm (0.008 to 0.024 in.) deep and extended about 90° around the tube on the side away from the pressure tube rupture. They were smooth and did not appear to be stress raisers.

3.2 Calandria Tube Burst Tests

Burst tests were done (using the test arrangement in Fig. 3b) on five 45 cm (18 in.) long specimens taken from the tube used in the full scale tests. When the hot pressurized water discharged from the reservoir into the test specimen, the pressure rose rapidly to a peak of about 9.7 MPa (1400 psi) and then dropped slowly; rupture of the calandria tube usually occurred after 0.3 to 0.7 s at 9.1 MPa (1325 psi) ±6%. There was no significant difference in burst strength of specimens damaged by scraping or denting during the full scale tests, and undamaged specimens. A typical pressure-time curve is shown in Fig. 6, curve A. In these tests there was no water on the outside of the tube to simulate moderator. The pressure drop in the specimen (due to cooling and leakage through the specimen seals) was slow. In a preliminary series of tests with water on the outside of the tube, delayed failure did not occur. The tube either ruptured at peak pressure or did not rupture; the pressure dropped rapidly after 0.2 to 0.3 s. The maximum outer surface temperatures were between 380 to 395 K when there was water on the outside. With no water, temperatures of about 470 K were reached after a few seconds.

The results from the burst tests of irradiated and unirradiated Zircaloy calandria tubes (using the test rig of Fig. 3a) are given in Table 2. Typical curves are shown in
Fig. 6. These tests were conducted with no water cooling on the outside and in most instances rupture of the tube occurred after peak pressure was reached due to the heating of the tube and its resultant decrease in strength (curve B). Curve C is typical of the tests in which the calandria tube did not rupture. The fracture path in both the irradiated and unirradiated specimens was along the side of the weld metal adjacent to the heat affected zone. The wall thickness measurements across the fracture in unirradiated specimen #11 showed a reduction of about 8-10% across the heat affected zone and 5-10% across the weld metal. Similar measurements on irradiated specimen #5 showed 8-12% reduction across the heat affected zone and 1-10% across the weld metal. For both the irradiated and unirradiated specimens the highly localized necking at the point of fracture was 20-25% of the original wall thickness.

The results from the burst tests to show the effect of exhaust nozzle area are shown in Fig. 7. The orifice between the reservoir and test specimen was 1.9 cm (0.75 in.) diameter. The exhaust orifices from the test specimen were 1.3, 1.9, and 3.2 cm; the respective area ratios were 0.45, 1.0 and 2.8. To produce high pressures in the test specimen, temperatures and hence the enthalpy of the water in the reservoir was higher than in the full scale channel tests (560 K). Maximum reservoir temperature was about 610 K and enthalpy about 1.54 MJ/kg (660 BTU lb⁻¹). The tests were conducted over a range of reservoir conditions; lines representing peak pressures for conditions of constant enthalpy are shown in Fig. 7.

4. Discussion of Results

The full scale tests covered a range of temperatures (or coolant enthalpies) and defect lengths. In general, the smaller the crack or lower the temperature, the lower the annulus pressure, but the effects were masked by the unpredictable variations in discharge area through the narrow, irregular passages. The flow area through the rupture was reduced by the bowed or broken fuel elements and the flow through the channel to the rupture area was restricted because of the small hydraulic radius (cross-section flow area/wetted perimeter) of about 0.8 cm (0.32 in.) through the fuel bundles.

The tests with the inlet and exhaust orifices (Fig. 7) more effectively show the effect of area ratio and enthalpy. As expected, the higher the area ratio, and the lower the enthalpy, the lower the pressure in the calandria tube between the two orifices. The results of the full scale and small specimen tests cannot be related since the flow area through the fuel and rupture on the full scale tests could not be accurately defined.

The burst test results in the irradiated calandria tube show irradiation strengthening, and little loss of ductility. After irradiation the burst strengths had increased about 10 percent. The grooves cut into the test specimens did not reduce the burst strength in proportion to the local reduction in wall thickness; the irradiated tubes are not notch sensitive. Similarly, the scrapes and dents on the calandria tube, which occurred in the full scale tests, produced no significant loss in strength in the tests conducted on unirradiated tubes. It appears unlikely that minor damage would significantly affect the containment strength of the Zircaloy calandria tubes in a power reactor.

The delayed burst, i.e., rupture after peak pressure was reached, indicates the effect of heating. The thermocouple results, the observed delay of 0.5 to 2 s before surface boiling started on the outside of the tube, and the delayed burst all indicate that it takes about 0.5 s for the tube burst strength to drop about 10 percent below the stress
which occurs when peak pressure is reached. The loss in strength of annealed Zircaloy-2 (7) is about 75 MPa (11,000 psi) per 100 K.

