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Experimental investigations into consequences of a fuel channel failure in a CANDU reactor

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ABSTRACT: One of the hypothetical accidents considered in the safety and licensing analysis is the simultaneous failure of pressure and calandria tubes in a fuel channel. This accident is also considered as the design basis event for the evaluation of structural integrity of the calandria vessel and in-core structures. In order to provide experimental data base to validate the theoretical models used in accident analysis, a test program has been on going to simulate a sudden failure of a fuel channel. An over view of the experimental programs and the results from these programs is presented.

INTRODUCTION

In CANDU (CANada Deuterium Uranium) pressurised heavy water reactors, the pressure tubes form the coolant pressure boundary within the core and are designed to meet the requirements of class I pressure components. The pressure tubes are separated from the cool moderator by surrounding calandria tubes. Based on the fracture behaviour of Zr-2.5% Nb pressure tube material, no unstable crack propagation is likely in the pressure tubes and leak-before-break is the expected. The surrounding calandria tube is likely to withstand any unstable crack propagation in the pressure tube. One of the hypothetical accidents considered in the safety and licensing analysis is the simultaneous failure of a pressure and calandria tube in a fuel channel. This accident is also considered as the design basis event for the evaluation of structural integrity of the calandria vessel and in-core structures due to the high pressure high temperature primary coolant discharge into the low pressure moderator following a sudden channel rupture. In order to provide experimental data base to validate the theoretical models used in accident analysis, an experimental program has been on going to simulate a sudden failure of a pressure tube. The initial series of tests (Ref 1 and 2) investigated the response of the calandria tube to a sudden pressure tube failure. The experimental and analysis (Ref 3) results indicate that the calandria tube is likely to withstand both the transient as well as the steady loads imposed on it due to a pressure tube failure. The experimental results (Ref 4) on bursting of calandria tubes under fast pressurisation also support these conclusions. The next series of tests, called the integrated burst tests, (Ref 5) attempted to simulate failure of a single channel in open as well as closed tanks. The results from these tests while confirming the calandria tube strength margins, also indicated the necessity to introduce a defect in the calandria tube to ensure its prompt failure due to pressurisation after pressure tube failure.

The current series of tests are intended to simulate a simultaneous failure of both the pressure and calandria tubes. These tests were conducted in a specially designed multichannel burst test facility. The details of the test facility, the instrumentation used and the test procedures are given in Ref 6. This paper presents the salient results from these tests and main conclusions after a brief review of the test details.

TEST FACILITY

The multi-channel burst test (MCBT) facility, shown schematically in Fig 1, consists of a 3x3 array of nine fuel channels housed inside a containment vessel, 6 m long, 1.18 m inside diameter and 19 mm wall thickness. The schematic of the test loop with the main components (ie., the 2 m^3 capacity supply tank, the electrical powered boiler, the auxiliary pressure bump system, control and isolation valve etc) identified is shown in Figure 1. The central fuel channel was chosen as the burst channel for these tests and all the channel components have been included in its simulation. The pressure tube defect, typical geometry of which is shown in Figure 2, was located at the 6 O'clock position. The surrounding calandria tube on the burst channel was also defected to ensure that the calandria tube will fail due to pressure tube failure based on the results from the integrated burst tests (Ref 5). The calandria tube defect was oriented at the 12 O'clock position on the tube cross section. This arrangement of pressure tube and calandria tube defects was chosen to ensure that the top central channel will be impacted by the burst pressure tube while the bottom central channel will be subjected to the discharging jet forces and the impact of the ejected fuel bundles. The remaining six channels in the array were simulated channels made up of carbon steel pressure tubes surrounded by the stainless steel calandria tube. The test facility is very extensively instrumented with fast response thermocouples, pressure gauges, strain gages, accelerometers and LVDTs placed at various locations on test facility and the instrumentation used in the test was connected to three data acquisition systems.

