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External cooling of a reactor vessel under severe accident conditions

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The TMI-2 accident demonstrated that a significant quantity of molten core debris could drain into the lower plenum during a severe accident. For such conditions, the Individual Plant Examinations (IPEs) and severe accident management evaluations, consider the possibility that water could not be injected to the RCS. However, depending on the plant specific configuration and the accident sequence, water may be accumulated within the containment sufficient to submerge the lower head and part of the reactor vessel cylinder. This could provide external cooling of the RPV to prevent failure of the lower head and discharge of core debris into the containment.

This paper evaluates the heat removal capabilities for external cooling of an insulated RPV in terms of (a) the water inflow through the insulation, (b) the two-phase heat removal in the gap between the insulation and the vessel and (c) the flow of steam through the insulation. These results show no significant limitation to heat removal from the bottom of the reactor vessel other than thermal conduction through the reactor vessel wall. Hence, external cooling is a possible means of preventing core debris from failing the reactor, which if successful, would eliminate the considerations of ex-vessel steam explosions, debris coolability, etc. and their uncertainties. Therefore, external cooling should be a major consideration in accident management evaluations and decision-making for current plants, as well as a possible design consideration for future plants.

1. Summary

The most crucial action for recovery from the accident state is to cool the core debris and prevent attack on the remaining fission product barriers. One means of preventing debris attack of the containment structures is to retain the core debris within the reactor vessel. The TMI-2 accident demonstrated that this could be accomplished by water in the reactor vessel which quenched the debris and removed decay heat. Some accidents could result in the transport of molten core debris to the lower plenum, as occurred to some extent ($\sim$ 20 tonnes) during the TMI-2 accident, boiloff of water in the lower plenum, and an inability to add water to the reactor coolant system (RCS). Others may result in a debris configuration in the lower plenum which has limited coolability. In either of these extreme set of circumstances, sufficient external cooling of the RPV may be available to prevent failure of the reactor pressure vessel (RPV) lower head and thereby retain the core debris within the vessel.

Containment configurations similar to that of Zion [CECo, 1981; Henry, et al., 1991] would result in substantial accumulation of water around the lower parts of the reactor vessel for most accident sequences. For some PWR containments and for possible future designs, such as AP600 [Bruschi and Vijuk, 1990], there could be substantial water accumulation around the reactor vessel and the hot and cold legs before core damage and thus before drainage of debris to the lower plenum. If this water contacts the carbon steel vessel surface and RCS piping resulting in nucleate boiling on the surface, substantial energy could be removed from the RCS and in particular from the RPV lower head.

Since most reactor vessels are surrounded by thermal insulation, this could act as a barrier to the heat removal process. This paper analyzes the potential limitations to the heat removal due to the insulation. Included in the analyses are the:
- energy transfer rate potentially imposed on the RPV lower head and cylinder by the accumulated debris,
- ingression of water through the joints between the insulation panels in the lower regions,

- hydrodynamic limitations associated with the two-phase heat removal process in the gap region between the insulation and the RPV outer surface, and
- steam outflow through the panel junctions in the upper regions of the insulation.

For this evaluation, insulation typical of current plants is used to assess this heat removal process. The analyses conclude that, for those designs which can submerge the lower head and parts of the vessel cylinder, there is no significant limitation to external heat removal other than heat conduction through the RPV wall. It is also noted that future plants may provide conditions which further reduce any limitations with respect to water availability and removal of the steam produced in the process.

2. Introduction

In an accident, a loss of water inventory from the reactor coolant system (RCS) could jeopardize the critical core cooling function. Therefore, the central focus of recovering from any accident condition is to recover the core cooling function by water addition to the RCS. This is accomplished through the Emergency Operating Procedures (EOPs) for control room operators (both BWR and PWR designs) and will continue to be the central focus for all EOPs and accident management guidelines.

PRA and PSA studies for both BWR and PWR reactors, for example [CECo, 1981; IDCOR, 1984; Drouin, 1989] have shown that, while very unlikely, there are accident situations in which water may not be available for injection to the reactor system. Severe accident analysis and accident management evaluations address the ways to terminate such accident conditions, i.e., to create a safe stable state. For such a state, the power generated is removed, and the debris does not thermally, mechanically or chemically attack any of the structural components associated with debris and/or fission product barriers.

Water injection to the RCS is the preferred recovery mode directed in the EOPs, which was the ultimate means of terminating the TMI-2 accident [Epstein and Fauske, 1989]. However, if RCS injection could not be established, water could possibly be added to, and accumulated within, the containment. Depending on the containment design, this may cause the submergence of the RPV lower head and other parts of the reactor vessel and RCS piping. Figure 1 illustrates such a state for the Zion reactor if the refueling water

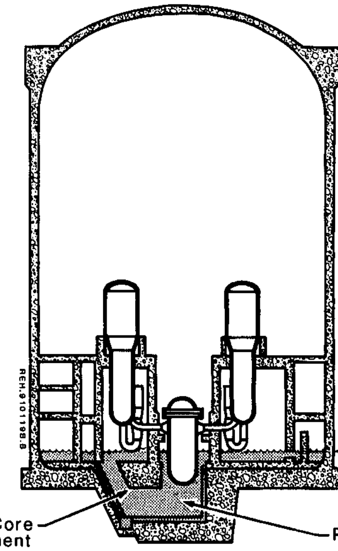

Fig. 1. Water accumulation on the containment floor after RWST injection.

storage tank (RWST) water inventory were injected and accumulated on the containment floor. Cooling of the RPV and piping outer surfaces, through nucleate boiling, would create a heat removal state from the RCS which is comparable to, or in excess of, the decay [Henry, et al., 1991]. Some of the advanced designs, such as AP600 [Bruschi and Vijuk, 1990] may also have considerable water around the reactor vessel lower head and cylinder.