The only significant difference between the full scale tests reported here and the earlier ones (6) was in the exhaust area from the gas annulus to atmosphere. In the earlier tests the exhaust to inlet area ratio was probably about 2 or 3. In the tests with the annulus open at the ends the exhaust to inlet area ratio is probably greater than 5. The results (Fig. 4) show a maximum pressure of about 2.8 MPa (400 psi) and a high pressure gradient. At comparable coolant conditions the results in ref. (6) indicate peak pressures greater than 3.8 MPa (550 psi), and a low pressure gradient along the gas annulus. Also, the tests in ref. (6) showed pressures in the annulus of 2.8 MPa (400 psi) with lower coolant temperatures and/or smaller inlet areas. When exhaust areas are small pressures are high and a maximum when the annulus is closed; in which case, system pressure would be reached as soon as the annulus filled with water from the coolant circuit. For fuel channels with exhaust areas less than the full annulus cross-section area, the annulus pressure may still not be high enough to rupture the calandria tube. Designers can decrease the possibility of calandria tube rupture by increasing the burst strength of the calandria tube by using stronger Zircaloy (i.e. cold-worked), or by using a strong alloy.

All of the tests were directed at determining the behaviour of the channel and calandria tube within the first 0.5 s following the release of the pressurized hot water. Conditions after the first 0.5 s are not likely to be as severe. Should a pressure tube ever rupture the coolant pressure in the channel would drop to about 8.2 MPa (1200 psi), i.e. saturation pressure at 570 K, and coolant would discharge into the annulus at critical velocity. According to Moody (8), during blowdown of saturated liquid at 8.2 MPa, the mass velocity is about 41.5 Mgm⁻²s⁻¹ (8500 lbs ft⁻²s⁻¹). If the effective area in the pressure tube opening is about 6 cm² (1 in.²), then the mass ejected by the time peak pressure (or equilibrium of fluid in and fluid out of the annulus) is reached, is about 4 kg (8 lbs) and could come from the 20 kg (45 lbs) in the pressure tube. After about 0.5 s most of the discharging coolant must come from the inlet or outlet feeder and header. If the coolant comes from the inlet header, then there is relatively little concern since the coolant water at 522 K would produce steam at less than the saturation pressure of 4.1 MPa (600 psi).

The worst condition is all the coolant coming from the outlet header where the saturation pressure is about 8.2 MPa (1200 psi) at 570 K. However, the pressure drop across the feeder between the channel outlet and outlet header in the CANDU-PWR reactors is about 0.14 to 0.28 MPa (20 to 40 psi) for a coolant mass velocity from 5.4 to 6.9 Mgm⁻².s⁻¹ (1100 to 1400 lbs ft⁻².s⁻¹). High mass velocities from the outlet header to the rupture in the pressure tube cannot be sustained for two reasons. First, the pressure drop for two phase flow through a pipe increases rapidly with increasing flow (9), hence the inlet stagnation pressure at the rupture would be much less than the pressure at the outlet header. Second, as shown by Moody (8), for an enthalpy of 1.32 MJ/kg (567 BTU/lb), the mass velocity for two phase flow through an opening is almost linearly proportional to the stagnation pressure at inlet to the opening. Hence the rate of discharge of coolant which came only from the outlet header, would be less than the initial rate of discharge of coolant with the same enthalpy from within the pressure tube. As shown in Fig. 4, as the system pressure decreases, the pressure in the annulus decreases. The
possibility of calandria tube bursting after the first 0.5 s due to loss of strength of the calandria tube from an increase in temperature through heating by the discharging coolant would be more than offset by the decrease in pressure of the coolant discharging into the annulus.

5. Conclusions

1. The results of the full scale tests on the fuel channel and the small specimen tests show that in a channel with a large exhaust area from the gas annulus between pressure and calandria tubes to atmosphere, the possibility of rupturing the calandria tube by overpressure following the rupture of a pressure tube is extremely small.

2. Irradiation increases the strength and containment capability of Zircaloy calandria tubes.

6. Acknowledgements

The author acknowledges the assistance of L. Belanger, J. Escott, J. Harvie, L. Mooler and J. Widger in performing the tests and analyzing results.

7. References


<table>
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<tr>
<th>REACTOR NAME</th>
<th>NP &amp; DOUGLAS POINT</th>
<th>PICKERING 1 &amp; II</th>
<th>PICKERING III &amp; IV</th>
<th>BRUCE I, II, III &amp; IV</th>
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<td>Reactor Output, MWe</td>
<td>25</td>
<td>200</td>
<td>508</td>
<td>508</td>
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<tr>
<td>No. of Channels</td>
<td>132</td>
<td>306</td>
<td>390</td>
<td>390</td>
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<td>Lattice, cm (ln.)</td>
<td>26 (10.25)</td>
<td>22.9 (9.0)</td>
<td>28.5 (11.25)</td>
<td>28.5 (11.25)</td>
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</table>

**PRESSURE TUBE DATA**

| Length, cm (ln.) | 406 (160) | 513 (202) | 620 (244) | 620 (244) | 620 (244) |
| I.D., cm (ln.) | 8.3 (3.25) | 8.3 (3.25) | 10.3 (4.07) | 10.3 (4.07) | 10.3 (4.07) |
| Wall Thick., cm (ln.) | 0.42 (0.165) | 0.41 (0.160) | 0.51 (0.200) | 0.41 (0.160) | 0.41 (0.160) |
| Material | Cold-Worked Zircaloy-2 | Cold-Worked Zr-2.5% Nb |

**CALANDRIA TUBE DATA**

| Length, cm (ln.) | 396 (156) | 500 (197) | 594 (234) | 594 (234) | 594 (234) |
| I.D., cm (ln.) | 10.2 (4.00) | 10.8 (4.24) | 13.1 (5.15) | 13.1 (5.15) | 13.1 (5.15) |
| Wall Thick., cm (ln.) | 0.137 (0.054) | 0.127 (0.050) | 0.155 (0.061) | 0.165 (0.061) | 0.130 (0.051) |
| Material | 575 Aluminum | Cold-Worked Zircaloy-2 or 4 |

**SPACER DATA**

| Quantity | 1 | 2 | 2 | 2 | 2 |
| Diameter, cm (ln.) | 0.47 (0.187) | 0.76 (0.300) | 0.68 (0.266) | 0.68 (0.266) | 0.68 (0.266) |

**OPERATING CONDITIONS**

| Outlet Pressure, MPA (psig) | 7.5 (1080) | 9.2 (1338) | 8.8 (1280) | 8.8 (1280) | 8.8 (1280) |
| Inlet Temp., K | 521 | 521 | 521 | 521 | 521 |
| Outlet Temp., K | 550 | 556 | 556 | 556 | 556 |
| Coolant Flow, kg/(s/k) | 5 (39000) | 10 (79000) | 20 (157000) | 20 (157000) | 20 (157000) |

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**TABLE 2**

BURST TEST RESULTS ON ZIRCALOY CALANDRIA TUBE SPECIMENS

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Peak Pressure MPA (psig)</th>
<th>Time to Peak Pressure Time to Burst Pressure</th>
<th>Burst Pressure MPA (psig)</th>
<th>Failure Location</th>
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<td>Unirradiated: No Defects</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>12</td>
<td>9.9 (1437)</td>
<td>0.12</td>
<td>9.65 (1405)</td>
<td>0.29</td>
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<td>1</td>
<td>11.1 (1610)</td>
<td>10.9 (1580)</td>
<td>0.1</td>
<td>420 (61,000)</td>
</tr>
<tr>
<td>11</td>
<td>9.9 (1438)</td>
<td>9.35 (1335)</td>
<td>0.5</td>
<td>420 (61,000)</td>
</tr>
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<td>Unirradiated: Defects</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.65 (1312)</td>
<td>0.12</td>
<td>8.95 (1300)</td>
<td>0.16</td>
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<tr>
<td>Irradiated: No Defects</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11.75 (1675)</td>
<td>0.12</td>
<td>11.05 (1665)</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>10.8 (1562)</td>
<td>9.7 (1412)</td>
<td>0.6</td>
<td>467 (66,400)</td>
</tr>
<tr>
<td>Irradiated: Defects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.27 (1200)</td>
<td>0.15</td>
<td>7.92 (1160)</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>8.95 (1300)</td>
<td>8.77 (1275)</td>
<td>0.26</td>
<td>360 (55,200) at 0.015&quot; deep defect</td>
</tr>
<tr>
<td>1</td>
<td>8.16 (1187)</td>
<td>7.75 (1125)</td>
<td>0.62</td>
<td>348 (50,500) at 0.015&quot; deep defect</td>
</tr>
</tbody>
</table>

1) 0.010" deep groove in weld and heat affected zone. 0.015" deep groove in parent metal at 120°F to weld. Hammer, dents, chisel marks at 240°F to weld.
2) Groove as in note (1) except in parent metal at 180°F to weld.
3) 0.012" deep grooves in weld and heat affected zones. Groove in parent metal as in (2).

* The larger value is the average stress based on the reduced wall thickness at the groove where failure occurred.
Fig. 1 Schematic of a fuel channel for a CANDU reactor with pressurized water coolant.

Fig. 2 Sketch of the test facility.
Fig. 3 Calandria tube burst test rigs.
Fig. 4 Pressure versus time: full scale channel tests.

Fig. 5 Pressure tubes after rupture in the full scale channel tests.
Fig. 6 Pressure versus time: calandria tube burst tests.

Fig. 7 Peak pressure versus exhaust/inlet area ratio.