TEST RESULTS

The main test conditions and test results for all the Multi-Channel Burst Tests (MCBT) are summarised in Table-1. Typical sequence of events in the test was as follows. Following the initiation of rupture in the pressure tube by the auxiliary pressurisation system, the pressure drops to saturation pressure corresponding to the coolant temperature in the pressure tube. The coolant discharge into the annulus results in pressure build up which generally exceeds the system pressure and leads to the calandria tube failure. Typical annulus fill up time is of the order of 200-300 msec. Following the calandria tube rupture, the pressure tube is re-pressurised momentarily and also reacts to the thrust forces from the discharging jet. The pressure transients in the pressure and calandria tubes obtained in Test #3, which illustrates the above pattern, is shown in Fig 3. The calandria tube rupture causes transient pressurisation of the containment vessel and the in-core structures. The neighbouring calandria tubes were all collapsed on to their pressure tubes resulting in fin like deformations which were generally pointing away from the burst channel. The main test results for each test can be briefly summarised as follows:

MCBT #1: The test was effectively a commissioning test to provide confidence in the new test rig and the instrumentation system. Consequently the calandria tube was not defected. The peak pressure on the calandria tube reached 11.1 MPa and the tube survived the pressure tube rupture. The maximum/mean diametral strain on the calandria tube were 5.5/4.1% while the maximum weld strain was up to 11.7%. The leak rate after the bellows burst was around 1 Kg/s while it increased to 43 Kg/s after the calandria tube rolled joint failure.

MCBT #2: In this test, the pressure tube burst at 14.8 MPa and the calandria tube burst at 11.2 MPa. The crack in the pressure tube only propagated 2.92 m while the crack in calandria tube ran the full length of tube in the weld.

MCBT #3: In this test the burst pressures of pressure and calandria tubes were 11.95 and 11 MPa respectively. As the pressure tube was deeply defected along the entire length of the tube, the crack propagated the full length of defect and resulted in guillotine failure at the inlet end. The crack in the calandria tube only propagated in the weld towards the inlet while it branched in to the parent material towards the outlet.

MCBT #4: The burst pressures of pressure and calandria tubes were 14.7 and 10.48 MPa respectively. The crack in the pressure tube propagated beyond the initial defect in to parent material along the stepped groove and there was no crack branching. The calandria tube crack remained in the weld.

CONCLUSIONS

Based on the test results it is noted that the crack propagation in the pressure tube is generally limited to the length of defect. The second pressurisation after the annulus fill up, due to calandria tube failure, did not result in any additional crack growth. The transient pressure in the containment vessel results in collapsing of the calandria tubes on to their pressure tubes which is likely to limit the magnitude of pressure load on the containment vessel. Only the impacted target channels showed small permanent bending while the pressure tubes in other neighbouring channels were unaffected.

A guillotine failure or circumferential crack propagation in the pressure tube occurred only in test #2 when the pressure tube was defected almost the full length and with defect depth equal to half the tube thickness. Similar results were also obtained in previous tests reported in Ref 5.

It is to be noted that the bellows failed in Test #1 when the calandria tube survived the pressure tube rupture while they were intact in all other tests where calandria failed. This was also the case in all previous test series.

The multichannel burst test program is continuing to provide very useful data for modelling of pressure tube rupture accidents in safety analysis of CANDU reactors.

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Table - 1

SUMMARY OF TEST CONDITIONS AND RESULTS

Test Parameter	Test #1	Test #2	Test #3	Test #4
PT Defect	1.07 mm for 0.3 m 2.17 mm for 1.7 m and 0.84m Tapered	1.07 mm for 0.3m 2.17 mm for 1.7m and 1 m tapered	1.07 mm for 0.03m and 2.17 mm for 5.5 m	1.07 mm for 0.3m 2.17 mm for 3.5m and 2m tapered
CT Defect	None	0.13 mm for 0.4m	0.13 mm for 0.4 m	0.13 mm for 0.4m
Loop Pressure	10.9 MPa	11.7 MPa	11.0 MPa	10.9 MPa
Loop Temp	259 Deg C	260 Deg C	265 Deg C	264 Deg C
Banded Bundles	None	#6, 7 an 8	#6, 7 and 8	#6, 7 and 8
Moderator Temp	24 Deg C	69 Deg C	63 Deg C	54 Deg C
Results and Post Test Observations				
PT Burst Pressure	12.9 MPa	14.8 MPa	11.95 MPa	14.7 MPa
CT Burst Pressure	(11.6 MPa no burst). R/J failed	12.9 MPa	11.4 MPa	11.6 MPa
Bellows Pressure	6.8 MPa (Bellows Burst)	2.6 MPa	3.6 MPa	3.8 MPa
PT Crack length	2.74 m (96% of defect)	2.92 m (97% of Defect length)	5.5 m (95% of Defect) Guillotine at inlet end.	5.98 m (103% of Defect)
CT Crack	None. CT rolled joint failed.	Whole Length	55% in weld. 40% in parent material	whole length. Guillotine at both ends.
Axial Strains	PT - 0.087% CT - 0.7%	PT - 0.061% CT - 0.027%	PT - 0.057% CT - 0.019%	CT - 0.019%
Annulus fill up time	250 ms	205 ms	270 ms	256 ms
Flow rate from rupture	100 Kg/s (peak at 125 Kg/s) into annulus.	125 Kg/s into annulus. 120 Kg/s after CT rupture.	130 Kg/s into annulus. 145 Kg/s after CT rupture	126 Kg/s into annulus. 145 Kg/s after CT burst.
End fitting movement	15 mm	9 mm	-27 mm	10 mm

