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EXPERIMENTAL DETERMINATION

OF

LOWER PLENUM ECC INJECTION EFFECTIVENESS

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MASTER

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ABSTRACT

The effectiveness of lower plenum emergency core coolant (ECC) injection during a double ended offset shear cold leg break loss-of-coolant accident (LOCA) was investigated experimentally in a small-scale model of a pressurized water reactor (PWR). In order to determine relative merit of the lower plenum injection concept to mitigate the severity of a large break LOCA, data from lower plenum injection experiments were compared to data from an experiment in the Semiscale Mod-3 system in which cold leg ECC injection was utilized. The results indicated that lower plenum injection was extremely effective in initiating early reflooding of the core and earlier rod quenching than was observed in the cold leg injection experiment. Experimental data from three lower plenum injection integral blowdown-reflood experiments were compared to determine the effect that several injection variables had on the overall system thermal-hydraulic response. An optimum time of injection initiation appeared to exist due to the presence of strong countercurrent flow early in the blowdown portion of the experiment. Nitrogen injection into the lower plenum after ECC accumulator water depletion resulted in voiding of downcomer liquid (hydrostatic driving head for reflood) as well as the liquid inventory in the core. Since the core was not completely quenched when nitrogen injection began, heater rod quenching was delayed until core reflood resumed.

Introduction

A loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR) can result in a system depressurization that activates the emergency core cooling system (ECCS). The ECCS, which supplies water to the primary coolant system, is intended to provide cooling of the fuel rods in the event that departure from nucleate boiling (DNB) occurs as a result of system depressurization and core voiding. In most PWRs the ECCS liquid is injected into the cold legs of the primary coolant loops just upstream of the vessel inlet annulus. The injected fluid enters the core through the downcomer. In the cold leg injection configuration the potential exists for ECC fluid to bypass the downcomer in the event a large piping break occurs in one of the cold legs. An alternate ECCS configuration would inject water directly into the lower plenum. This configuration has the potential for earlier initiation of core reflood since when the water is delivered directly to the lower plenum the tendency to bypass ECC fluid is diminished. The concept and potential of lower plenum ECC injection were evaluated in the Semiscale Mod-3 facility, which is part of the overall Semiscale Program conducted by EG&G Idaho, Inc., for the United States Nuclear Regulatory Commission. The Semiscale Mod-3 facility is a small nonnuclear experimental facility scaled from a PWR and is used for the purpose of providing data for computer code development and assessment and for evaluating system and core behavior during a simulated accident. Although the Semiscale Mod-3 facility has some atypicalities inherent from its scaling rationale, demonstration of a more effective ECCS configuration in the small facility may be extrapolated in a general way to a large plant. This paper therefore discusses the results of the investigation and draws conclusions concerning the effectiveness of lower plenum ECC injection in the Semiscale Mod-3 system and the expected effectiveness in a large PWR.

Semiscale Experimental System and Operating Procedure. The Semiscale Mod-3 experimental facility,[1] shown in Figure 1, is a small, scaled model of a four-loop pressurized water reactor. The facility is used to obtain transient thermal-hydraulic data under simulated loss-of-coolant accident conditions. The Semiscale system consists of a pressure vessel and internals; an external downcomer pipe; an intact loop consisting of a pressurizer, steam generator, coolant pump, and associated piping and a broken loop consisting of a steam generator, coolant pump and piping. The intact loop simulates three loops of a four loop PWR and the broken loop simulates the remaining loop. LOCA pipe breaks are simulated by blowing out rupture disks in the broken loop break assembly. The effluent from the system enters a pressure suppression system designed to simulate the containment conditions in a large PWR.

The Semiscale Mod-3 core consists of 23 full-length (3.66 m) electrically heated rods, one unpowered rod, and a liquid level probe. The rods are of typical PWR fuel rod diameter (1.072 cm) and are arranged in a typical PWR fuel bundle pitch. Each heater rod has six chromel-alumel thermocouples swaged between an inner and outer clad to provide cladding temperature measurements at different axial elevations along the rod. The heater rods extend from the top of the core down to the core inlet, and heater rod leads exit the vessel through the lower plenum. The powered rods have a chopped cosine axial power profile with a peak power factor of 1.55. Total core power at rated load conditions is 2 MW.

Fluid density, flow rate, pressure, and temperature are measured at the core inlet and outlet, and at several locations in the intact and broken loop piping. Fluid temperatures in the core are measured at several grid spacer locations. In-core, downcomer, and loop fluid densities are measured using gamma attenuation devices. Mass flow is determined by combining a volumetric flow measurement, made by a turbine meter or a momentum flux measurement made by a drag device, with a fluid density measurement.

Three lower plenum ECC injection experiments were performed in the Semiscale Mod-3 system. Each of the experiments was an integral blowdown-reflood test in which the system was brought up to initial conditions typical of PWR normal operation at full power prior to the initiation of the LOCA transient. The initial conditions were identical to those in a cold leg injection experiment that was also performed in the Mod-3 system.[2] The only conditions varied in the tests involved operation of the ECC system. Transient core power was controlled to simulate the ANS + 20%[3] power decay profile. Conditions at the time of rupture included a system pressure of 15.5 MPa and a core differential temperature of 38.5 K.

