Experimental Investigations into Consequences of Pressure Tube Rupture

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ABSTRACT

The pressure tubes, which form the pressure boundary within the reactor core, generally show leak-before-break behaviour. However, in the safety assessment of CANDU reactors, a hypothetical channel failure (a sudden failure of both pressure and calandria tubes) is considered as a design basis event for evaluation of integrity of in-core structures. In order to provide support to the safety analysis, an experimental program has been on going which is aimed at providing test data to support the safety/licensing assessments. This paper summarises the main results from these experimental programs and the implications for safety assessment. The paper also discusses the significance of the results on some of the unresolved generic safety issues concerned with consequences of a pressure tube rupture.

INTRODUCTION

The pressure tubes in a CANDU reactor form the primary pressure boundary to the PHT coolant within the core. Based on the design, material fracture behaviour and operating experience, no sudden failure of the pressure tubes is expected and leak-before-break is likely. However, in the safety assessment of CANDU reactors, all possible modes of pressure tube (PT) failure are considered to evaluate its consequences. Also a hypothetical channel failure (a sudden failure of both pressure and calandria tubes) is considered as a design basis event for evaluation of integrity of in-core structures. In order to provide support to the safety analysis, an experimental program has been on going, since 1984, which is aimed at providing test data to support the safety/licensing assessments. The program has evolved in the following distinct phases over the years, from calandria tube integrity assessments to evaluation of in-core structural damage:

Phase 1 - Pressure tube burst tests with very strong calandria tubes.
Phase 2 - Pressure tube burst tests with prototypic calandria tubes.
Phase 3 - Integrated burst tests.
Phase 4 - Multi-Channel burst tests.

In the initial phase of tests, a single fuel channel simulation was used to assess the calandria tube (CT) response to pressure tube rupture. In the later tests, an array of fuel channels was simulated to assess the effect of a simultaneous pressure tube and calandria tube rupture on surrounding in-core devices. These experimental programs have provided relevant data regarding various transient thermal hydraulic phenomenon and mechanical loading arising on in-core structures following a pressure tube rupture. This paper provides an overview and summary of the results from the full-scale PT rupture experimental program. The results from earlier test series are only given in brief. The focus of this paper is the current tests (i.e., Phase 4) that are being conducted in a specially designed multi-channel burst test (MCBT) facility. The results obtained in the test program and the implications of test results for safety assessment are also discussed.

Overview of test results in Phases 1 and 2

The results from these two phases of tests are reported in detail in Reference 1 to 3. The tests were conducted on a full scale simulation of a fuel channel. In Phase 1 of the program (1984-85), the objective was to quantify the basic phenomena such as the timing and magnitude of annulus and bellows pressurisation, the resulting calandria tube response, the impact loading on the calandria tube inner wall, and the dependence of these on the pressure tube crack velocity. Five burst tests were performed in this phase with the coolant pressure in the range of 7.5-11.6 MPa and coolant temperatures in the range of 255 to 307 ^{0}C, starting with a very strong (5 mm thick) stainless steel calandria tube, and progressing to thinner stainless steel tubes. The crack velocity in the pressure tube was increased by grooving or hydriding the prototypic Zr-2.5%Nb PT. Phase 2 (1985-86) consisted of four similar burst experiments using prototypic Zr-2 calandria tubes, with pressures in the range of 7.7-8.5 MPa and coolant temperature in the range of 250-270 ^{0}C. The main test conditions, the relevant test results and the final crack lengths obtained in the PT are given in Table-1.

The main conclusions from tests in Phase 1 and 2 were that:

a) There is a transient overpressure in the annulus due to the water-hammer effect and the peak annulus pressure increases with increasing coolant subcooling;

b) This overpressure is attenuated via fluid-structure interaction which results from rapid straining of the calandria tube;

c) The impact loading on the calandria tube is a relatively weak failure mechanism;

d) When the calandria tube is pressurised, the calandria tube rolled joint experiences a tensile pull out load due to Zr-2 material anisotropy; and

e) The bellows failed in all the tests in the pressure range of 5.5 to 7.5 MPa , the time to pressurise and fail the bellows was in the range of 530 - 715 ms.

Based on these test results and the analysis (references 1 to 3), it is predicted that the calandria tube integrity will be maintained following a sudden PT rupture.

INTEGRATED BURST TESTS (IBT- Phase 3)

The objectives of these tests were to determine the consequences of calandria tube rupture following pressure tube rupture and to identify modes of failure of the pressure tube and calandria tube. The tests were again limited to a single channel simulation in all the six tests completed in this series. The following summary gives the main test conditions and observations from these tests.

Test Apparatus

A schematic of the test loop used for the integrated burst tests is shown in Figure-1. The test loop consists of a circulating pump, an electric boiler, control and isolation valves, a 2 m^3 supply vessel, a boiler feed pump, pressuriser and inter-connecting piping. The loop is used to heat and pressurise the test section and supply vessel and provide control and isolation during the test. A 0.2 m^3 auxiliary pressurising tank (shown as the "bump pressure system" in the figure) is also available to provide over-pressurisation of the test pressure tube to initiate pressure tube failure.

The test section consists of full scale simulation of a fuel channel (i.e., Zr-2.5% Nb pressure tube, two prototypic end fittings, a prototypic calandria tube and four garter springs). The pressure tube is filled with 13 Bruce/Darlington type (thirty-seven elements) simulated fuel bundles with copper pellets. The end fittings are installed in simulated end shield assemblies which have representative lattice tubes and cooling water flowing over the outside of the lattice tubes. The assembly also simulated the pressure tube to end fitting conventional rolled joints as well as the calandria tube rolled joints with belled ends. The fuel channel assembly was immersed in a tank of water to simulate appropriate temperature conditions on the calandria tube. A U-shaped open tank was used for the first two tests. For the subsequent four tests, a closed tank with openings at the ends was used to simulate the presence of moderator around the ruptured channel. The inside wall of the closed tank was lined with collapsible thin aluminium tubes to simulate moderator fluid compressibility in tests #3 to #5. In test #6, these tubes were replaced with a flexible elastomer, which simulated the moderator compressibility.

Instrumentation & Data Acquisition

Dynamic measurements were recorded on high and low speed data acquisition systems. The long term signals were recorded on the low speed data acquisition system to keep track of trends while short term burst related signals were recorded on the Hewlett Packard A600 computer at a scan rate of 1.3 kHz per channel. This system can store data for a maximum of 9 seconds. In order to record relevant burst data in the test, data from this instrumentation system was continuously recorded in a carousel fashion over existing data and the burst event was used to stop data recording. The usual practice was to stop recording data eight seconds after the pressure in the annulus reaches 3.5 MPa. This provided one second of pre-burst data and 8 seconds of post-burst data. The instruments used in the tests consisted of spot welded and ungrounded thermocouples, absolute and differential Viatran pressure transducers, force transducers, accelerometers and strain gauges.