It is noteworthy that the water level in the TMI-2 containment, at the time that molten core debris drained into the lower plenum, was well below the RPV lower head. Post accident calculations [Thinnes and Moore, 1989] and material analyses [Lipford, et al., 1991] of parts of the vessel wall show that the vessel wall reached temperatures in excess of 1400 K, even with the RPV filled with water.

At a uniform metal temperature in excess of about 800 K, the vessel steel would begin to lose strength and creep [Combustion Eng., 1982 and Rempe, et al., 1990], a diffusion controlled process [Ashby and Jones 1980], would begin. If this were to continue unchecked, it could result in failure of the RPV wall. As with all diffusion processes, material creep is a strong function of temperature. Nucleate boiling on the vessel outer surface would maintain this boundary at the saturation temperature, and given the heat flux through the lower plenum wall, one can evaluate the thickness of the wall which would retain essentially all of its design strength.

This is given by

$$\delta = \frac{k_s(800 - T_{sat})}{q/A_{wall}}. \tag{1}$$

For example consider a heat flux of 2×10^5 W m^{-2}, a thickness of about 8 cm would have a temperature less than 800 K. Assuming the lower head can be approximated as a thin shell, this wall thickness could support the nominal RCS operating pressure for a PWR. As will be discussed shortly, the upper bound of the heat flux uncertainty is $\sim 4.5 \times 10^5$ W/m^2. For this value the thickness greater than 800 K is approximately 4 cm, which could support a pressure of 15 MPa. This example illustrates two important aspects for accident management evaluations. First, external cooling could maintain most of the RPV wall strength. Secondly, depressurization of the RPV, either intentionally or as a consequence of the accident, in conjunction with external cooling would decrease the stress on vessel wall and increase the margin with respect to uncertainties associated with the molten pool circulation and the creep properties of the vessel steel.

External cooling as a means to prevent vessel failure was discussed by Tong [1968], and in addition, such considerations were applied to an analysis of the Brown's Ferry by Condon et al. [1982] and also by Hodge [1991]. These evaluations did not consider the role of the RPV insulation in potentially limiting the heat removal process. To address this we will first determine the distribution of heat flux imposed on the vessel wall by the circulating debris.

Consider an accident state in which molten core debris would drain into the lower plenum. How much energy would be transferred to the RPV lower head? Let us evaluate a vessel lower head with a 4.6 m diameter, filled with 100% of the core material and a decay power of 20 MW. (This corresponds to a 1000 MWe plant three hours after shutdown, with the noble gases and volatile fission products driven-off as a result of the core melt process.) Molten debris with internal heat generation would circulate as shown in fig. 2. Following the analysis of Epstein and Fauske [1989] and incorporating the correlations of Mayinger et al. [1976] with the correction for the debris not filling the lower head, we have

$$q_u = 0.36 \frac{k_c \Delta T}{R} \mathrm{Ra}^{0.23} \tag{2}$$

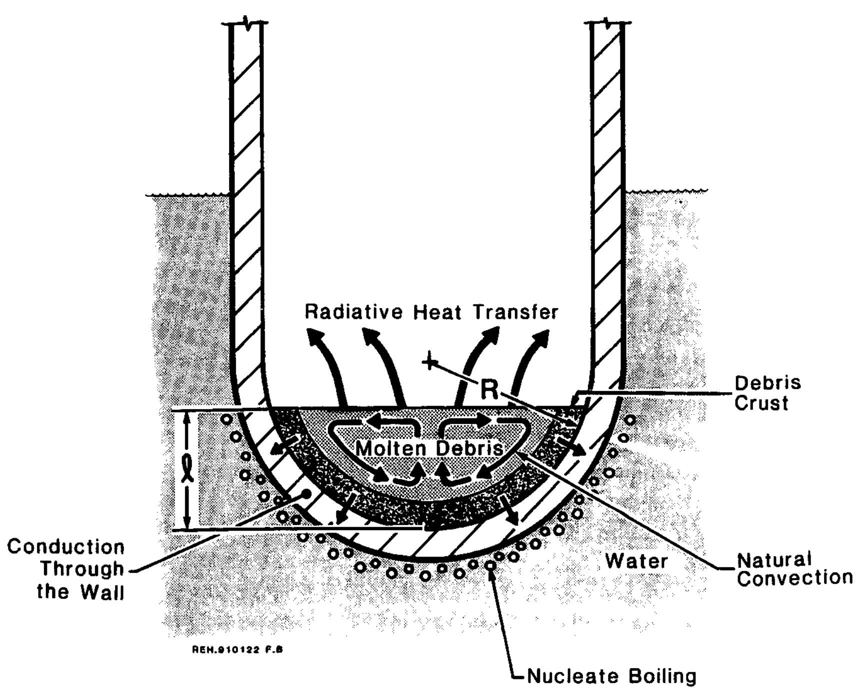

Fig. 2. Possible debris accumulation and heat transfer in the RPV lower plenum.