The first of the lower plenum injection tests[4] (base test) specified that all the ECC fluid be injected into the lower plenum. The high pressure injection system (HPIS) had a set point of 12.41 MPa, the accumulator injection set point was 4.14 MPa, and the low pressure injection system (LPIS) was activiated at 1.03 MPa. The ECC water temperature was about 300 K. The second lower plenum injection test[5] was the same as the first except that the accumulator set point was changed to 6.89 MPa. The final lower plenum injection test[6] was also identical to the base test except nitrogen injection was permitted following depletion of the accumulator water. The accumulator was isolated from the system prior to nitrogen injection in the first and second lower plenum injection tests. The lower plenum injection tests were compared with the cold leg injection experiment which specified that all ECC liquid would enter the cold leg upstream of the vessel inlet annulus.

General Blowdown Response. In each of the LOCA experiments (with lower plenum injection and cold leg injection) the thermal-hydraulic response was essentially the same prior to the initiation of accumulator injection. The core heater rods experienced critical heat flux and began heating up as system mass exited the break. The effectiveness of lower plenum injection relative to cold leg injection and the effect of varying lower plenum injection parameters were determined by comparing the reflood and rod quenching behavior in the various experiments.

A phenomenon referred to as ECC bypass occurs in the Semiscale facility when cold leg injection is used during a large break LOCA simulation. The bypass is due to the reverse flow of steam up the downcomer at a velocity greater than the flooding velocity[6] thus preventing the penetration of ECC fluid to the lower plenum. The ECC fluid flows around the inlet annulus to the broken loop cold leg and out the break. The condition persists until reverse downcomer flow drops below the flooding velocity limit, which is generally not reached until system and containment pressures equilibrate. In experiments using cold leg injection the presence of cool ECC liquid in the cold leg and inlet annulus tend to promote stronger reverse flow in the core and downcomer due to condensation. The contribution to the reverse core flow in the cold leg injection experiment was estimated in a manner similar to an analysis performed in the Semiscale Mod-1 system which had an annular downcomer configuration).[7] The expression used for relatively low downcomer flowrates[8] was

$$U_g = \frac{j_g}{\rho_g} = \left(\frac{2\sigma}{2-\sigma}\right) \left(\frac{M}{2\pi R}\right)^{0.5} \left[\frac{P_g}{(T_g)^{0.5}} - \frac{P_f}{(T_f)^{0.5}}\right] \left(\frac{1}{\rho_g}\right)$$

where j_g is the molecular mass flux, P_g, and P_f are the steam and liquid pressures, T_g and T_f are the steam and liquid temperatures, ρ_g is the steam density, σ is the condensation coefficient U_g is the vapor velocity, M is the molecular weight of water, and R is the universal gas constant. For a value of condensation coefficient (σ) of 0.04 for water, the downcomer steam velocity during accumulator injection was calculated to be within about 30 to 50% of the downcomer velocity measurements. Break induced reverse flow, with the contributing effect of condensation in addition to the steam generation resulting when ECC liquid contacted the hot downcomer walls, contributed to upward steam flows in the downcomer capable of holding the ECC liquid. The minimum steam flow required to prevent ECC penetration was estimated using the Wallis flooding correlation.[9] The correlation is of the form

$$J_g^{*1/2} + m\,J_f^{*1/2} = C$$

where J_g^* and J_f^* are dimensionless groups relating the vapor and liquid momentum fluxes to the hydrostatic forces, m is a constant equal to 1.0 for turbulent flow conditions, and C is a constant dependent on geometric conditions. For a flooding condition $J_f^* = 0$ and the value of C was assumed to be about 0.9. A minimum steam velocity in the downcomer of 10 to 12 m/s would result in flooding which prevented the ECC from penetrating the downcomer. Measurements of the downcomer velocity indicated flooding existed through about 50 s into the transient.

Injection of ECC liquid directly into the lower plenum would be expected to alleviate or at least reduce the ECC bypass problem. Locating ECC injection in the lower plenum would result in condensing a portion of the reverse steam flow from the core and, as the lower plenum fills, the path from the core to downcomer would be plugged. The following section discusses the results of the first lower plenum injection test.

Effectiveness of Lower Plenum ECC Injection. The relative effectiveness of the lower plenum injection concept is illustrated in Figure 2, which compares the mid-core cladding temperature response for the cold leg injection test and an axial variation of the temperature response for the lower plenum injection tests. The thermal response is similar until about 32 s when, in the lower plenum injection test, the cladding began to cool indicating core reflood had begun. A similar decrease in cladding temperature in the cold leg injection test occurred about 20 s later when cold leg injected ECC fluid was able to penetrate the downcomer.

Data from the lower plenum injection test shows that the cladding cool-down rate was about 7 K/s during the early reflood period between 32 and 58 s and decreased to about 2.2 K/s at 58 s. The decrease in cool-down rate at 58 s corresponded to the time in the transient at which the accumulator injection was terminated (no nitrogen injection was allowed in the first and second lower plenum injection tests). Accumulator injection resulted in a higher mass flow into the core than LPIS flow alone and provided a greater heat transfer potential. The cool down rate in the cold leg injection test during reflood (which began at about 60 s) was about 2.2 K/s, similar to the post-accumulator injection period in the lower plenum experiment. Figure 2 shows rod quenching occurred prior to 150 s in the lower plenum injection test, whereas in the cold leg injection test quenching did not occur until much later in the transient.[a]

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a. In the cold leg injection test periodic depletion of mass from the core precluded the timely and orderly quenching of the core.

Figure 3 shows the individual heater rod thermocouple quench time and the core collapsed liquid level during the lower plenum injection test and illustrates the large increase in core liquid inventory due to accumulator injection between 32 and 58 s. The presence of this liquid resulted in early heater rod quenches throughout the core. Several quenches were observed above the collapsed liquid level and are due to considerable liquid entrainment and fallback. Figure 3 shows the core was completely quenched by about 150 s. Figure 4 presents the thermal-hydraulic response at the core hot spot in the lower plenum injection test. Shown in Figure 4 are the core hot spot heater rod clad temperature and the measured void fraction. At 32 s (initiation of reflood) the high rate of cooling was accompanied by a decreasing void fraction. The decreasing void fraction trend continued after accumulator injection ended at 58 s since LPIS injection continued. The rod surface quenched at a temperature of about 700 K and a void fraction of approximately 0.7.

In the lower plenum injection base case test the accumulator flow began at about 18.5 s (4.14 MPa) and reflooding was initiated at about 32 s. Figure 1 shows that during the lower plenum refill period (18.5 s to 32 s) a second cladding temperature increase was observed following the initial cool down which was due to draining of the upper head liquid (ending at about 25 s). In an effort to extend the effective cooling observed during the 10 to 25 s period of the transient and perhaps eliminate the temperature rise observed at 25 s, a second lower plenum injection test was conducted in which the accumulator pressure was increased to 6.89 MPa. This would result in earlier initiation of accumulator flow and was expected to result in earlier reflooding of the core. The following section discusses the effect this change of accumulator pressure had on the core thermal response.

Effect of Accumulator Pressure on Lower Plenum ECC Effectiveness. The axial variation in core thermal response for the second lower plenum injection test is compared to the base test data in Figure 5. The data indicates that, rather than inproving core cooling, earlier activation of lower plenum accumulator injection resulted in an overall degradation of the lower plenum injection effectiveness. Figure 5 also shows that while the heater rod reheat previously observed at 25 s in the base test was eliminated, the heater rod temperatures throughout the core were typically 50 K higher when accumulator injection ended, which represents more stored energy. As a result of the greater core energy content, a longer period of reflood was required to reduce the surface temperature sufficiently to allow quenching to occur. Heater rod temperature decay in the high pressure test was affected by a slightly lower LPIS flowrate relative to the base test.

Investigation of the core hydraulic response for the two experiments indicates that a considerable difference existed during the periods of accumulator injection. Activation of the accumulator in the second test occurred at about 8 s compared to 18.5 s in the first test. Figure 6 compares the lower plenum average fluid density in the two tests and indicates that earlier activation of the accumulator maintained the liquid inventory, whereas in the first test the lower plenum mass inventory decreased prior to the beginning of accumulator injection at 18.5 s. However, comparison of the core collapsed liquid levels from the base and high pressure tests, shown in Figure 7, indicates that reflood did not begin until about 28 s in the high pressure test suggesting partial ECC bypass occurred between 15 s and 28 s. The bypassed ECC fluid was carried up the downcomer to the break by reverse core and downcomer flow which was stronger earlier in the blowdown when system pressure was higher relative to the containment pressure. The bypassed ECC fluid was evident at the break by a lower volumetric break flow. Figure 7 shows the core collapsed liquid levels initially increased at about the same rate for the two tests reaching the 2.5-m elevation at about the same time. In the high pressure test accumulator injection continued for 4 s after the collapsed level reached the 2.5-m elevation. In the base test, however, 16 s of accumulator injection remained after the collapsed liquid level reached the 2.5-m elevation. The higher observed heater rod temperatures following accumulator injection in the high pressure test were primarily the result of the short period of accumulator injection after reflood began which resulted in less coolant being delivered to the core to cool the rods.

It was expected that if nitrogen injection into the lower plenum were allowed to occur following the depletion of ECC accumulator liquid, the core and downcomer mass were expected to be blown out into the loops and to the break and result in adversely influencing core heat transfer. A lower plenum injection experiment in the Semiscale Mod-1 system[10] in which nitrogen injection was allowed exhibited complete core quenching prior to nitrogen injection. However, since the Mod-1 system had a short (1.68-m) core, and in view of the fact that the Mod-3 core was not completely quenched when the accumulator liquid was depleted, it was anticipated that nitrogen injection might produce adverse results in the Mod-3 system. A third lower plenum injection test was therefore conducted in which nitrogen in the accumulator was allowed to enter the lower plenum after liquid depletion. The following section will discuss the results of the third lower plenum injection test.

Effect of Nitrogen Injection on Thermal-Hydraulic Response. With nitrogen injection into the lower plenum, the downcomer and core liquid levels were expected to be swept out by the noncondensible nitrogen, and a core heatup was expected to result. Figure 8 compares the core collapsed liquid levels for the base test and the repeat experiment with nitrogen injection. The adverse influence of nitrogen injection is indicated by a drastic reduction in the core liquid inventory. A similar response was observed in the downcomer. Figure 9 emphasizes the effect on heater rod clad temperature of the sudden reduction of coolant in the core in the third test. A cladding heatup began coincident with nitrogen injection and continued until LPIS flow reestablished core reflood following accumulator nitrogen depletion.

CONCLUSIONS

The results of the base lower plenum ECC injection test indicated that lower plenum injection was effective in inducing earlier reflood initiation and quenching in the Semiscale Mod-3 system than was observed when cold leg injection was used.

Increasing accumulator pressure to cause earlier core reflood and quenching produced the reverse situation. Earlier accumulator activation resulted in ECC liquid bypass to the break thereby reducing the amount of mass delivered to the core.

Permitting nitrogen injection into the lower plenum following the depletion of ECC accumulator liquid was also shown to diminish the effectiveness of lower plenum injection. Cooling was reduced when the nitrogen swept the liquid from the core, reducing vessel liquid inventory and resulting in rising heater temperatures.

Extrapolation of results from the lower plenum injection tests in the Semiscale Mod-3 system indicate that the lower plenum injection configuration may be more effective than cold leg injection in a large PWR. The effect of reverse core flow during a large cold leg LOCA in a full size PWR would be expected to hold up the ECC liquid (to a lesser degree than in the Semiscale facility), and therefore direct delivery of ECC to the lower plenum would result in earlier reflood initiation. However, revision of the present ECC system design would require a complete safety analysis to determine overall plant safety. In particular, the failure of the lower plenum injection line itself could be a safety problem.

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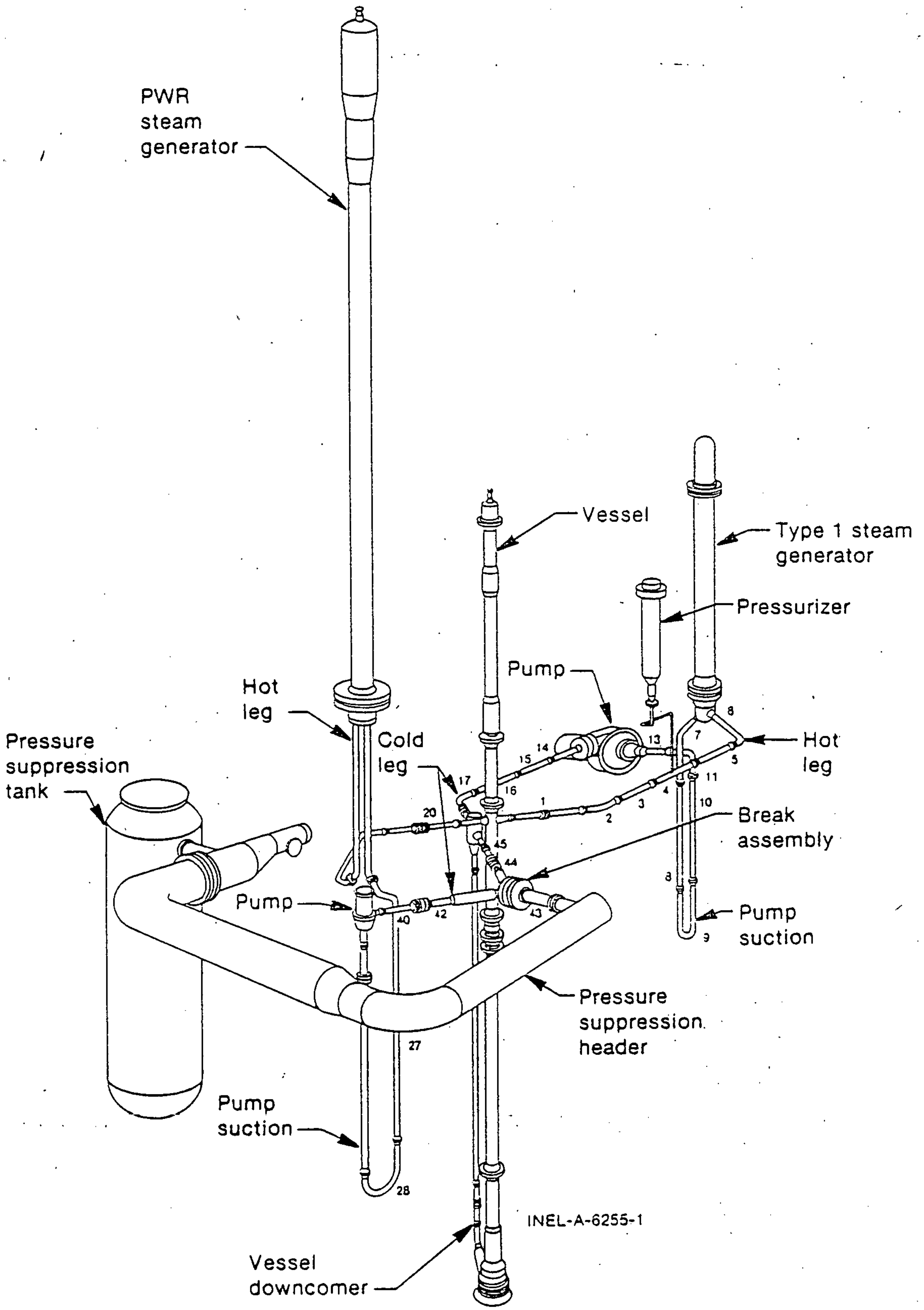

Figure 1. Semiscale Mod-3 system cold leg noncommunicative break configuration isometric.

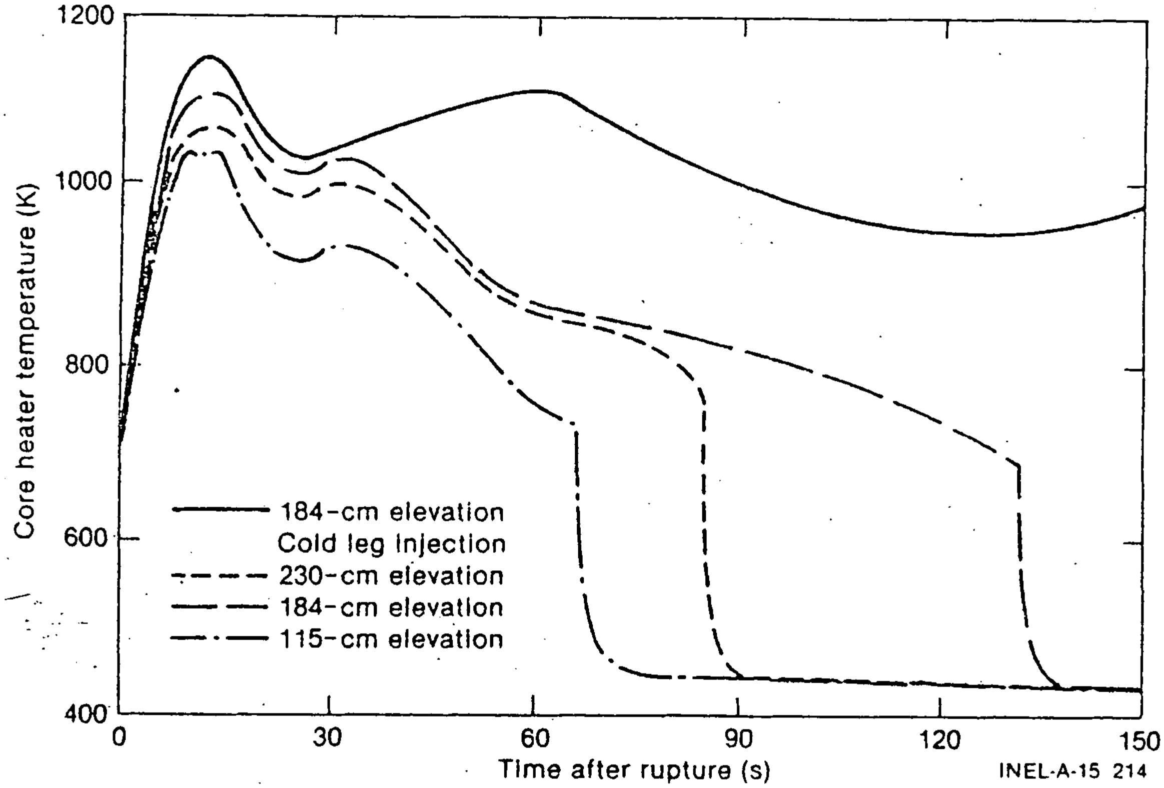

Figure 2. Comparison of the core thermal response in the lower plenum injection experiment and the cold leg injection experiment.

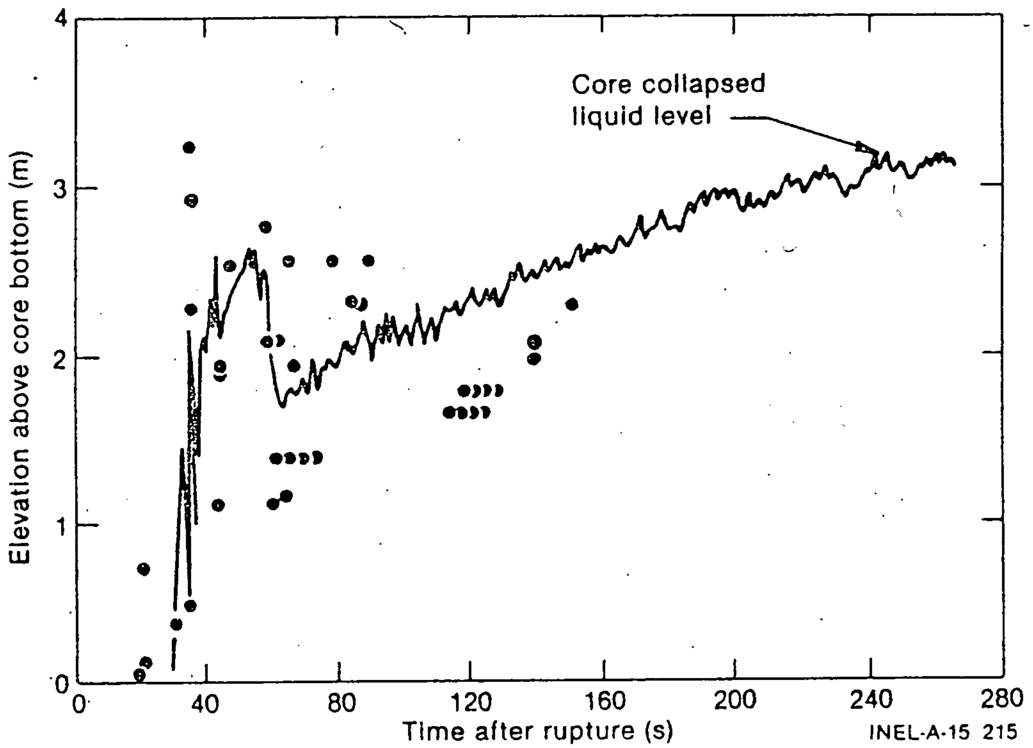

Figure 3. Heater rod thermocouple quench time and core collapsed liquid level for the lower plenum injection (base) test.

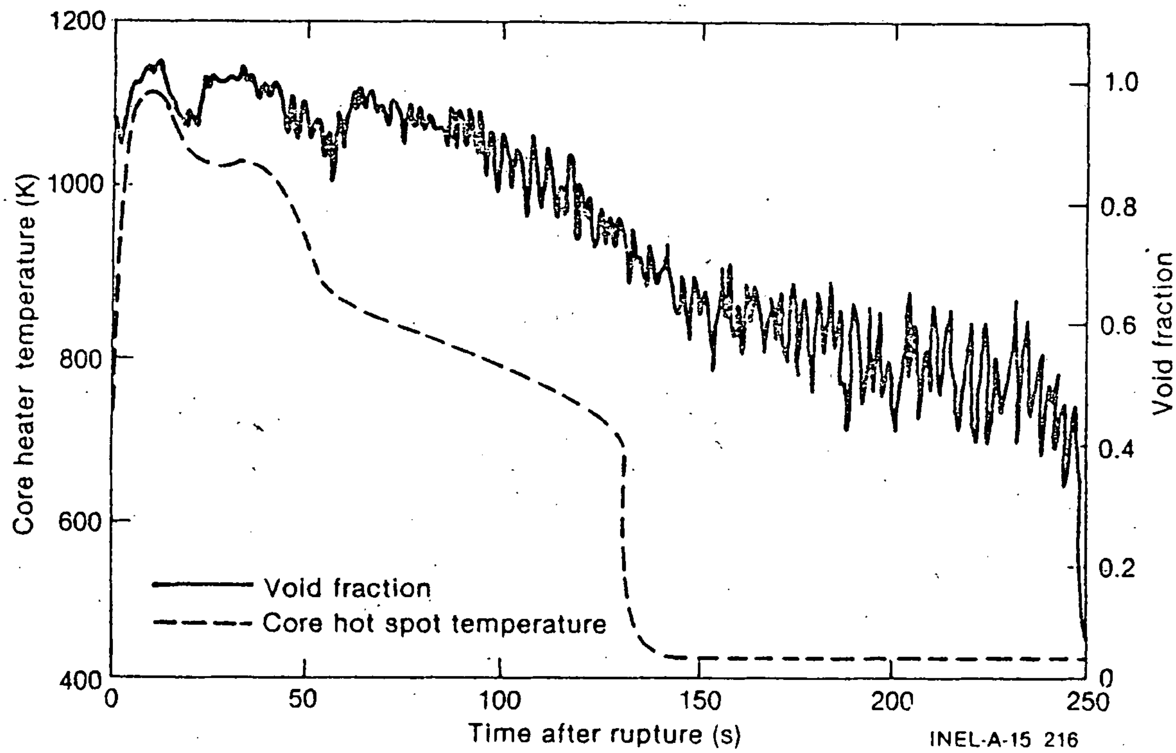

Figure 4. Core hot spot temperature and void fraction for the lower plenum injection (base) test.

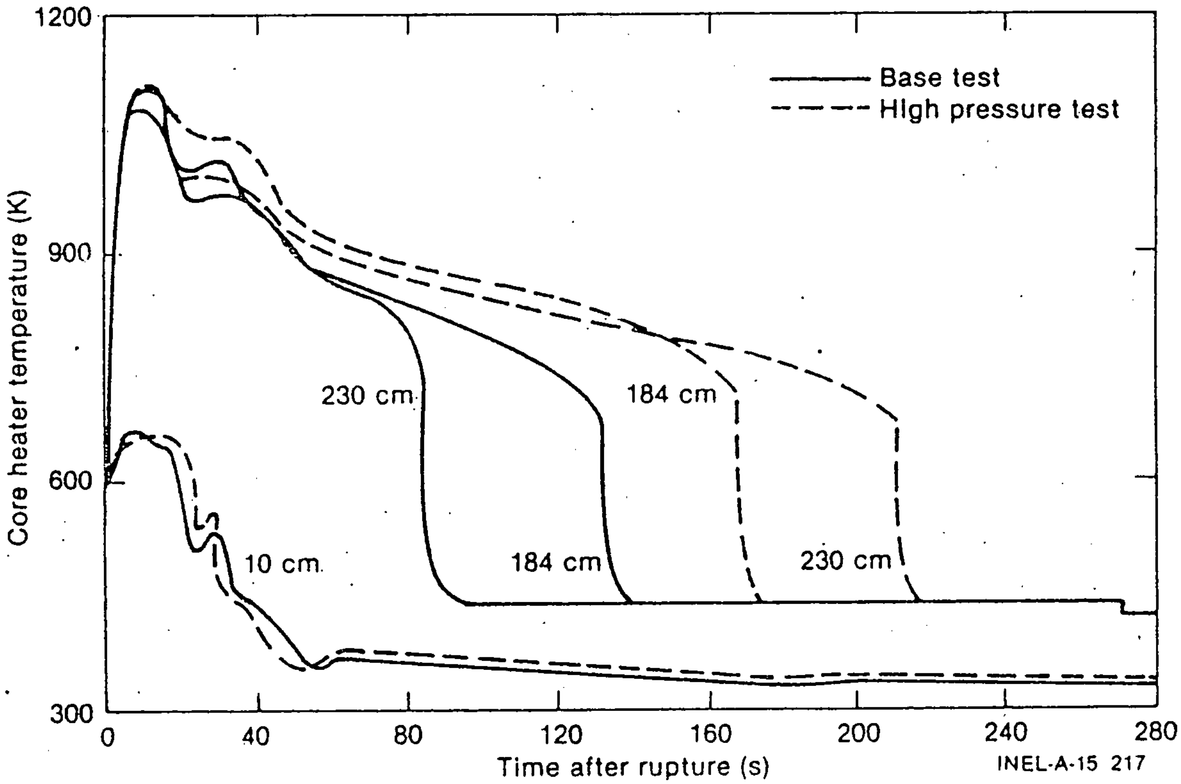

Figure 5. Comparison of the core thermal response in the base and high pressure accumulator lower plenum injection test.

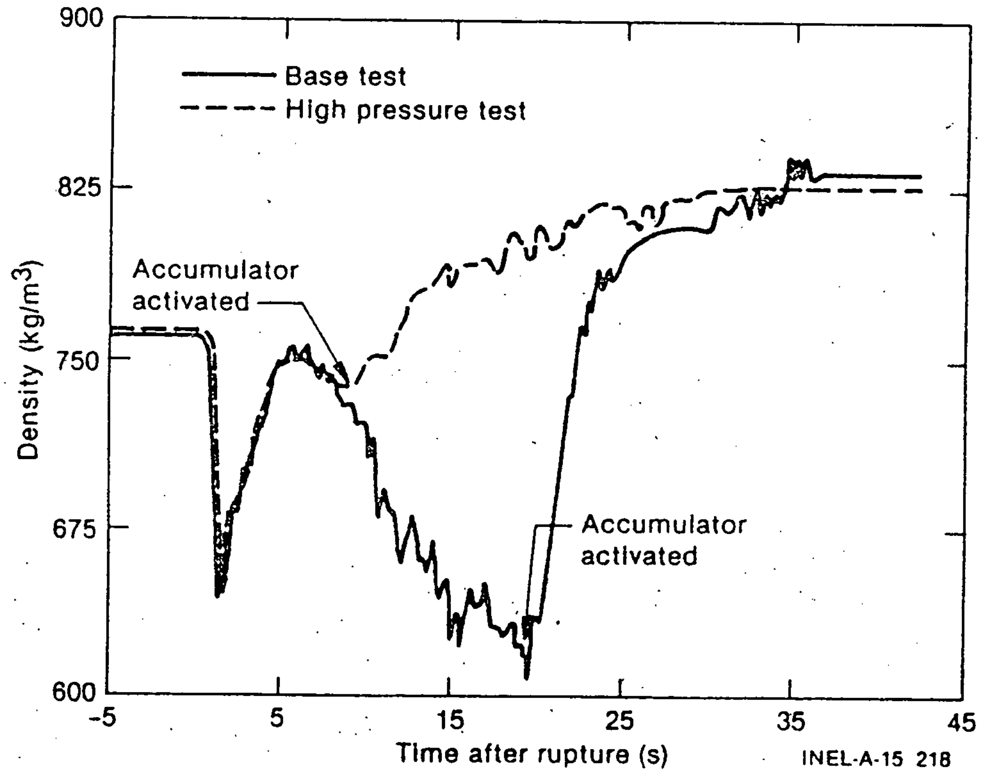

Figure 6. Comparison of the average lower plenum density for the base and high pressure accumulator lower plenum injection tests.

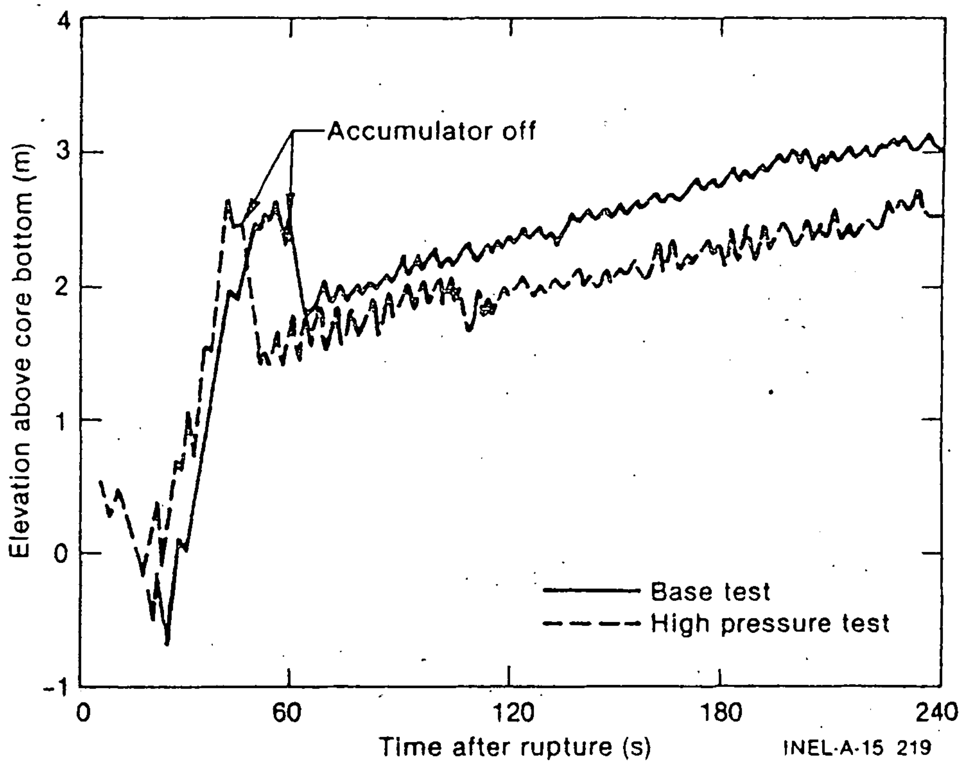

Figure 7. Comparison of the core collapsed liquid level from the base and high pressure lower plenum injection tests.

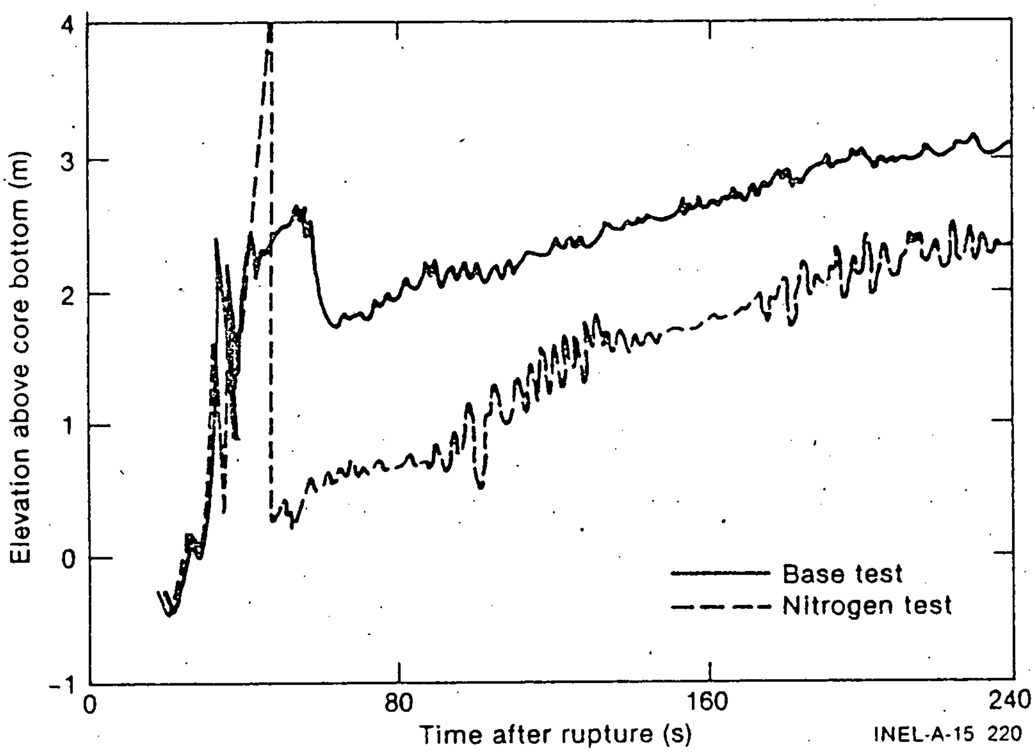

Figure 8. Comparison of the core collapsed liquid level from the base and nitrogen injection lower plenum injection tests.

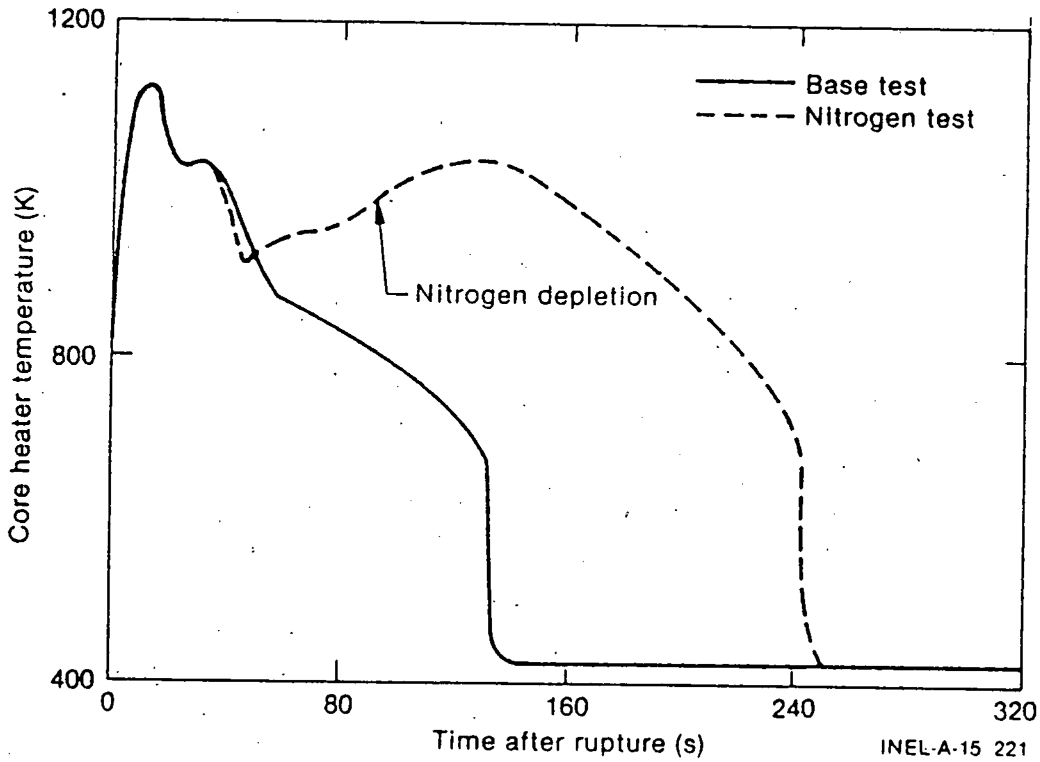

Figure 9. Comparison of the core hot spot thermal response from the base and nitrogen injection lower plenum injection test.