PT- Pressure Tube and CT- Calandria Tube.

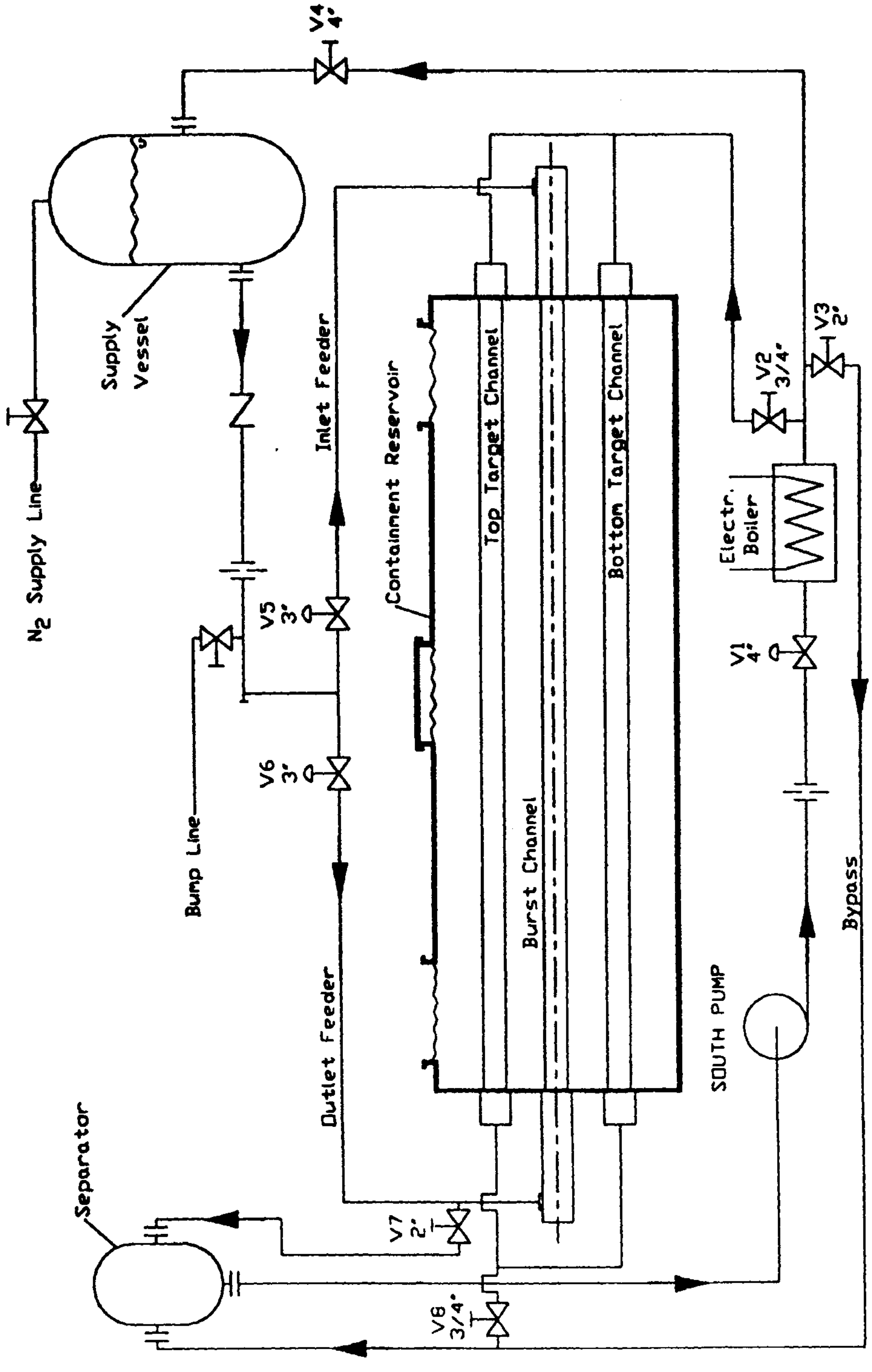

Fig 1: Loop Schematic

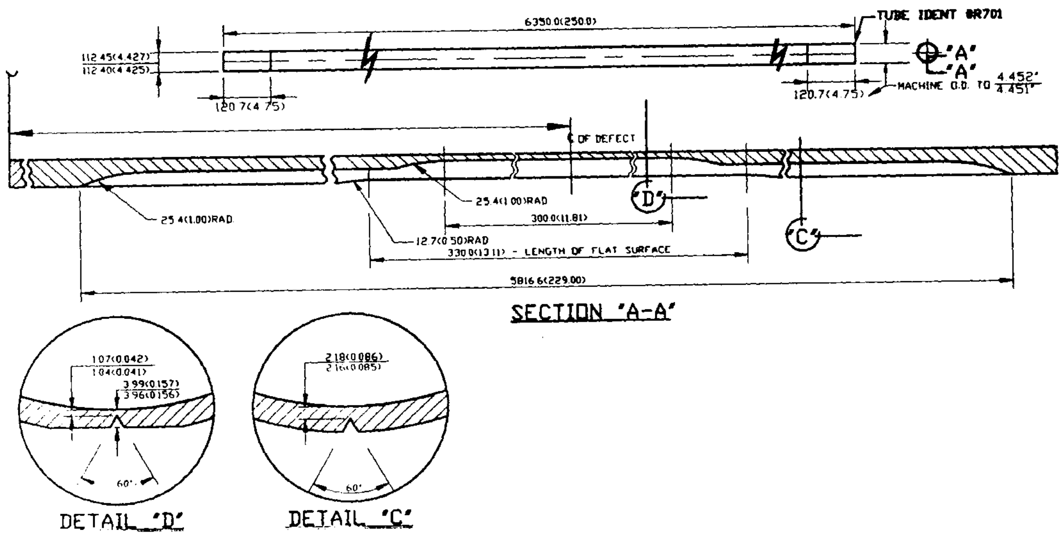

Fig 2: Pressure Tube Defect Geometry

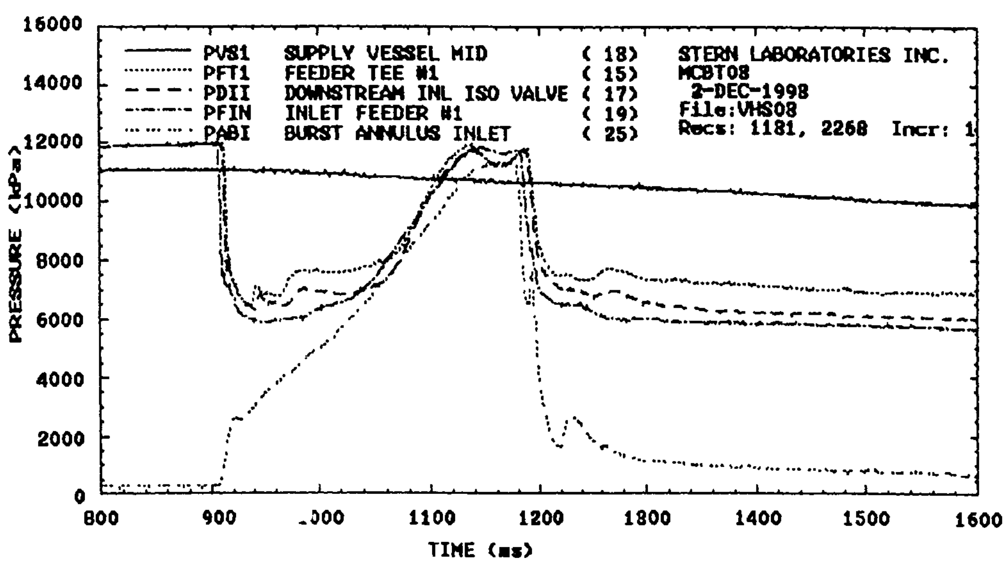

Fig 3:

Pressure Transients in Pressure and Calandria Tubes