for the upward heat flux and

$$q_d = 0.54 \frac{k_c \Delta T}{R} \mathrm{Ra}^{0.18} \left(\frac{l}{R} \right)^{0.26} \tag{3}$$

for the average downward heat flux. The Rayleigh number for a heat generating pool is defined as

$$\mathrm{Ra} = \frac{g \beta \dot{q} R^5}{\alpha \nu k_c}. \tag{4}$$

It is noted that these correlations are developed from experiments with a substantially smaller scale than a reactor vessel lower plenum. Consequently, the Rayleigh numbers extend to a value of about 10^{11}, whereas the values in a reactor case with 100% of the core debris would be of the order 10^{16}. However, there is every indication from these experiments, as well as those performed on molten layers heated from below [Globe and Dropkin, 1959] that the experiments performed by Mayinger are for fully developed turbulent flow. However, to consider uncertainties in the energy transferred to the RPV wall, such as those reported by O'Brien and Hawkes [1991], we will consider that even more energy could be transferred downward than is represented by the above calculations.

Assuming a steady-state condition, the overall energy balance dictates

$$V_{\mathrm{melt}} \dot{q} = A_u q_u + A_d q_d. \tag{5}$$

Substituting the correlations proposed by Mayinger et al. and solving for the superheat in the pool results in

$$\Delta T = \frac{R V_{\mathrm{melt}} \dot{q}}{k_c} \left[0.36 A_u \mathrm{Ra}^{0.23} + 0.54 A_d \mathrm{Ra}^{0.18} \left(\frac{l}{R} \right)^{0.26} \right]^{-1}. \tag{6}$$

For the parameters given in table 1, the calculated superheat is about 304°C, resulting in an average downward heat flux of 2.1×10^5 W/m^2. With this heat flux and the area for downward heat transfer, approximately 4.9 MW or about one-fourth of the decay heat would be transferred downward. This is a significant fraction of the energy generated. To include uncertainties with respect to the molten pool circulation, let us consider the stronger circulations calculated by O'Brien and Hawkes, with an average downward heat flux of about 3×10^5 W/m^2 and a maximum value of approximately 4.5×10^5 W/m^2 at the top of the debris.

Boiling heat flux experiments, performed on horizontal and inclined downward facing surfaces [Chen, 1978], show that exactly horizontal surfaces have a very low heat removal capability. However, small inclinations from the horizontal resulted in much greater heat removal capabilities, i.e. a larger heat transfer coefficient, than even a horizontal *upward* facing plate. Transition boiling experiments [Bui and Dhir, 1985] show that the onset of a critical heat flux condition on a vertical plate was close to the value obtained on horizontal upward facing surfaces. These studies are helpful in assessing the behavior for a reactor system.

Table 1
Molten pool properties

Input
$k = 3$ W m^{-1} K^{-1}
$\alpha = 7 \times 10^{-7}$ m^2 s^{-1}
$\nu = 6 \times 10^{-7}$ m^2 s^{-1}
$\beta = 10^{-4}$ K^{-1}
$\dot{q} = 1.5$ W m^{-3}
$R = 2.3$ m
$V_{\mathrm{melt}} = 14.2$ m^3
Calculated
$l = 1.6$ m
$A_u = 15.1$ m^2
$A_d = 23.1$ m^2

An additional complexity is that commercial reactor vessels are generally insulated, including the lower head although some do not insulate this part of the vessel. Typically, the insulation is installed as panels and is neither intended to be, nor is desired to be, water-tight. However, the capability to sustain nucleate boiling on the vessel outer surface requires that sufficient water would flow through the joints in the insulation panels to wet the surface and make-up the boiloff rate.

As will be shown, nucleate boiling of water flowing between the vessel surface and the insulation could remove the imposed heat fluxes and would maintain the vessel wall outer surface at essentially the saturation temperature. This demonstrates that external cooling of the RPV could play a substantial role in preventing vessel failure and terminating the accident. Maintaining RPV integrity is one of the major considerations for accident management. Considering the uncertainties with respect to the rate of debris cooling in the RPV lower plenum, water addition to the containment under severe accident conditions may be prudent even if ECCS injection can be established.

Two-phase free convection flows in confined spaces such as the gap between the insulation material and the reactor vessel wall is of interest in assessing the maximum power heat removal in connection with the in-vessel debris coolability assessment. As discussed above, the insulation is typically installed in sections and is not water-tight. Hence, the necessary water to remove the imposed heat flux on the RPV wall by two-phase flow in the gap is provided by leakage through the insulation. As such, the static liquid pressure outside the insulation must support both the leakage through the insulation and the two-phase flow.

3. Free convection two-phase cooling analysis

The coolability provided by boiling-driven liquid circulation can be estimated by treating the two-phase system as a single fluid. The force balance for the saturated incompressible flow regime can be simplified as follows

$$\Delta P = \frac{G^2 x}{\rho_g} + f\frac{L_c G^2 x}{D\rho_g}. \tag{7}$$

Note that the gravitational term in eq. (7) has been neglected since the prevailing flow regime is characterized by an average channel void fraction close to 1.0 for values of x and pressure, P, of interest.

Since for saturated inlet conditions, the heat removal is entirely by latent heat of vaporization, the driving head can be approximated by

$$\Delta P = \rho_l g L_c \sin\theta \tag{8}$$

and the heat removal, Q is simply given by

$$Q = G A_c \lambda x. \tag{9}$$

Considering geometries of interest, i.e., channel-like geometries with only one side heated, the limiting heat flux is obtained by combining eqs. (7) through (9)

$$q = \frac{s}{L}\lambda\left(\frac{x g \rho_g \rho_l L \sin\theta}{(1 + fL/2s)}\right)^{1/2}. \tag{10}$$

The upper limit heat flux is obtained by setting $x = 1.0$ in eq. (10). This simple theory is compared to relevant channel data reported in Fujita and Uchida [1991]. Various orientations of the channels submerged in a pool of saturated water at 1 atm pressure are illustrated in fig. 3 and comparison between measured and predicted heat fluxes is shown in fig. 4. The effects of gap thickness, as well as the inclination angle, appear to be well represented. Furthermore, no noticeable difference is detected between upward and downward facing heat transfer limit in the narrow channels. Equation (10) with $x = 1.0$ also produces good agreement with tube data submerged in saturated water, as shown in fig. 5 [Monde and Yamaji, 1989].

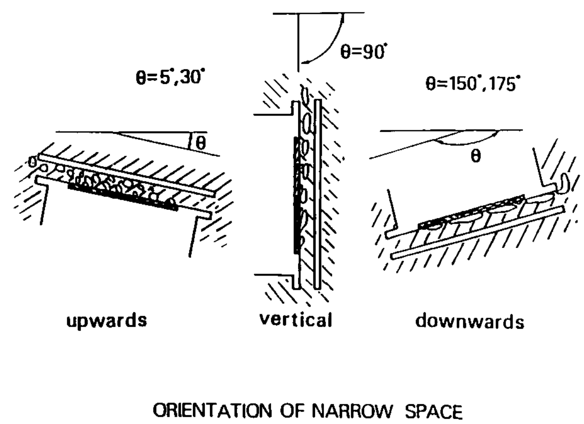

Fig. 3. Illustration of narrow channels heated on one side with saturated inlet conditions.

4. Limited scale integral experiments

Integral experiments for heat transfer from a downward facing lower head, both with and without insulation (fig. 6) were performed by Henry, et al. [1991]. Table 2 shows the matrix of tests used to investigate the possible limitations to downward facing boiling heat transfer. Prior to the insulated tests, a separate effect experiment was performed to determine the water inleakage rate through the joints between the newly purchased, as received, reflective insulation pan-

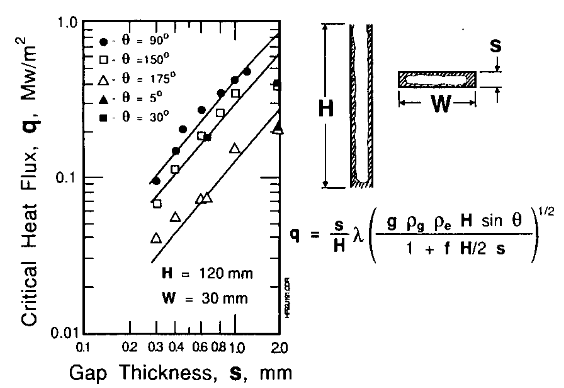

Fig. 4. Comparison of predicted and measured critical heat fluxes for narrow channels.

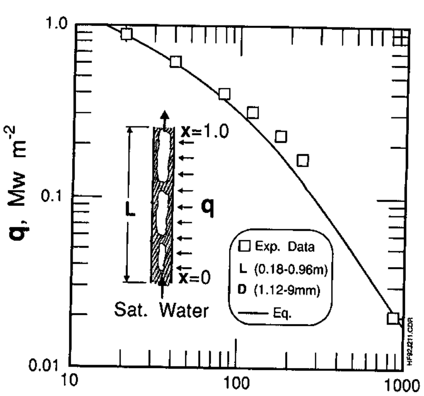

Fig. 5. Comparison of predicted and measured critical heat fluxes in a vertical cylindrical tube.

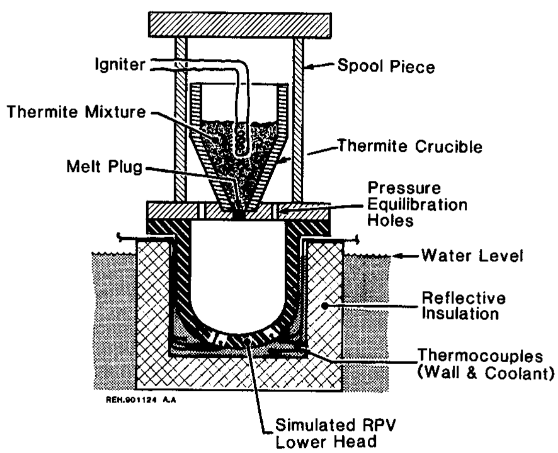

Fig. 6. Schematic of the experimental apparatus.

Table 2
Experimental matrix

Test	Thermite mass (kg)	Vessel wall thickness (cm)	Insulated	Pressure equilibration method
1	10		Shakedown	
2	10		Shakedown	
3	10	3.3	No	External pipe
4	10	1.75	No	External pipe
5	10	3.3	Yes	Vent holes
6	20	3.3	Yes	Vent holes

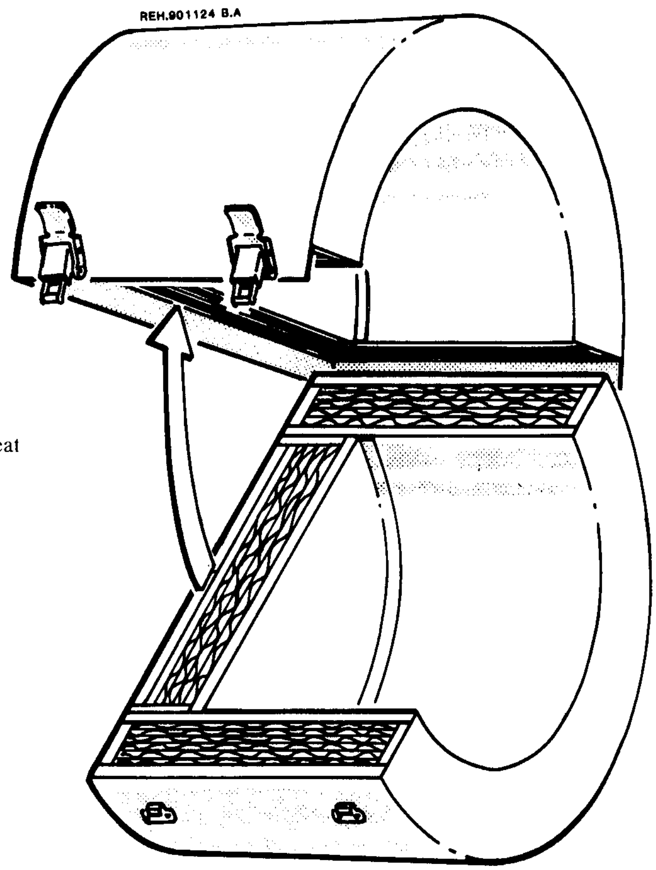

Fig. 7. Description of the reflective insulation used in these tests.

els. In these tests, the two halves, see fig. 7, were buckled together and submerged in a water tank to within about 2.5 cm of the top of the insulation cylinder. Water accumulation to the central cavity was timed until the depth reached 10 cm, which corresponds to a water static head difference of 0.3 m at the beginning and 0.2 m at the end. Drainage tests were also performed by lifting the insulation out of the water pool and measuring the time required to decrease the water level from the 10 cm mark to the floor of the central cavity. These tests were repeated several times and a nominal value for the time to fill or drain was 80 s. The central cavity of the insulation had a diameter of 0.35 m such that an accumulation to a depth of 10 cm represents a water mass of 9 kg, or an average flow rate of 0.12 kg/s over the 80 s fill/drain time.

Another important aspect of this submergence test is its relationship to the reactor system. In the experiments, the potential for flow through the insulation is well defined. As for any buoyancy driven flow through an aperture, the water flow rate (W_w) can be expressed as:

$$W_w = C_d A_F \sqrt{2\rho_l \Delta P} \sim C_d A_F \rho_l \sqrt{2gh}\,. \tag{11}$$

The aperture area is the product of the gap length (L) and width, the latter of which is not known. Therefore, the product of the gap width and discharge coefficient can be combined into an empirical constant C_1 such that

$$W = C_1 L \sqrt{2\rho \Delta P} = C_1 L \sqrt{2\rho(\rho_l - \rho_g)gh}\,, \tag{12}$$

where ρ represents the flowing fluid, i.e. either steam or water. For water flow this reduces to:

$$W_w = C_1 L \rho_l \sqrt{2gh}\,. \tag{13}$$

For the separate effects data discussed above the length of the gap is about 1 m, C_1 has a value of $\sim 10^{-4}$. Equation (12) can then be used to model the inflow for reactor systems given the submergence depth and the total length of submerged insulation joints.

In these integral experiments, molten thermite was dropped into the simulated RPV lower head and the stored energy within the debris was transferred through the vessel wall. These were strictly heat transfer tests to determine if there was any limitation of energy removal off the vessel outer surface for the range of heat fluxes anticipated during an accident. Since there is no internal heat generation, there is no significant potential for establishing circulation within the melt. In addition, due to the density differences, the thermite separates into iron and aluminum oxide, with the molten iron lying on the bottom of the vessel head covered by the aluminum oxide. Iron has a much higher thermal conductivity than aluminum oxide resulting in a faster release of stored energy from the iron leading to much higher heat fluxes downward in this experiment than would be typical of a circulating pool as discussed previously in this paper. On the other hand, this provides a substantial test for the capabilities of the two-phase cooling on the outer surface of the vessel head. The information considered here will be the measured heat fluxes from the outer surface, and of course, the water ingression through the insulation.

Figures 8 and 9 show examples of the measured heat fluxes for Test 5, which was a test with insulation.

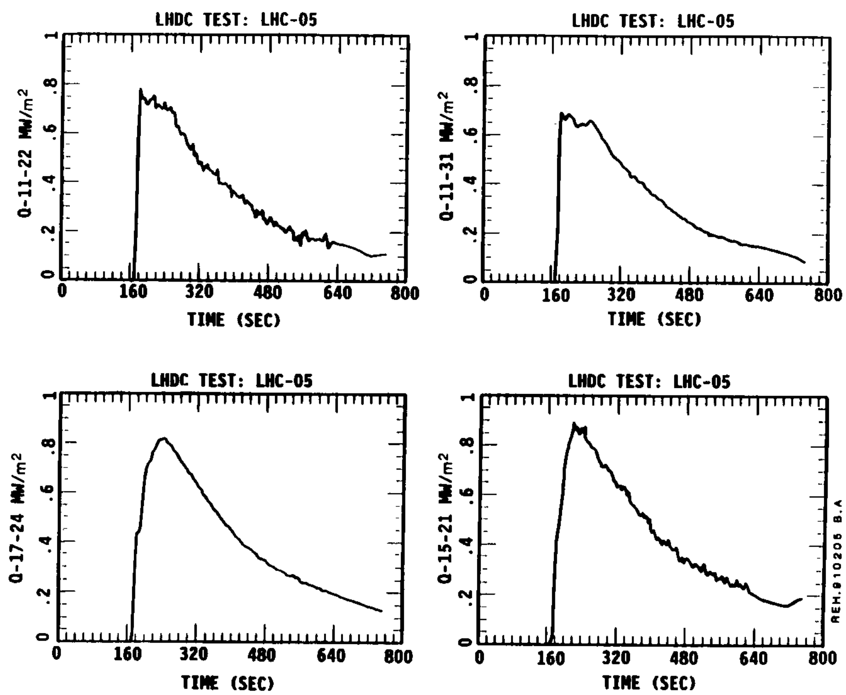

Fig. 8. Measured heat fluxes from the vessel to the water near the bottom of the lower head for Test 5. (The numbers on the ordinate indicate different thermocouple pairs.)

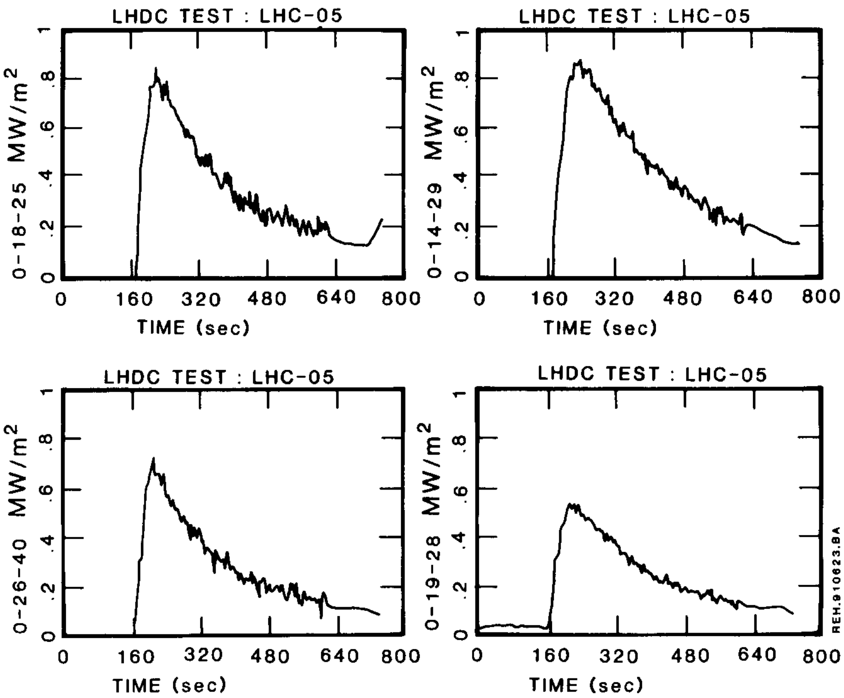

Fig. 9. Measured heat fluxes from the vessel to the water away from the bottom of the lower head for Test 5. (The numbers on the ordinate indicate different thermocouple pairs.)

(The identifier Q-11-22 indicates the calculated heat flux using thermocouples 11 and 22 which are at two different depths in the wall.) These are well in excess of both the average and maximum heat fluxes calculated for a reactor system including the uncertainties in the molten pool circulation. The temperatures on the vessel outer surface recorded values of 100°C and show no indication of film boiling behavior. This is further verified by linearly extrapolating the measurements of several pairs of internal thermocouples to the vessel wall, which also results in a wall temperature close to the saturation value. Hence, there was no indication of the significant wall overheating typical of film boiling.

Figure 10 shows that the bulk water temperature in the region between the vessel and the insulation asymptotically approaches 100°C, typically reaching a value of about 80°C within 40 seconds. As a result, the boiling processes in the insulated tests were only moderately subcooled and are essentially saturated after about two minutes, and the measured heat fluxes are still several hundred thousand W/m^2. This is consistent with the water addition tests which demonstrated that sufficient water flow could be added through the junction of the two insulation pieces to make up the inventory at a rate that equals or exceeds the vaporization rate.

Test 6 was performed with 20 kg of iron thermite and an insulated lower head. The principal goals were to increase the time of the transient and to move the aluminum oxide layer higher on the test apparatus wall. The typical heat fluxes at the middle of the head are given in fig. 11. The measured peak values are essentially the same as those observed in Test 5, however, the test duration was doubled. Figure 12 shows the heat fluxes measured in the aluminum oxide region (Q-12-35), with typical values being about 100,000 W/m^2. This demonstrates the influence of the comparatively low thermal diffusivity of the aluminum oxide. These heat fluxes are more typical of the heat fluxes for the reactor system which has a thicker vessel wall and would experience approximately the same temperature difference.

Before analyzing the reactor system, let us apply the two-phase natural circulation approach to the limited scale integral tests. For the experimental conditions we will assume $s = 0.013$ m, $L = 0.39$ m, $h = 0.3$ m and

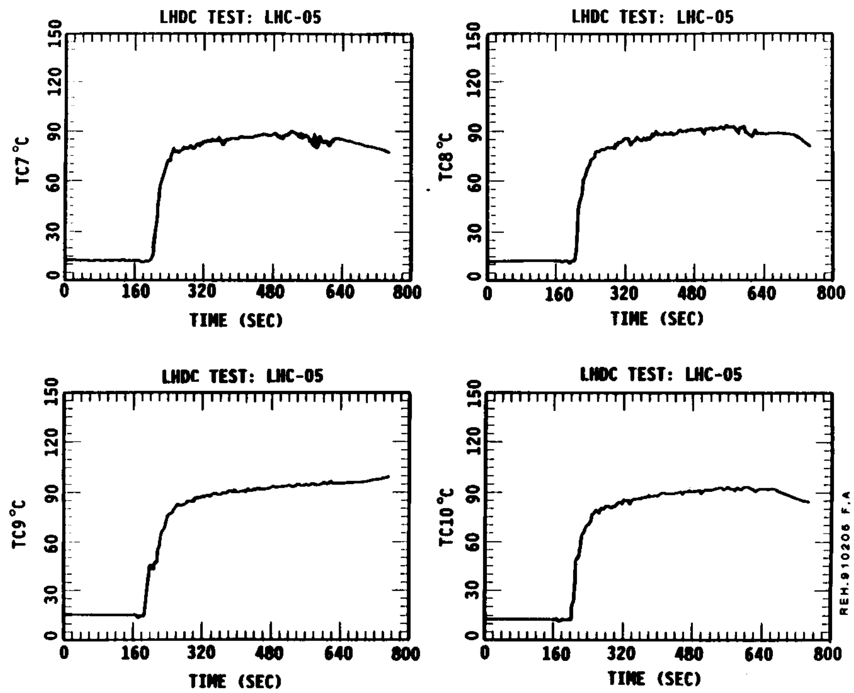

Fig. 10. Measured water temperatures between the insulation and the vessel for Test 5.

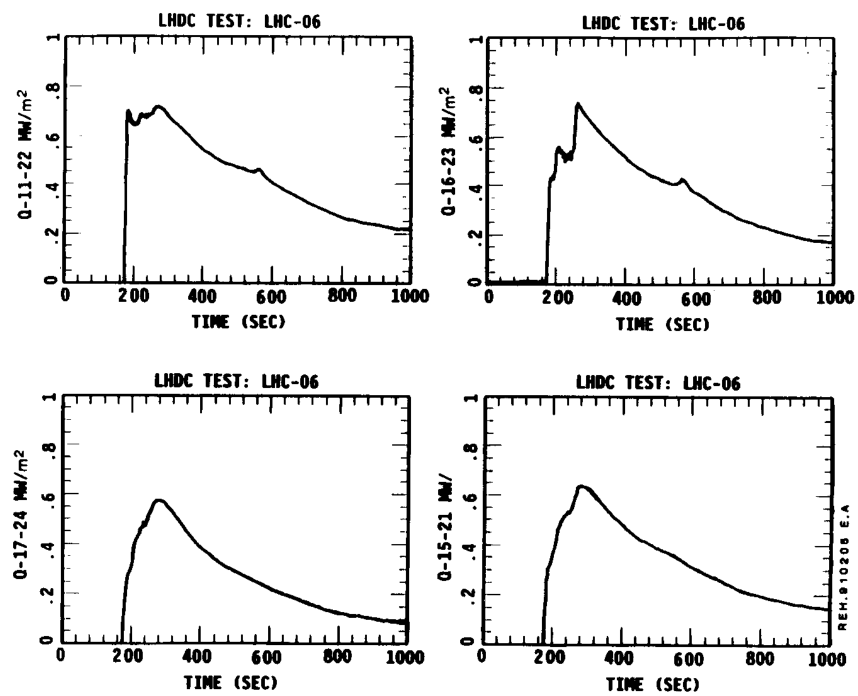

Fig. 11. Measured heat fluxes from the vessel to the water near the bottom of the lower head for Test 6. (The numbers on the ordinate indicate different thermocouple pairs.)

$\rho_g = 0.6$ kg m^{-3} and substituting into eq. (10) we obtain the heat flux as a function of available pressure drop ΔP as

$$q = \frac{0.0127}{0.39} 2.2 \times 10^6 \left[\frac{0.6 \Delta P}{1 + 0.005 \dfrac{0.39}{2 \times 0.0127}} \right]^{1/2}, \quad (14)$$

$$q_{\max} = 53\,500 \Delta P^{1/2}. \quad (15)$$

The available pressure drop can be obtained by considering the necessary pressure drop to support the leakage flow

$$W = C_1 L_w (2(\rho_l g h - \Delta P) \rho_l)^{1/2}, \quad (16)$$

where $C_1 = 10^{-4}$ m and $L_w = 1$ m. Since eq. (16) is related to eq. (15) by $W = q\ A/\lambda$ where A is the heated surface of about 0.15 m^2, we obtain an upper limit for the average heat flux of 2.2 MW m^{-2}, which is well in excess of the local measured heat flux. The above analyses suggest that the experiment should be coolable (no film boiling) which was verified by all the measurements.

5. Two-phase cooling applied to a reactor system

5.1. Two-phase hydrodynamics

In considering the reactor case, we will first examine the effect of the inclination angle, θ, by evaluating the free convection two-phase cooling associated with individual insulation section. Taking the length, L, of a typical insulation section to be 1 m and a characteristic gap thickness, s, between the insulation and the lower hemispherical vessel head wall to be about 0.02 m, we calculate a heat flux of 0.53 MW m^{-2} from eq. (10) for a value of $\theta = 179°$, i.e. almost horizontal. We can check from this consideration that the downward facing surface poses no limitation to heat removal by nucleate boiling, which is consistent with the experiment findings.

We will next consider that the generated vapor remains in the gap, i.e., the vapor is assumed not to escape between the insulation segments. We conservatively assume that the required inflow of water to remove the total power by latent heat of vaporization, takes place by leakage through the insulation in the hemispherical portion of the reactor vessel. (The role

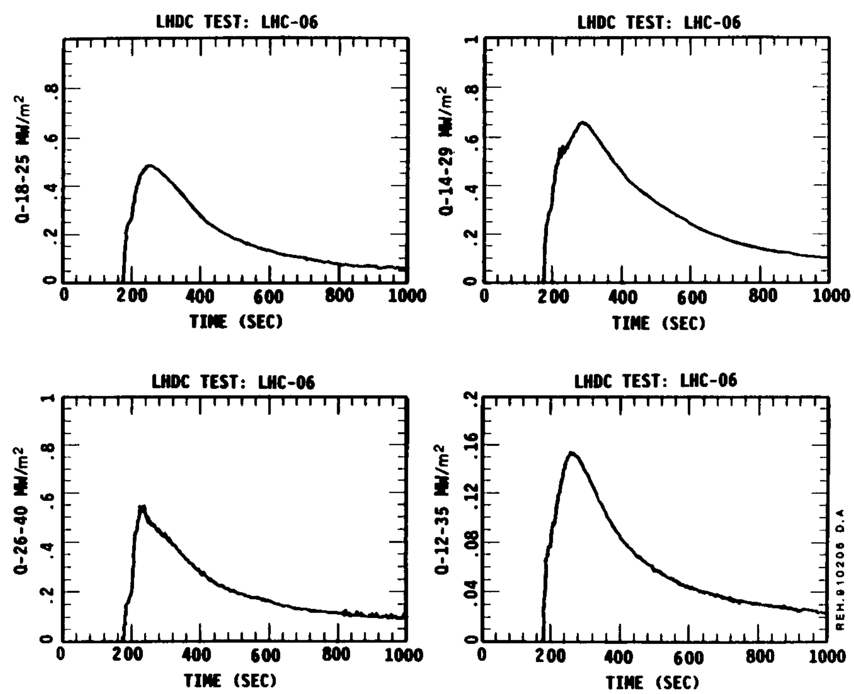

Fig. 12. Measured heat fluxes from the vessel to the water away from the bottom of the lower head for Test 6. (The numbers on the ordinate indicate different thermocouple pairs.)

of steam outflow through the leakage area is discussed below.) Furthermore, for illustration purposes, we will assume that one third of the total power is transferred downward. It follows that the exit quality to be used in eq. (10) should be set equal to 0.33. Considering the static liquid pressure ($\rho_l gh$) of 22540 Pa, which is available to support the necessary inleakage of water (with L_w in eq. (16) set equal to 30 m), and two-phase flow through the hemispherical gap (with $s = 0.02$, $L = \pi D/4 = 3.6$ m, $L \sin\theta = D/2 = 2.3$ m in eq. (10)), we obtain a total power removal of about 40 MW. This power level corresponds to an average heat flux in the hemispherical portion of the reactor vessel of 0.4 MW m^2, which is well in excess of the anticipated heat flux of less than 0.3 MW m^{-2} (note that the total decay power in the reactor case is less than 20 MW).

5.2. Steam flow limitations

If water submerges the lower head, and perhaps part of the vessel cylinder, the water static head would provide the driving pressure for water flow into the region around the lower head and out through the upper region. As discussed previously, the experiments described in [Henry et al., 1991] include separate effects tests to quantify the leakage flow rate through new, as manufactured reflective insulation. This is expressed as a flow rate per unit length of joint between insulation panels in eq. (13). To conservatively (underestimate) the flow of water inflow and steam outflow, assume steady-state, no significant frictional or static head pressure decrease in the vessel-insulation gap, no steam flow out of the top of the gap (to be conservative) and using the measured flow resistance for an insulation junction, the static head ($\rho_l gh$) is divided between the water inflow and steam outflow.

$$(\rho_l - \rho_g) gh = \frac{W_w^2}{2C_1^2}\left\{\frac{1}{\rho_l L_l^2} + \frac{1}{\rho_g L_g^2}\right\}. \tag{17}$$

Solving for the flow rate results in

$$W_w = C_1\left\{\frac{2(\rho_l - \rho_g) gh}{\dfrac{1}{\rho_l L_l^2} + \dfrac{1}{\rho_g L_g^2}}\right\}^{1/2}. \tag{18}$$

For the convenience of this example we will assume that the water enters through the joints in the insulation panels covering the lower head and exits through those in the insulation panels on the RPV cylinder as illustrated in fig. 13. The insulation installation is specific to each reactor, but the cylindrical section is typically covered by panels that are approximately 1 m high and 2 m wide, resulting in about 300 m of joints between the panels for a PWR vessel. Trapezoidal and rectangular sections are generally used to cover the lower head and these have 30 m or more of joint length. If we use a value of 10^{-4} for C_1, as deduced from the insulation separate effects tests, a water head of 5 m and a steam density of 1 kg/m^3, would result in a flow rate of almost 9 kg/s. