EXPERIMENTAL INVESTIGATION OF THERMAL BEHAVIOR OF CONCENTRIC TUBES DURING A SEVERE ACCIDENT

K. KUMASAKA
R. J. HAMMERSLEY
R. E. HENRY
K. MIZUNO

Hitachi, Ltd., Hitachi Works
Fauske & Associates, Inc.
Fauske & Associates, Inc.
Hitachi, Ltd., Hitachi Works

ABSTRACT

A pair of experiments were conceived and executed to provide data and a technical basis for investigating selected aspects of postulated severe accidents in a pressure tube/calandria tube configuration. The response to core damage and debris relocation within the pressure tube was investigated experimentally. The experimental objectives of the two tests were: 1) to assess the potential for failure of an unflawed pair of concentric tubes when prototypic wall stress is produced while high temperature debris is resident within the inner tube and sub-cooled water is present outside the outer tube, and 2) to assess the dynamic and energetic interaction given the rupture of the concentric tubes and the discharge of molten debris under steam pressure into the surrounding sub-cooled water pool. These experiments provide an effective demonstration of the passive cooling mechanism which can prevent calandria tube failure and of the interaction between molten debris and water if a calandria tube were to fail.

EXPERIMENTAL OBJECTIVES AND APPROACH

The experimental objectives of these tests were:

1. To assess the potential for failure of an unflawed pair of concentric tubes when prototypic wall stress is produced while high temperature debris is resident within the inner tube and sub-cooled water is present outside the outer tube.

2. To assess the dynamic and energetic interaction given the rupture of the concentric tubes and the discharge of molten debris under steam pressure into the surrounding sub-cooled water pool.

Test elements were fabricated that represented a full scale segment of a pair of concentric tubes. The inner tube represented a ballooned tube which had expanded until it contacted the outer tube. High temperature (2500°K) aluminum oxide was used as the debris simulant. This was produced by an iron thermite powder which was ignited in a crucible.

The exothermic reaction for the ignited iron thermite is

$$Fe_2O_3 + 2\,A\ell \rightarrow 2\,Fe + A\ell_2O_3 + Q$$

where Q is approximately 2.2 MJ per kilogram of the thermite used in these experiments.

The molten iron formed by the iron thermite reaction was separated and retained in a melt separator. The molten aluminum oxide was delivered to the concentric tube test element. In Test 1 50 kg of iron thermite were used and 35 kg of iron thermite were used in Test 2. The vertically oriented test element was submerged in a sub-cooled water pool which initially was at 70°C.

In Test 1 the crucible, melt separator, and test element were pressurized with nitrogen to 1.9 MPa prior to igniting the thermite. The pressure subsequently increased to 4.9 MPa during the thermite burn and draining. The combination of tube wall thicknesses, diameter, and this pressure (4.9 MPa) resulted in prototypic wall stress. The structural capability of the concentric tube pair to survive these conditions was then observed.

For Test 2 the crucible, melt separator and test element were pressurized to 2 MPa with saturated steam following the arrival of debris in the test element. For these tests the test element was initially flawed to induce its failure. Following its pressurization and consequential rupture molten aluminum oxide and steam were discharged into the initially sub-cooled water pool. The resulting dynamic interactions were recorded by the test instrumentation. The data was used to quantify the conversion ratio of the thermal energy in the discharged debris into mechanical energy.

TEST FACILITY AND TEST CONDITIONS

Figure 1 illustrates the general features of the test facility and the specific arrangement used for these tests. The test facility configuration consists of (1) a melt delivery assembly, (2) a melt separator, (3) the test element, (4) steam and nitrogen supplies, and (5) safety features. Thermal insulation was added to the containment vessel for Test 2. Six electrical heaters (1.5 KW each) were attached to the outer surface of the cylindrical portion of the containment vessel. The combination of the strip heaters and thermal insulation provided a means of maintaining the containment vessel water at approximately 70°C once it was added to the vessel.

The melt delivery assembly contained within the spool piece included a crucible which received the initial thermite powder charge and contained it, following its ignition by the igniter and prior to its discharge through the failed melt plug. The molten thermite separates into two layers with the less dense aluminum oxide on top of the more dense iron. The crucible was located inside a heavy walled metal (carbon steel) spool piece, providing a portion of the pressure boundary for the test element. The flange containing the melt plug and supporting the crucible had cut-outs allowing good pressure equilibration between the spool piece and the melt separator. This configuration was employed to insure that molten high temperature debris relocation following melt plug failure was gravity driven. This reduced the potential for ablation of the base plate of the melt separator.

The crucible contained a thin wire heater acting as the igniter. After remote ignition, the thermite burned completely, melted through the lead plug at the bottom of the conical crucible section, and then was released directly into the melt separator. The thermite burning rate is such that the thermite powder was burned and the molten layers were formed (iron layer on the bottom since its density is greater than aluminum oxide's density) prior to melt plug failure. The complete burning and molten layer formation occurred in less than approximately 20 to 35 seconds.

The melt separator consisted of a thick walled metal (carbon steel) and a baseplate with a 5 cm (ID), thick walled, carbon steel overflow tube. The height of the overflow tube above the base plate was sized to retain the molten iron in the melt separator and allow the molten aluminum oxide to overflow into the test element. A refractory capped deflector was installed over the top of the overflow tube to prevent the direct discharge of molten iron as it drained through the failed melt plug.

The test elements were attached by a stainless steel flange to the base plate of the melt separator. The test elements were made of stainless steel concentric tubes.

The steam generator produced the high temperature water and steam used in these tests. The steam generator used electrical heaters installed on the outer surface of the carbon steel vessel. For Test 1 the steam generator was used only to supply both the hot water used to fill the containment vessel. Nitrogen bottles (15 MPa) were used to pressurize the test element in Test 1. In Test 2 the steam generator was used to supply both the hot water used to fill the containment vessel and the steam (2 MPa) that was used to pressurize the test element.

Two test elements were fabricated for these tests. Each was fabricated of stainless steel components (concentric tubes, flange, and end plate). Each concentric tube was welded at both the upper flange and the end plate. The leak tightness of each element was demonstrated before its use by a hydrostatic test.

Each test element was installed in the test facility with a vertical orientation by attaching its flange directly to the bottom of the melt separator base plate and centering on the separator tube exit.

The test elements were designed to represent a segment of a pair of concentric tubes with the inner tube ballooned until it contacted the outer tube. The tube diameters and wall thicknesses were designed to represent the full scale, prototypic tubes. The dimensions of each element that represented prototypic (in cross-section) dimensions are provided in Figure 2. The length of each test element was 0.76 m.

For Test 1 an unflawed test element was used and for Test 2 a flawed test element was used. The flaw was designed to assure that the concentric tubes would fail once the high temperature oxidic debris was resident in them and the tubes were then pressurized. The objective of Test 2 was to study the energetic interactions following the concentric tube rupture and the subsequent discharge of debris and steam into the surrounding water pool. The flaw performed as anticipated and a "fish mouth" failure was produced when the flawed test element was pressurized.

The instrumentation for these tests (see Figure 3) was selected and configured to support the tests' objectives and to support the safe operation of the test facility. The instrumentation included pressure transducers, thermocouples and a load cell. The data collection system provided a sampling interval of approximately 85 ms between data points for each signal. All of the measurements were recorded in the memory of the data collection system for subsequent conversion to engineering units and processing. All but one of the thermocouples were Type K Cromel-Alumel thermocouples. The maximum temperatures measurable with this type of thermocouple is approximately 1250°C. One high temperature Type C Tungsten-Rhenium thermocouple was used. This high temperature thermocouple is designed for measurements as high as 3000°C. It was only used in Test 1 and did not survive the severe thermal transient and ablation during the debris delivery to the test element.

The accuracy of the Type K thermocouples is given as $\pm$ 2.2°C or $\pm$ 0.75% and their response time to local temperature changes is 2 or 3 seconds. Pressure measurements were made with Validyne Corporation diaphragm pressure transducers which have an accuracy of $\pm$.5%.

Table 1 provides the test matrix and initial conditions used for these experiments. For both tests the test element was submerged in a water pool in the containment vessel whose initial temperature was approximately 70°C and the initial vessel pressure was 0.1 MPa (absolute). Each test included a melt separator such that the iron component produced by burning the iron thermite was retained and isolated from the test element. Thus, the mass of molten debris simulant (aluminum oxide) available for each test was approximately 1/2 of the iron thermite mass stated in Table 1. From separate effects tests the temperature of the molten aluminum oxide was estimated to be 2525°K which represented approximately 200°K of super-heat compared to its melting point.

The initial conditions for each test were adjusted as appropriate for each test's objective. For Test 1 the containment vessel water level was initialized to 0.97 m. This level was used to assure that the entire concentric tube test element was submerged in the sub-cooled water pool. For Test 1 nitrogen was used the pressurize the test element.

For Test 2 the initial level of the water pool in the containment vessel was 0.61 m. This assured that the flawed test element was submerged sufficiently such that the maximum elevations of both the debris accumulated with the test element and the test element flaw were submerged. This was the appropriate initial configuration for these tests whose objective was to study the discharge of debris and steam from a failed concentric tube pair. This initial water depth also satisfied the facility's safety requirements regarding the potential loads which could be imparted to the containment vessel's wall and lid. For Test 2 the test element was pressurized by a 2 MPa saturated steam supply. The thermite was first ignited and an indication of debris relocation to the test element was obtained prior to pressurizing the test element with steam. This sequence of events was employed to insure that the desired initial test conditions were established. Specifically, molten debris was resident within the unfailed but flawed test element prior to the test element's failure due to pressurization by steam.

TEST RESULTS

For Test 1 approximately 16.6 kg of the 25 kg of Al_2O_3 produced by igniting the 50 kg mass of iron thermite was delivered to the test element. The test element did not fail nor discharge debris into the surrounding water pool. Thus, the test element of concentric tubes when subjected to high temperature oxidic debris (approximately 2500°K) and 4.9 MPa overpressure did not rupture and discharge debris into the surrounding water pool (initially at 70°C). The observed survivability of the concentric tubes is a very positive result. This result demonstrated the effectiveness of the water pool as a heat sink that removed the energy in the debris.

Figure 4 depicts the debris distribution observed following the test. A crust due to a debris film is observed on the inner surface in the upper portion of the test element and what appears to be essentially a solid plug of debris resides in the bottom half of the test element. The depth of the accumulated debris in the inner tube is approximately 0.39 m. A post-test sample of the debris was used to estimate the density which was approximately 2630 kg/m^3 versus a theoretical density of 3800 kg/m^3. The layer of metal shot (3 mm diameter) was used to protect the bottom of the test element as the molten debris was delivered to it. The separator was approximately 86% efficient in removing the molten iron from the reacted thermite.

A slight bulge (localized strain) was observed on the outer surface of the calandria tube. The heat affected zone was approximately 3.8 cm wide and 11.4 cm tall and was discolored due to the high localized temperature. Two smaller (approximately 1.9 cm diameter) heat affected spots were located on either side of the bulge. The remainder of the stainless steel test element appeared to be as prior to the test per visual inspection. The measured surface temperature of the bulge increased from the initial pool temperature (73°C) to approximately the saturation temperature (100-102°C) for the containment vessel's pressure once debris was delivered to the test element. Since the surface temperature did not escalate beyond essentially saturated conditions, it can be concluded that film boiling was not established. Thus, a nucleate boiling condition was apparently maintained while the debris within the test element was quenched and cooled.

The calandria tube was sectioned and removed from the pressure tube. This exposed a region of the pressure tube which had been melted by the high temperature debris inside it such that the molten debris had attempted to enter the limited gap between the ballooned pressure tube and calandria tube. The average gap thickness was approximately 1 mm between the two concentric tubes. However, due to surface irregularities and variations in the precise radius of curvature of each tube intermittent points of contact occurred between the two tubes. It is significant to note that the water on the outside of the calandria tube prevented its failure even when it was in direct contact with the molten high temperature oxide inside it. The calandria tube was removed from the pressure tube and no adherence between the refrozen oxide debris and calandria tube was experienced. The calandria tube in the localized area in contact with the oxide had been sufficiently heated by the molten oxide such that the sustained wall stress due to the 4.9 MPa pressure within the concentric tubes led to the formation of a bulge, i.e., localized permanent strain.

In Test 2 approximately 3.6 kg of the 17.5 kg of aluminum oxide produced by igniting the 35 kg mass of iron thermite remained in the failed test element following the tests. The separation in the melt separator was very efficient and a minimal amount (approximately 0.5 kg) of aluminum oxide was retained in the melt separator. Thus, approximately 13 kg of aluminum oxide were discharged through the calandria tube failure into the containment vessel. The desired tube failure was induced following the arrival of high temperature oxidic debris (approximately 2500°K) in the test element and its pressurization with saturated steam at 2 MPa.

A flaw was designed and incorporated in the concentric tube configuration such that a forced rupture could be induced. The flaw was produced by cutting a slot in the pressure tube wall approximately 30 cm in height and 2.5 cm in width. The portion of the calandria tube opposite this slot in the pressure tube was thinned by milling a flat on the outer surface of the calandria tube. The minimum thickness of the flatted portion of the calandria tube was approximately 0.76 mm. Following the installation of the thermocouples on the outer surface of the calandria tube and thinned wall section, heavy duty tape was placed over the thinned portion of the calandria tube. The tape was used to inhibit heat transfer between the surrounding water and the outer surface of the flatted region of the calandria tube. This technique successfully satisfied the objectives of avoiding failure of the calandria tube while molten debris collected in the test element but allowing failure once the test element was pressurized with steam. A "fish-mouth" shaped failure was produced as shown in the photograph in Figure 5. The height of the fish-mouth break was approximately 30 cm which corresponds to the length of the flatted portion of the calandria tube. The maximum width was found to be approximately 3.5 - 3.8 cm. The approximate failure area is 45 cm^2.

Samples of the debris were retrieved from the floor of the containment vessel following the test. Each sample was dried and passed through a series of standard screens in order to determine the particle size distribution. The particle size distribution was determined by calculating the mass fraction of the sample collected on each of the screens and by calculating the cumulative fraction of the debris that would pass through the series of screens. The resulting particle size distributions obtained from the four samples are presented in Table 2.

The discharge of the molten debris in the water pool in the containment vessel resulted in energetic interactions. The pressure histories recorded on the bottom of the calandria vessel and its roof and sides indicated a transient response when the debris was discharged into the subcooled water pool. These observed pressures on the boundaries of the containment vessel were bounded by a value of approximately 1.3 bar gauge pressure.

With the observed small particle sizes exhibited by this experiment, there is no question that there was effective quenching of debris as it came out of the failed test element. However, this also demonstrates that high pressure discharge of molten debris from a failed pressure tube is not the means whereby an energetic steam explosion is effectively created. The debris would be quenched at essentially the rate at which it is discharged from the failure site. The entrainment of subcooled water into the high temperature material as it is being discharged makes effective use of the substantial subcooling in the moderator water. In addition, the rapid growth of the steam/two-phase region also would cause effective condensation at the interface (surface) between this region and the subcooled water. Consequently, there is no mechanism to accumulate large quantities of dispersed molten debris within the water pool. Apparently these are the major reasons why there is a substantial limitation to the energetics of the debris water interaction. Specifically, the size of the debris provides no limitation to the dynamics of the situation, rather the substantial limitations are inherent to the containment vessel (moderator tank) behavior and the high pressure discharge of the molten material.

CONCLUSIONS

The basic conclusions provided by these tests are as follows:

1. An unflawed pair of concentric tubes can survive when prototypic wall stresses are produced while high temperature debris is resident within the inner tube and moderator water is present outside the outer tube. The water pool provided sufficient cooling to maintain the outer tube wall temperature sufficiently low that the material strength was not exceeded during prototypic full-scale wall stress. The average energy removal heat flux for Test 1 was estimated from the measured pool temperature histories to be approximately 0.35 to 0.45 MW/m^2.

2. The discharge of molten debris under steam pressure from a ruptured calandria tube into a subcooled water pool rapidly entrains water which quenches the debris. This results in an energetic interaction that is ineffective (low percentage) in converting the debris' thermal energy into mechanical energy (work).

These tests achieved all of their major objectives. They provide effective demonstrations of the passive cooling mechanism which can prevent calandria tube failure and of the interaction between molten debris and water if a calandria tube were to fail.

TABLE 1 INITIAL CONDITIONS

Test Number	Iron Thermite Mass (kg)	Test Pressure/Fluid (MPa)	Test Element
1	50	5.0/Nitrogen	Unflawed
2	35	2.0/Steam	Flawed

TABLE 2 PARTICLE SIZE DISTRIBUTION

Particle Size (μm)	Sample 1		Sample 2		Sample 3		Sample 4	
	Mass Fraction	Cumulative Mass Fraction	Mass Fraction	Cumulative Mass Fraction	Mass Fraction	Cumulative Mass Fraction	Mass Fraction	Cumulative Mass Fraction
>4000	0.14	0.14	0.15	0.15	0.078	0.078	0.11	0.11
2000 - 4000	0.32	0.46	0.21	0.36	0.25	0.33	0.23	0.34
850 - 2000	0.20	0.66	0.21	0.57	0.30	0.64	0.26	0.60
600 - 850	0.096	0.76	0.11	0.68	0.15	0.79	0.14	0.74
425 - 600	0.035	0.79	0.059	0.74	0.061	0.85	0.068	0.81
300 - 425	0.026	0.82	0.058	0.79	0.052	0.90	0.056	0.86
250 - 300	0.017	0.83	0.024	0.82	0.020	0.92	0.025	0.89
180 - 250	0.031	0.87	0.035	0.85	0.023	0.94	0.029	0.92
150 - 180	0.017	0.88	0.026	0.88	0.014	0.96	0.019	0.94
125 - 150	0.031	0.913	0.020	0.898	0.0077	0.967	0.012	0.949
75 - 125	0.031	0.944	0.052	0.95	0.018	0.985	0.027	0.976
32 - 75	0.053	0.997	0.049	0.999	0.012	0.997	0.022	0.998
<32	0.0	0.997	0.002	1.001	0.001	0.998	0.002	1.0

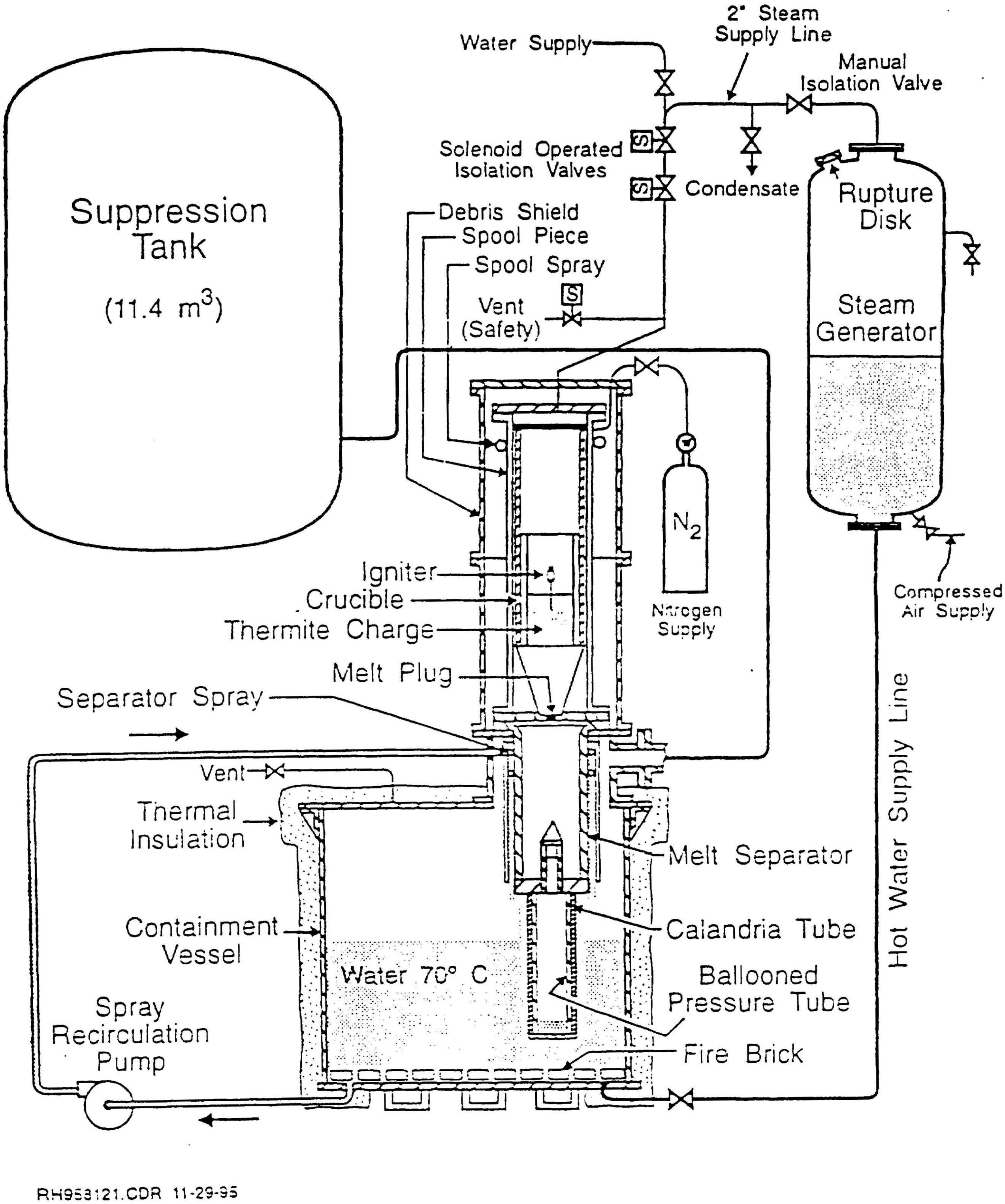

FIGURE 1 TEST FACILITY LAYOUT AND COMPONENTS

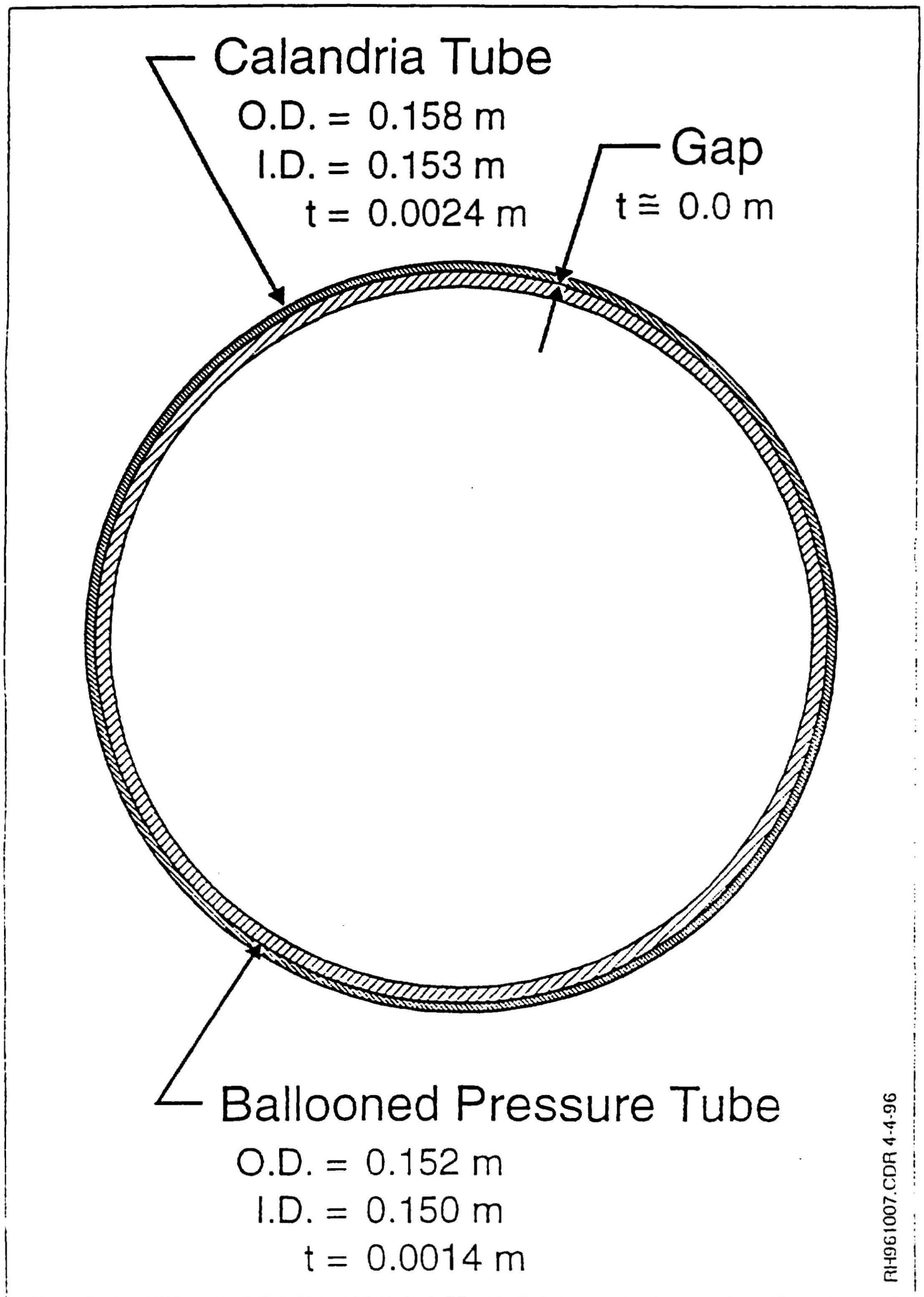

FIGURE 2 TEST ELEMENT CROSS SECTION

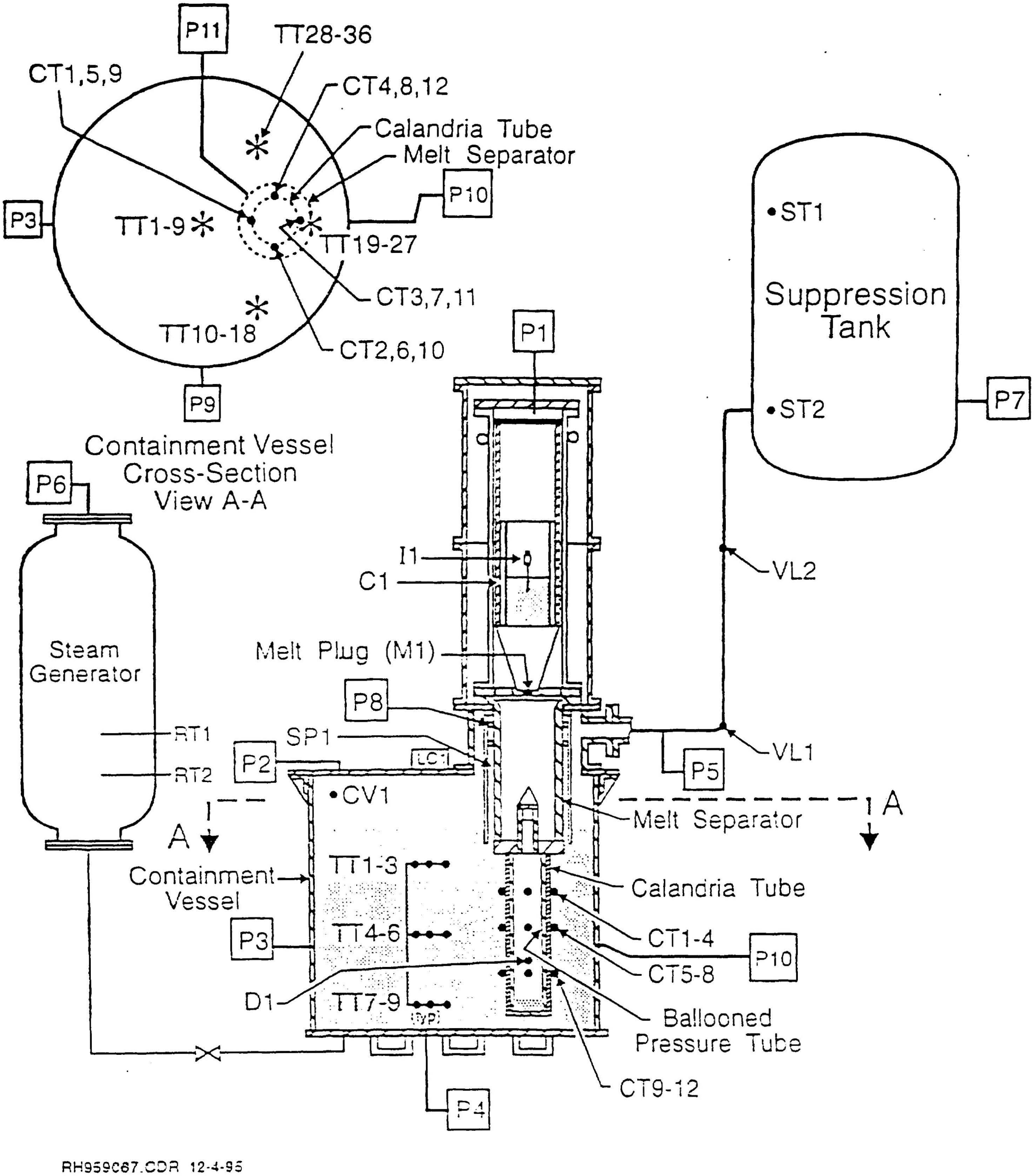

FIGURE 3 INSTRUMENTATION ARRANGEMENT

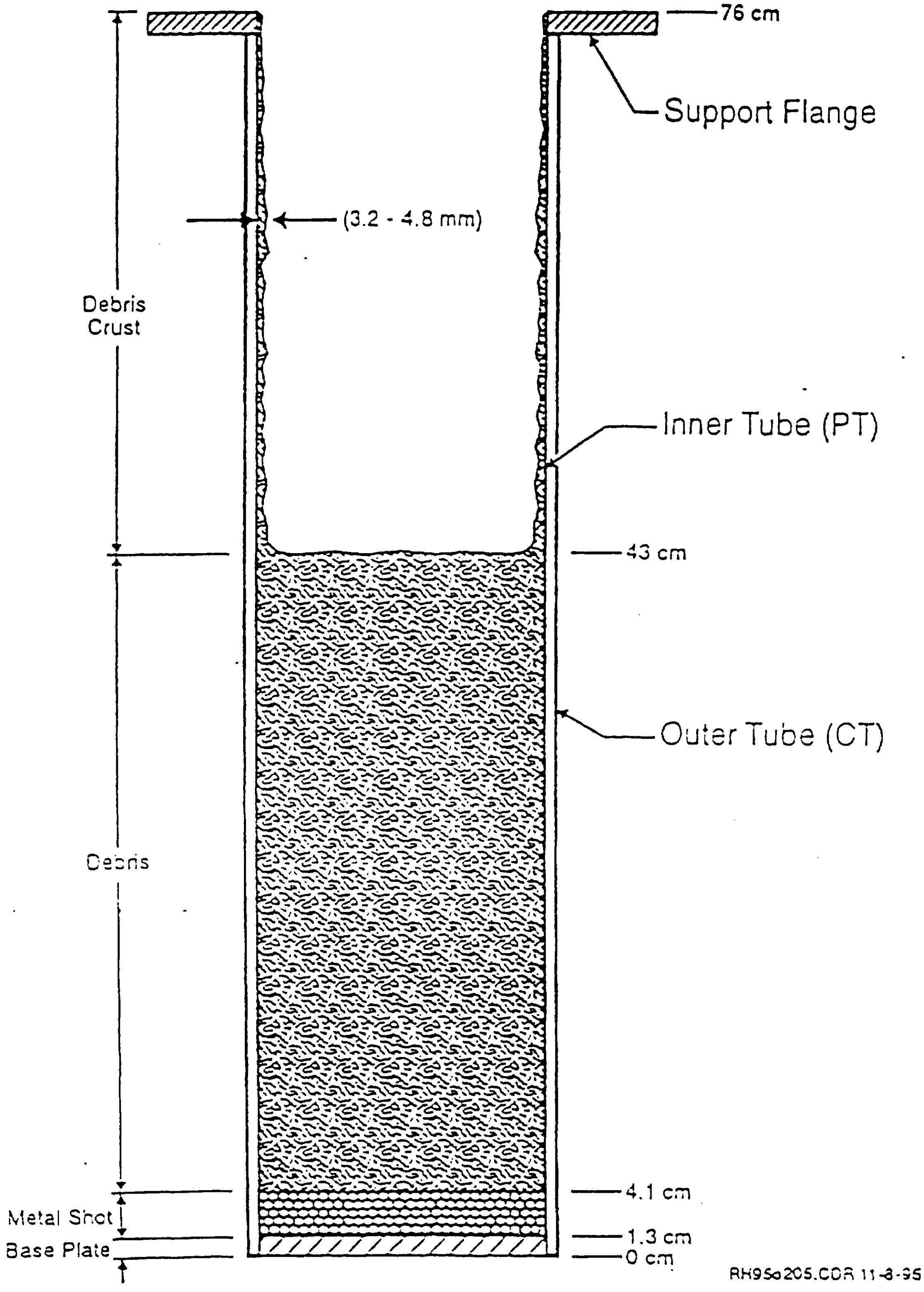

FIGURE 4 POST-TEST OBSERVATION OF DEBRIS CONFIGURATION

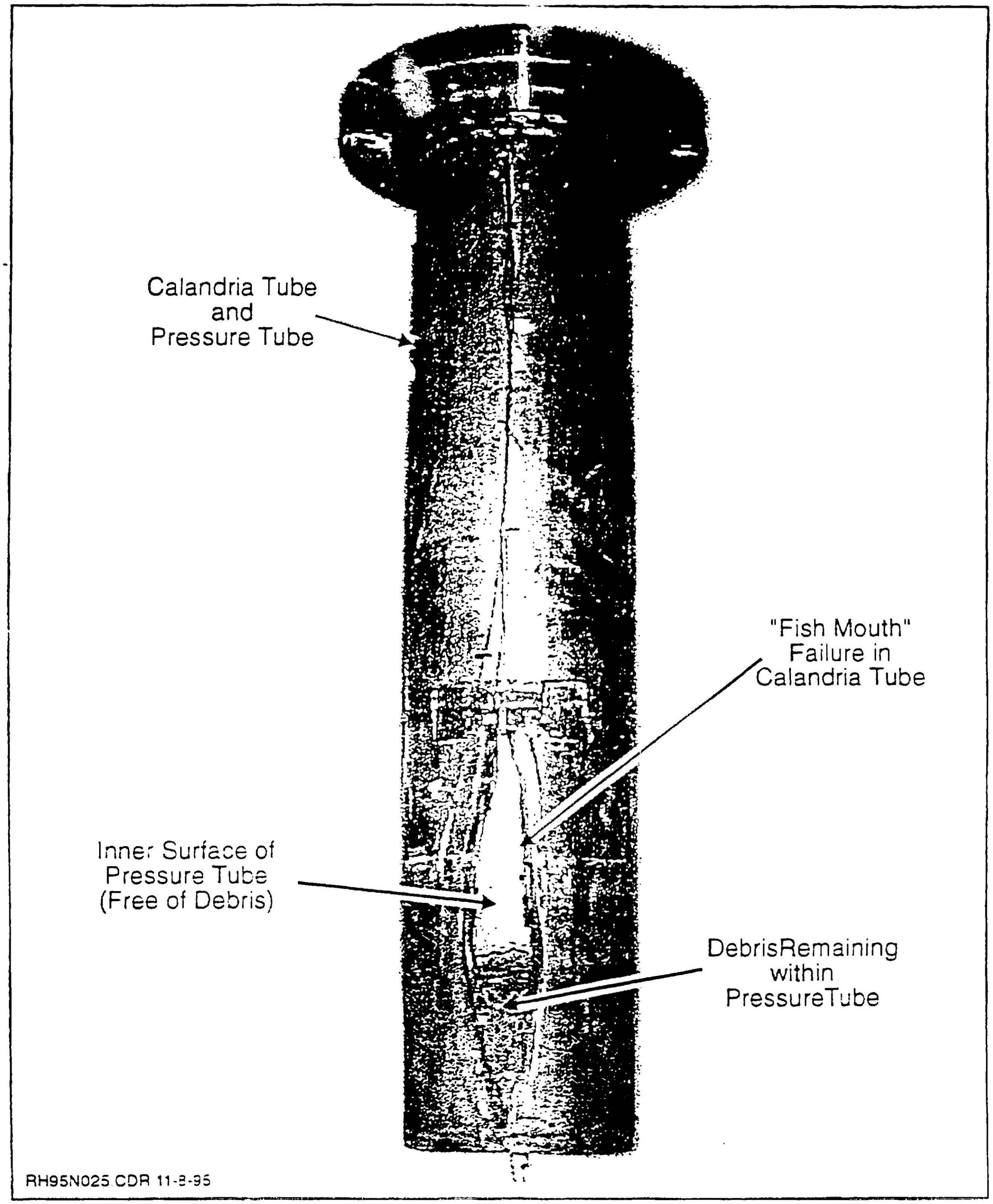

FIGURE 5 FAILED TEST ELEMENT