Test Procedure

A typical test procedure involves the following steps. After assembling the test hardware and instrumentation, the required pre-test conditions are established. The calandria tube is loaded by a tensile axial load of 15.5 kN at the beginning of a test (cold unpressurised condition). Initially, the gas annulus between the pressure and calandria tubes is maintained at 2 MPa to prevent any early failure of the pressure tube during warm up of the loop to required test conditions. When all required test conditions are attained in the test loop, the annulus is vented rapidly in order that the full system pressure will be experienced by the defected pressure tube. If the pressure tube does not rupture under these conditions, the auxiliary pressurising system (called the bump system) is used to raise the pressure in the test section and thus initiate pressure tube rupture.

IBT Test Results

In this section, the main test results for each test are presented in order to bring out any salient observations. The main test conditions, the test results and the post test observations are given in the Table-2.

Integrated Burst Test #1

The geometry of the initial defect in the PT (with nominal thickness of 4.2 mm) consisted of the central portion 300 mm long with the wall thickness reduced to 0.91 mm, and 2.77 m long portion on either end with half the original thickness of pressure tube remaining. The overall defect length was 5.84 m. In this test the pressure tube ruptured before the annulus could be depressurised from the initial pressure of 2 MPa. Consequently the effective burst pressure in the test was 7.7 MPa. The pressure tube/calandria tube annulus pressure transient indicated that the calandria tube experienced a water-hammer transient starting from an initial value of 2 MPa and reaching a peak value of 10.1 MPa. The pressure at the bellows location reached a maximum value of 5.2 MPa (at 100 ms) resulting in bellows failure. The bellows failure occurred in a comparatively short time as the bellows were initially at a pressure of 2 MPa. No failure of the calandria tube occurred in the test. Post test measurement of the pressure tube crack indicated that the crack did not propagate the full length of the machined defect and the final crack length was 3.85 m.

Integrated Burst Test #2

This test was also conducted in the open tank with a pressure tube defect similar to that used in IBT #1. The pressure tube burst at 11.9 MPa and it resulted in calandria tube failure along the weld when the annulus pressure was at about 10.9 MPa. Following failure of the calandria tube, a guillotine failure occurred in the PT at both the outlet and inlet ends. As a result, the PT was ejected from the tank, impacted on to the overhead feeder piping junction which caused an additional shear failure of pressure tube at the centre. The channel failure ejected all the bundles into the open tank and displaced the free end fitting axially until it was stopped by the restraining fixture. The open U-shaped containment tank, which was not designed to withstand any pressure loading, was completely flattened in the test. The bellows experienced a maximum pressure of 5.9 MPa but the bellows did not rupture in the test.

Integrated Burst Test #3

In order to simulate the effect of a surrounding moderator on pressure tube behaviour following calandria tube rupture, a closed tank design was used from IBT #3 onward. An adjacent end-fitting and feeder were also simulated in order to measure the impact forces arising due to the ejected end-fitting in the case of a guillotine failure of the pressure tube.

A short defect, 300 mm long with the remaining wall thickness of 1.12 mm, was used to initiate pressure tube rupture. In the test, the pressure tube ruptured at 11.7 MPa and resulted in a peak annulus pressure of 10.5 MPa, however, the calandria tube did not rupture. Post-test measurement indicated that the final crack length in the test was 540 mm. Two fuel elements ejected from the fuel bundle adjacent to the pressure tube machined defect were lodged in the crack. Blockage of the crack discharge area by the trapped fuel elements is considered to have resulted in a smaller crack opening for discharge and a slower pressurisation of the calandria tube annulus. This slower annulus pressurisation did not result in failure of the calandria tube even though the peak annulus pressure was 10.5 MPa. The pressure at the bellows reached a peak value of 7.4 MPa at rupture at about 735 ms after pressure tube rupture.

Integrated Burst Test #4

This test was conducted with a 3 m long machined defect placed symmetrically at the centre of the pressure tube. The defect consisted of central portion 0.3 m long with remaining wall thickness of

1.06 mm, 1.7 m long groove with 50% (or 2.1 mm) of original wall thickness and the end portion 1 m long with 75% of wall thickness remaining. The pressure tube burst at about 13 MPa. The peak annulus pressure was approximately 10.5 MPa and the calandria tube did not fail during the test. The maximum pressure at the bellows at the time of rupture was 5.8 MPa. After bellows failure, the inlet rolled joint of the pressure tube failed during the test, which resulted in displacement of the inlet end-fitting within the lattice tube. The measured acceleration and load cell readings indicate that the maximum force on the end fitting was about 150 kN. Post-test measurements indicated that the final crack length was 2.09 m which was less than the machined defect length.

Integrated Burst Test #5

This test was conducted again with a 3 m long machined defect in the central portion of pressure tube. The defect geometry was similar to that used in IBT #4 in the central 2 m length. The remaining 0.5 m length at either end, the defect depth was gradually reduced by a machined taper from 50% of wall thickness to 0% wall thickness. In order to ensure calandria tube failure during the annulus pressurisation period, the calandria tube was also defected (with a 0.25 mm deep and 5.25 m long groove). The central bundles (bundle # 5,6 and 7) were banded to prevent them from blocking the flow from the pressure tube crack into the annulus.

The pressure tube ruptured at 10.3 MPa. The pre-defected calandria tube burst during the annulus fill up stage at about 7 MPa before the annulus pressure reached the supply tank pressure. The failure of calandria tube resulted in the ejection of all fuel bundles from the pressure tube in to the containment vessel. The bellows did not fail during the transient even though the pressure reached 5.3 MPa. The final crack length in pressure tube was 3.28 m. The crack in the calandria tube extended the full length.

Integrated Burst Test #6

This test was carried out with the pressure tube defect at the top (12 o'clock position in the cross section) and with the defect aligned with the calandria tube weld. The pressure tube defect was similar to that used in IBT #4 and #5. In order to simulate the moderator compressibility, the aluminium tubes (used in IBT #5) in the closed tank were replaced with a renewable flexible liner. The calandria tube used in IBT #4 was used in this test. The pressure tube burst at about 15.3 MPa and this did not result in calandria tube failure. The maximum annulus pressure during the transient was around 11.4 MPa. The bellows failed at 7.6 MPa at about 390 ms after pressure tube rupture. The final crack length in the pressure tube was only 2.76 m which is less than the initial defect length.

Discussion of Test Results

The following conclusions can be made from the results of the IBT series:

1. When the calandria tube survived the pressure tube rupture, the final crack length in the pressure tube was less than the original defect length with long machined defects (IBT #1, #4 and #6). When the pressure tube contained a very short defect (0.3 m long), the crack propagated beyond the defect and the final crack length (0.54 m) indicates limited crack growth into the undefected (parent) pressure tube material beyond the defect length.

2. When the calandria tube survives a pressure tube failure (IBT #1, #3, #4 and #6), the bellows failure occurs due to pressurisation by coolant discharge through the bearings. Under transient

pressurisation, the bellows failure pressure is in the range 5.2 to 7.8 MPa. When the calandria tube failed during the transient annulus fill up (IBT #2 and #5), the bellows survived pressure transients without rupture even though the peak pressure reached was about 5.5 MPa.

3. The fuel bundles adjacent to the pressure tube crack tend to disassemble when the pressure tube ruptures which can cause the fuel elements to get trapped in the crack. The trapping of the fuel elements resulted in a slower pressurisation of the annulus. The annulus pressure transients obtained in the experiments with banded bundles are considered to be more severe.

MULTI-CHANNEL BURST TESTS (MCBT- Phase 4)

These tests were intended to simulate a simultaneous failure of both the pressure and calandria tubes in a fuel channel, in order to investigate the consequences of fuel channel rupture on in-core structural components. These tests were conducted in a specially designed multi-channel burst test facility. The details of the test facility, the instrumentation used, the test procedures and the salient results from these tests are given in this section. A few results of the first four tests are also given in Reference 4.

Test Facility

The multi-channel burst test facility consists of a 3x3 array of nine full scale fuel channels housed inside a containment vessel. The containment vessel is a cylindrical steel shell with the overall dimension being 6 m long, 1.18 m inside diameter and 19 mm wall thickness. The 3x3 array of fuel channels is arranged with a minimum radial clearance of 10 cms from the outer fuel channel to vessel wall. The inside of the tank is lined with a 25 mm thick elastomer membrane to simulate the moderator fluid compressibility. The cross section of the containment vessel showing the channel location is shown in Figure-2. The vessel has vents at the top, openings at the sides for post test examination and a specially designed structure to support the channels at the ends and to provide a vessel seal. The support structure complete with the 3x3 array of simulated fuel channels can be rolled in and out of the vessel for non-destructive post-test examination. The test loop for the multi-channel test facility is identical to that used for IBT tests (Figure-1). An isometric view of the test set up, with the multi-channel facility connected to the loop, is shown in Figure-3.

Any location in the 3x3 array (Figure-2) can be selected for simulating a burst channel. For the initial four tests, the central channel was chosen as the burst channel and all the channel components (i.e., prototypic calandria tube, four garter springs and end fittings etc) have been included in its simulation. The burst channel contained 13 prototypic fuel bundles filled with copper pellets. The axial defect in the pressure tube was located at the 6 o'clock position. The calandria tube defect was oriented at the 12 o'clock position in the calandria 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. Hence the top and bottom central channels in the array are designated as the target channels and these two channels contained standard Zr-2.5% Nb pressure tubes and Zr-2 calandria tubes with the garter springs. These two target channels also contained 9 simulated fuel bundles in the centre and two steel weights at each end to simulate end bundles.

The remaining six channels in the array were simulated channels made up of carbon steel pressure tubes (114.3 mm outer diameter and 3.4 mm wall thickness) surrounded by the stainless steel calandria tubes (133.3 mm outer diameter and 1.07 mm thick). These steel tubes in the dummy channels have the same flexural rigidity as the pressure and calandria tubes. These simulated channels also contain carbon steel weights to simulate the weight of fuel bundles.

Geometry of Pressure tube and Calandria tube Defects

In all MCBT, the pressure tubes in the burst channel location were pre-defected to ensure their rupture at selected test conditions. For example, in the first two tests, the defect in the pressure tube was a milled 3 m long groove with the central 0.3 m portion having 25% of original wall thickness (i.e., 1.08 mm), 1.7 m length groove having 50% of original wall thickness and the remaining length tapering to full thickness. The surrounding calandria tube in the burst channel was also defected to ensure that the calandria tube fails due to pressure tube failure (except in MCBT #1). The calandria tube defect was a centrally milled groove in the weld, which was 0.4 m long and 0.13 mm deep. The defect in the CT was generally located at 6 O'clock position in tube cross section.

Instrumentation and Test Procedure

The data acquisition system used in MCBT series is identical to that used in earlier tests with a few enhancements for resolution and recording transient data. The test facility is extensively instrumented as in IBT test series with fast response thermocouples, pressure gauges, strain gages, accelerometers and LVDTs placed at various locations of the test facility. The instrumentation used in the test was connected to three data acquisition systems, i.e., the high speed DEC system, the low speed DEC system and the high speed ZONIC system. The blast transducers were used in a few later tests to measure moderator pressure.

The test procedure in this series of tests was similar to that employed for conducting the integrated burst tests. After assembling the test hardware and instrumentation system, initially, the gas annulus between the pressure and calandria tubes is maintained at 2 MPa pressure during loop warm-up to the desired test conditions. When all the required test conditions are attained in the test loop, the annulus is vented rapidly so that the full system pressure acts on the defected pressure tube. If the defected pressure tube does not burst at the chosen test conditions, even after venting the gas annulus to atmospheric pressure, the auxiliary pressurising system (bump system) is activated to initiate rupture at a higher pressure. The transient test data regarding pressures, flows and forces as measured by various instruments is recorded by the high speed data acquisition system.

Multi-Channel Burst Test Results

Although extensive test data have been obtained in this test series regarding the thermal-hydraulic response and mechanical loading on adjacent channels, only the main results are reported here. The main test conditions and test results for all the Multi-Channel Burst Tests (MCBT) are summarised in Table-3. A typical sequence of events observed in this test is as follows. Following the initiation of rupture in the pressure tube by the auxiliary pressurisation system, the pressure in the pressure tube 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 due to water hammer. Generally, calandria tube failure occurs during this annulus over pressurisation period. Typical annulus fill up time is of the order of 200-300 ms. The pressure transients obtained in MCBT #5, which illustrate the above behaviour, are shown in Figure-4. Following calandria tube rupture, the pressure tube reacts to the jet and thrust forces from the discharging jet and it is also re-pressurised momentarily. This second pressure loading can also cause further crack propagation in the pressure tube.

Calandria tube rupture also causes transient pressurisation of the containment vessel and the in-core structures. Under dynamic external pressure loading, the neighbouring calandria tubes completely collapse on to their pressure tubes, resulting in formation of "fins" which are generally pointing away from the burst channel. The main test results for each test are briefly summarised in the following sections.

Multi-Channel Burst Test #1

MCBT #1 was a commissioning test to provide confidence in the new test rig and the instrumentation system. Consequently the calandria tube was not initially defected. The pressure tube contained a 2.84 m long defect and the tube ruptured at a pressure of 12.9 MPa. The peak annulus pressure reached 11.1 MPa and the calandria tube survived pressure tube rupture. The bellows were pressurised to about 6.8 MPa before bellows burst. When the calandria tube was held under loop pressure (for about 8 sec) the calandria tube rolled joint failed at the fixed end as it pulled out. Post test examinations showed that, the final crack length in the pressure tube was 2.74 m which is less than the original defect length. Under the transient water hammer loading, the maximum and mean diametral strain on the calandria tube were 5.5 and 4.1% respectively, while the maximum weld strain was up to 11.7%. This mode of calandria tube failure did not result in any significant transient pressurisation in the surrounding containment vessel.

Multi-Channel Burst Test #2

From this test onwards, the calandria tube was also initially defected to ensure its failure following pressure tube failure. In this test, the pressure tube contained a 3 m long initial defect and it ruptured at 14.8 MPa. The calandria tube burst at 11.2 MPa during transient annulus fill up. The bellows did not fail in the test. Post test measurements indicate that, 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. The crack in the pressure tube extended into parent material only at one end by 25 mm. All the simulated neighbouring calandria tubes as well as the Zr-2 calandria tubes in target channel locations in the 3x3 array collapsed on to their pressure tubes during the transient. Examination of the target channel indicated that there was no permanent deformation of target channel even after impact by the burst channel.

Multi-Channel Burst Test #3

This test was intended to verify the effect of a severe defect (i.e., a full length defect with half the wall thickness removed) on crack behaviour in a pressure tube. Hence, the crack geometry selected was identical to that chosen in IBT #2 which resulted in guillotine failure of the pressure tube. The coolant conditions were 11 MPa and 265 ^{0}C in the supply vessel. In this test the burst pressures of pressure and calandria tubes were 11.95 and 11 MPa, respectively. The crack in the calandria tube propagated in the weld towards the inlet end while it propagated in the parent material towards the outlet end in a brittle fracture mode. However, the crack did not propagate fully up to the outlet end. As a result, a stub of the calandria tube retaining its circular geometry was still present around the ruptured pressure tube at the outlet end at the end of test. As the pressure tube was deeply defected along the entire length of the tube, the crack propagated almost the full length of the defect and resulted in guillotine failure at the inlet end. At the fixed or outlet end, the pressure tube crack arrested just short of the end of the defect in the pressure tube.

Multi-Channel Burst Test #4

One of the objectives in this test was to confirm the observed crack propagation behaviour of long defects in the pressure tube. Hence again, a 5.8 m long defect was simulated in the test which was similar to that used in IBT #2 and MCBT #3, with the exception of a 1m taper at the ends which reduces the defect depth gradually from 50% of wall thickness to 0%. The burst pressures of the pressure and calandria tubes were 14.7 and 10.48 MPa, respectively. The crack in the pressure tube propagated beyond the initial defect, into parent material along the stepped groove and there was no crack branching. The final length of crack was 5.98 m. This test again indicated that crack propagation in the PT parent material is very limited. The calandria tube crack remained in the weld. The response of the surrounding structures in the tank was similar to that observed in earlier two tests.

Multi-Channel Burst Test #5

This test was intended to simulate the potential maximum travel distance of a ruptured channel within the core lattice and thus to evaluate the effect of bending stresses on the potential for pressure tube guillotine failure. The central channel in the bottom row was chosen as the burst channel and the outer channel in the top row was chosen as the target channel. The defects in the pressure and calandria tubes were located approximately at 5 o'clock and 11 o'clock position, respectively, in the cross section. This alignment was chosen in order that the pressure tube in the burst channel was able to bend towards the target channel under the discharging jet/thrust forces. Again, a 5.8 m long machined defect (similar to that used in MCBT #4) was milled in the pressure tube to investigate the potential for pressure tube guillotine failure following the failure of an initially defected calandria tube. The pressure tube ruptured at 14 MPa and the calandria tube ruptured at 9.1 MPa. The burst channel deflected under thrust forces towards the target channel. However, during deflection the burst channel impacted the central channel in the lattice, hence the potential maximum free displacement towards the target channel was not attained. Post-test observations indicate that the burst pressure tube had a maximum permanent displacement of about 198 mm towards the target channel (consisting of 178 mm vertical and 87 mm horizontal displacement). The final crack length in the pressure tube was 5.89 m, which is comparable to that obtained in MCBT #4. The additional bending stresses did not cause any additional crack propagation, nor was there any indication of crack bifurcation. The mechanical response of the surrounding channels was similar to that observed in other tests.

Multi-Channel Burst Tests #6 and #7

These two tests were intended to assess the effect of channel failure on the neighbouring shut off rod guide tubes (SORGTs). Each of the tests employed a full length SORGT parallel to the burst channel and short sections of SORGTs perpendicular to the burst channel at various locations. The central channel was chosen as the burst channel for both the tests. In test # 6, the coolant condition in the loop were 11.1 MPa and 285 ^{0}C at the time of PT burst. The initial defect lengths in the pressure tube was 5.8 m and the PT burst pressure was 15.1 MPa. The calandria tube burst at around 12 MPa and the final crack length in PT was 5.96 m. In test #7, the corresponding coolant conditions were 11.2 MPa and 296 ^{0}C. The initial defect length was 5.4 m and the PT burst at 12.7 MPa. The CT burst at 12.1 MPa and final crack length in the PT was 5.69 m. Post-test observations indicated that the SORGTs which were adjacent to the burst channel and which were impacted mechanically by the ejected bundles or burst channel were severely dented. The full length SORGT and other SORGTs which were located one lattice pitch away from the burst channel were not affected by the transient pressure loading generated by the channel rupture. The tests also measured the pressure transients at various locations in the containment tank. The other observations regarding the pressure transients and damage to surrounding structures was similar to that observed in the earlier tests.

Multi-Channel Burst Test #8

The objective of this test was to investigate the effect of an off central crack in the pressure tube. In all the previous tests the running cracks in the pressure and calandria tubes was simulated by central defects. The center of machined defect in the PT was shifted towards the inlet end by about 1.5 m to create an off central defect. Consequently, the machined defect was also shorter towards the inlet end. Adjacent SORGTs and a long inlet feeder were also simulated in the test. The coolant conditions during the test were 10.7 MPa and 305 ^{0}C. The pressure tube burst at 14 MPa and the calandria tube burst at 11.5 MPa. A long annulus fillup time was noted due to flashing of coolant in the long feeder. The running crack in the pressure tube resulted in guillotine failure at the inlet end of pressure tube and resulted in end fitting ejection. The calandria tube also indicated score marks due to indentation by PT rupture flaps. Only mechanical damage was observed on the simulated SORGTs adjacent to the burst channel. No damage was noted on SORGTs located one lattice pitch away from the burst channel.

Multi-Channel Burst Test #9

This test was again intended to study the effect of an off central crack in the PT on crack behaviour with coolant conditions typical of inlet end. Hence the crack geometry was almost identical to that in MCBT #8. A long flexible feeder was again simulated in the inlet end. The coolant conditions in the test were 10.9 MPa and temperature 273 ^{0}C. The central channel in the array was the burst channel with the top and bottom channels in the middle row being the target channels. The pressure tube burst at 13.7 MPa and the calandria tube burst at 9.5 MPa. The annulus fillup time of 207 ms and the flow rate following PT rupture was 92 Kg/s. Maximum bellow pressure was 2.8 MPa and there was no failure of bellows. Post test observations indicated that the crack in the pressure tube was arrested after propagating a short distance in the parent material with final length of crack being 4.24 m. At the end of test, the top target channel was displaced elastically by about 165 mm due to contact with the ruptured pressure tube.

Summary of Multi-Channel Burst Test Results

The following observations and conclusions can be made from the results of the MCBT series:

1. The bellows failed only in MCBT #1. In this test, the calandria tube survived the pressure tube rupture. The bellows remained intact in all other tests in which the calandria tube failed. This result is consistent with the observations in all previous test results, in which the calandria tube survived pressure tube rupture.

2. Considering all the tests in which the calandria tube ruptured and comparing the initial defect length and the corresponding final crack length, (including the crack growth in the second differential pressure loading following calandria tube rupture) it is noted that the crack propagation in the pressure tube is generally arrested when the crack enters the pressure tube (parent) material.

3. The transient pressure in the containment vessel results in "collapse" of the calandria tubes onto their pressure tubes which, effectively limits the magnitude of pressure load on the containment vessel.

4. The surrounding channels when impacted by the ruptured channel experience only limited elastic deformation.

5. The SORGTs that are adjacent to the burst channel were dented while the SORGTs, which are at least one lattice pitch away, were not affected.

6. Two tests (MCBT #3 and #8) resulted in guillotine failure of the PT due to crack branching.

Discussion of Results

From the safety analysis perspective, the main safety concerns associated with a fuel channel rupture are a) potential for cascading channel failure propagation, b) ability to shut down reactor by Shut off rod insertion and c) potential for calandria vessel failure due to pressurisation. The observed response of the target channels in these tests supports the safety analysis conclusion that the target channels will not experience any significant plastic deformation under jet, thrust and impact loading arising after a channel rupture. Hence cascading channel failure is not a concern. The damage observed on the simulated SORGTs, in MCBT #6, 7 and 8 indicates that the main damage mechanism is the mechanical interaction with the burst channel and the ejected bundles. The SORGTs are not affected by the transient pressure loads, as the perforated guide tubes appear to be transparent to the pressure waves generated. Hence the methodology used to evaluate the SORGT damage zone, in the safety analysis, due to transient pressure loads is very conservative. As regards the moderator pressure loading, the test results have confirmed that the calandria tube collapse can significantly reduce the calandria vessel loading. Due to the size limitations of the containment vessel, the measured pressure transients do not represent the far field pressure transients to assess the calandria integrity. However, the test results can be used for code validation.

The test results have also indicated the potential for crack branching that can result in guillotine failure of PT due to a running crack. Hence a better understanding of the dynamic crack propagation in PT following CT failure is needed. Analytical models are being developed to simulate the crack behaviour in PT. Also, an understanding of irradiation effects on crack propagation is needed to predict the consequences of PT rupture in a reactor.. This issue is currently addressed in the COG research program by burst tests on simulated irradiated tubes.

Conclusions

The full-scale experimental program has provided useful data for verification of the safety analysis codes. The tests have demonstrated that any hypothetical failure of a fuel channel will not lead to cascading channel failure. The assumed damage to the SORGTs resulting from a channel rupture for evaluation of SDS1 effectiveness is conservative.

Acknowledgements

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References

1. A.P. Muzumdar, G.I. Hadaller and R. Chase, "Experimental Program to Determine Consequences of Pressure Tube Rupture in CANDU Reactors", *Proc of Inter ANS/ENS Topical Meeting on Thermal Reactor Safety, San Diego, USA Feb 1986.*

2. G.I. Hadaller and A.P. Muzumdar, "Progress on an Experimental Program to Determine the Consequences of Pressure Tube Rupture", *Proc of 8th Canadian Nuclear Society Conference, St John, NB. June 1987.*

3. P.S. Kundurpi and A.P. Muzumdar, "Structural Response of Calandria Tube to a Spontaneous Rupture of the Pressure Tube" *Int. J. Pres. Ves. & Piping 31 (1988) 241-253.*

4. P.S. Kundurpi and G.I. Hadaller "Experimental Investigations into Consequences of fuel channel failure in CANDU reactor" Proc of 13th `Structural Mechanics in Reactor Technology' conference. Porto Allegre, Brazil. Aug 1995.

Table 1 Summary of Test Results from Phase 1 and 2 of Pressure Tube Rupture Tests.

	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8	Test #9
	PHASE 1					**PHASE 2**			
Type of Calandria Tube used.	5 mm thick Stainless Steel Tube		2.5 mm thick Stainless Steel Tube			Prototypic Zr-2 Calandria Tube			
	<u>Test Conditions</u>								
Supply Tank Pressure MPa	11.6	9.2	8.2	10.5	7.5	8.5	8.5	8.6	7.7
Coolant Temperature ^{0}C	290	301	295	307	255	256	251	271	251
Type of Pressure Tube	As received PT				Hydrided PT (160 ppm) over central 3 m		As received PT		
Defect Type	0.3 m long and 2 mm wide. Remaining wall thickness 0.88 mm			Full length Double side Grooved	Same as in Tests 1 to 3.		Full-length Double side grooved defect.		
Defect Location	The defect is located at centre in all tests.							End	Centre
Burst Pressure MPa	11.6	9.3	8.2	12	8.6	11.1	9.7	12.2	7.7
	<u>Test Results</u>								
Peak Annulus Pressure MPa	18 to 22	9.2	7.6	9	9.8	8.7	9.7	9.3	10.5
PT Crack Length m	2.5	0.6	0.37	5.9	2.75	2.75 (Multiple Cracks)	4.18	5.78	0.97
Bellows Burst Pressure MPa	7	6	7	6.1	5.5	6	7.8	7.4	7.5
Time to Bellows burst ms	-	550	715	525	530	550	-	540	-

Table -2: Summary of Integrated Burst Tests (IBT) - Test Conditions and Test Results.

	IBT #1	IBT #2	IBT #3	IBT #4	IBT #5	IBT #6
Supply Vessel Pressure (MPa)	9.4	10.3	9.65	10.3	10.8	10.9
Coolant Temperature (^{0}C)	274	279	249	253	274	285
Moderator Temperature ^{0}C	61	66	65	62	61	66
PT Defect (Length & remaining wall thickness)	0.3 m @ 0.91 mm, 5.54 m @ 2.17 mm Total Defect length 5.84 m		0.3 m @ 1.12 mm	0.3 m @ 1.07 mm, 1.7 m @ 2.17 mm, 1 m @ 3.25 mm	0.3 m @ 1.07 mm, 1.7 m @ 2.17 mm 1 m tapered to zero defect depth Total Defect length 3 m.	
CT Defect					0.25 mm deep, 5.25 m long.	
Main Results and Post test Observations						
PT Burst Pressure (MPa)	7.7	11.4	11.8	13.0	10.4	15.2
CT Burst Pressure (MPa)		10.9			7	
PT crack length m	3.85	5.84 axial and guillotine at ends	0.53	2.09	3.28	2.76
CT Deformation or crack Length	No CT failure. Max. diam strain 4.9%	Full length crack with circumferential tear at ends	No CT failure. Max diametral strain 3.1 %	No CT failure.	Full length crack along the defect.	No CT failure. Max diametral strain- 5.8 %
Max Bellow Pressure (MPa)	5.26	5.8	7.4	5.84	5.3	7.57
Bellows Burst time (ms)	136	No failure	736	357	No failure.	389

Table-3 Summary of Multi-Channel Burst Tests (MCBT) -

	MCBT #1	MCBT #2	MCBT #3	MCBT #4	MCBT #5	MCBT #6	MCBT #7	MCBT #8	MCBT #9
PT Defect length	2.84 m	3 m	5.8 m	5.8 m	5.4 m.	5.4 m	4.84 m	3.9 m Off Central Crack	3.935 m
Supply Vessel Pressure (MPa)	10.9	11.7	11.0	10.9	11.1	11.1	11.1	10.7	10.9
Coolant Temp (^{0}C)	259	260	265	264	265	285	296	305	273
Moderator Temp (^{0}C)	24	69	63	54	65	56 SORGTs simulated at various locations	58	59	59
Results and Post test Observations									
PT Burst Pressure (MPa)	12.9	14.8	11.95	14.7	14.1	15.1	12.7	14	13.7
Max. Bellows Pressure (MPa)	6.8 MPa Bellows Burst	2.6	3.6	3.8	2.39	3.78	4.57	3	2.84
PT Crack length (m)	2.74	2.92	5.5	5.98	5.89	5.95	5.69	4.22	4.24
Flow rate into annulus kg/s	100	125	130	128	120	110	100	62	92
Annulus fill time ms	250	205	270	256	212	244	281	409	270
CT burst Pressure MPa	No burst	12.9	11.4	11.6	9.6	11.9	12.1	11.5	9.5
Flow rate after CT burst kg/s	-	120	145	145	140	115	105	86	112

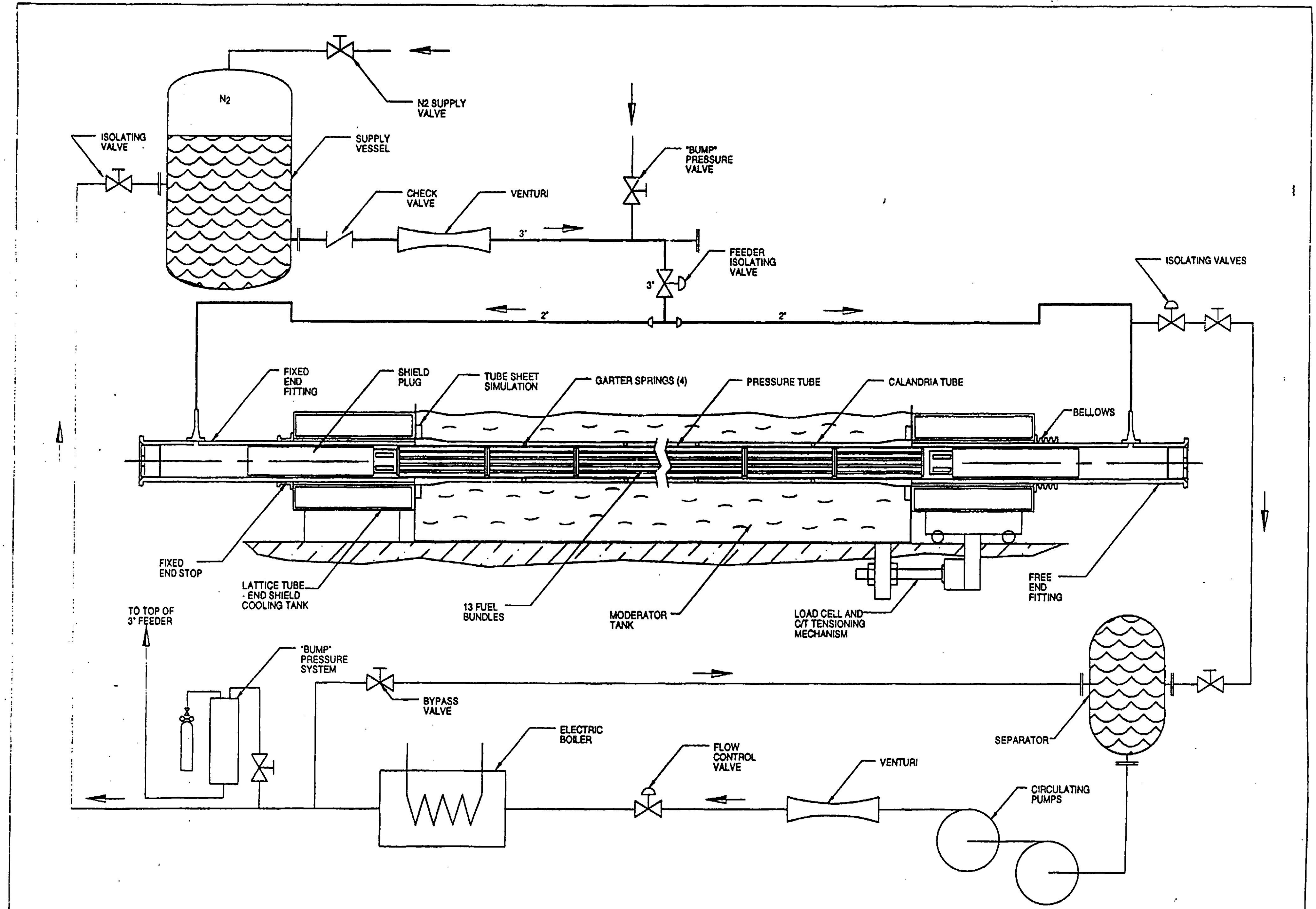

Figure - 1 Integrated Burst Test Loop Schematic

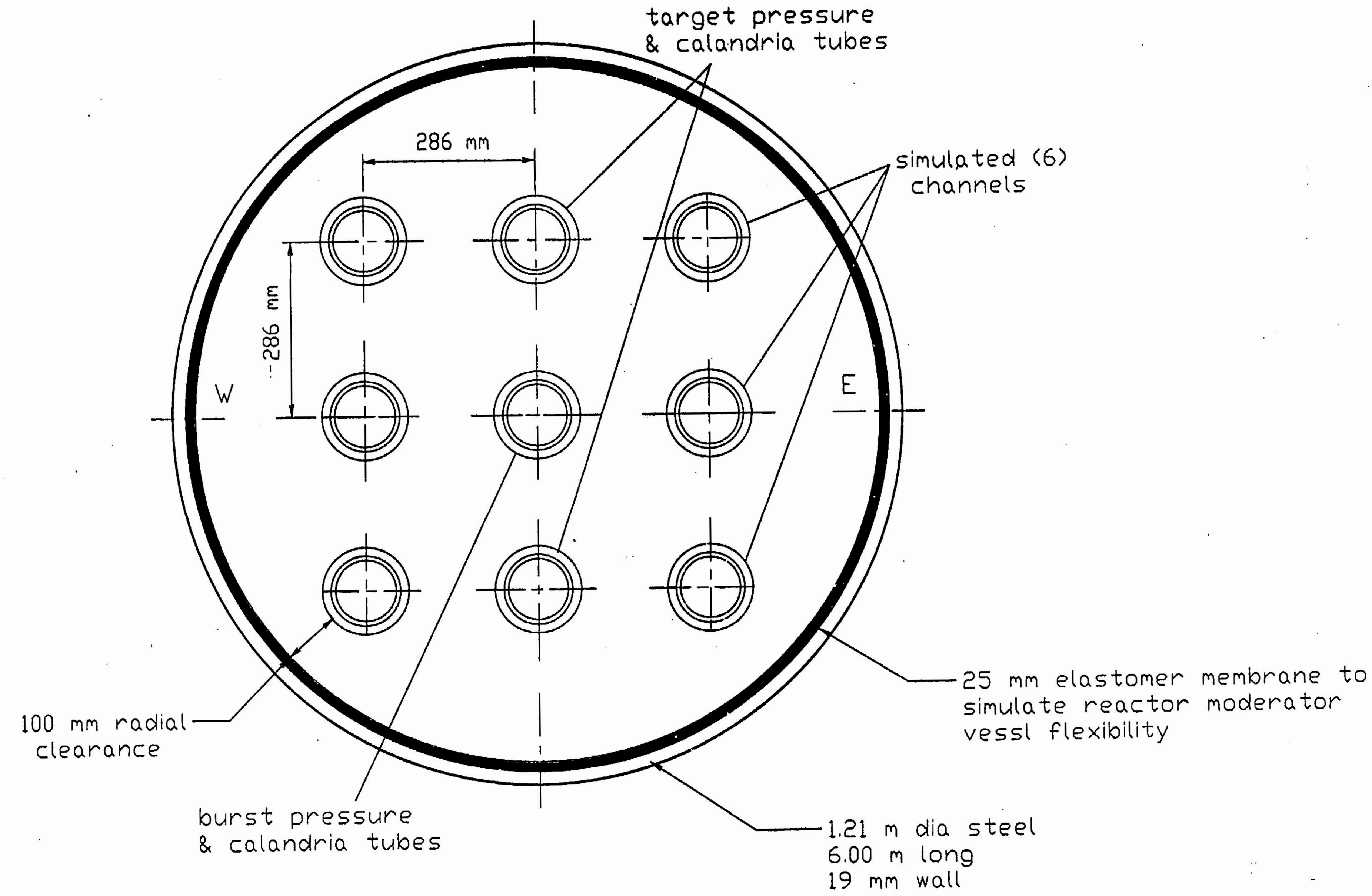

Figure - 2 Multi Channel Burst Test
Cross Section of Containment Vessel

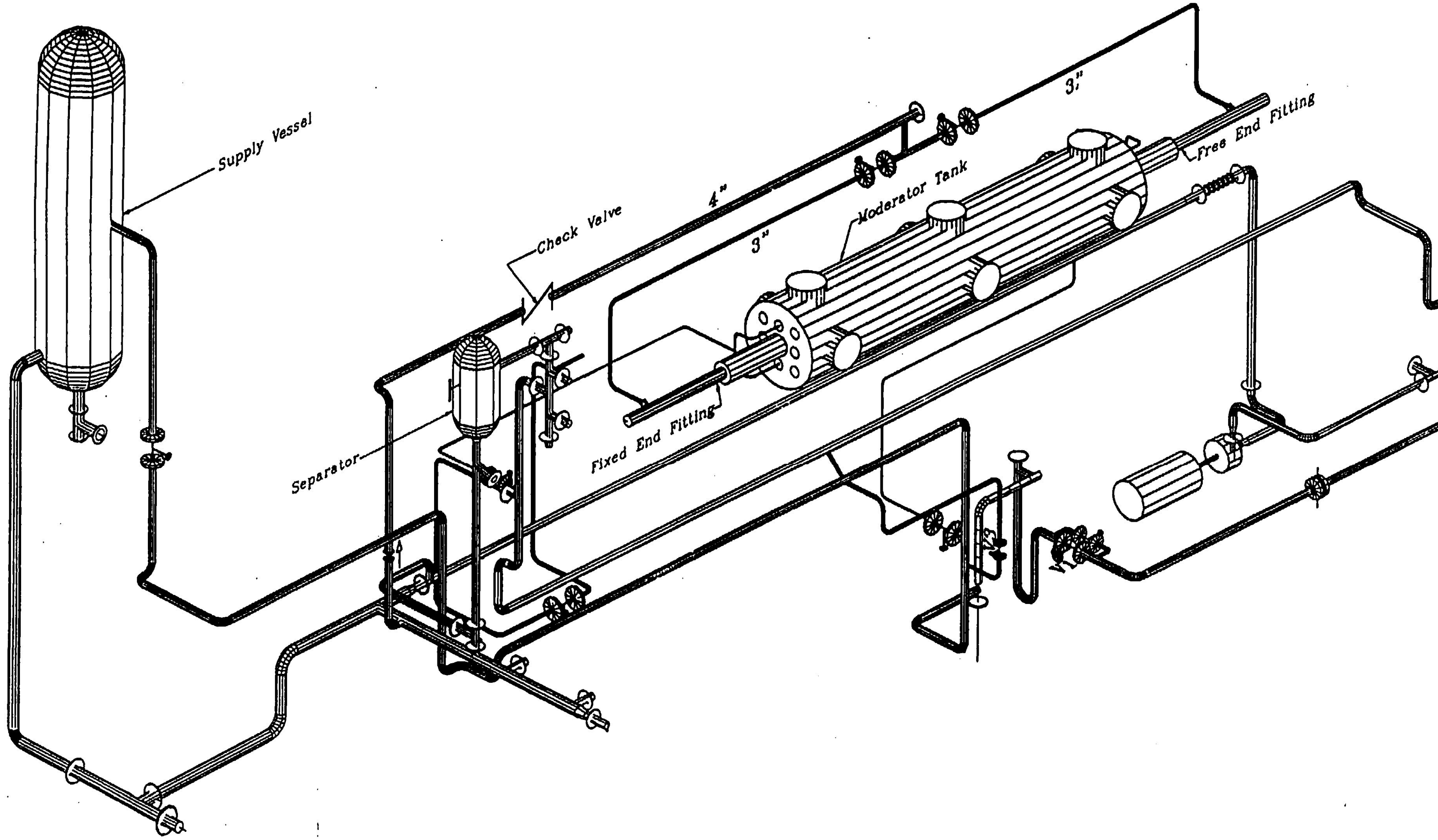

Figure 3. Multi Channel Burst Test
3-D Piping Schematic

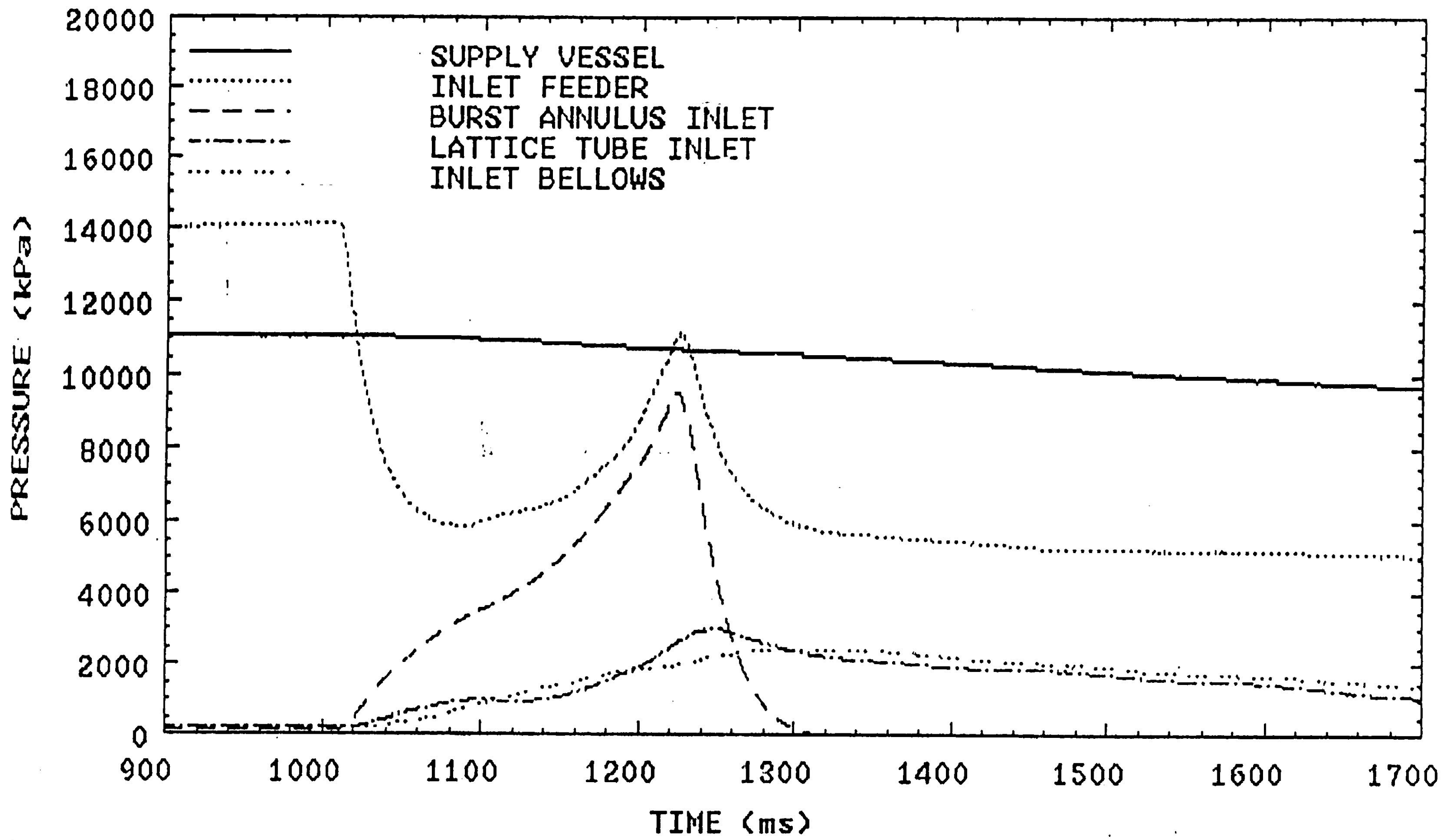

Figure - 4 Multi Channel Burst Test #5
Typical Annulus Pressure Transients following Pressure Tube Rupture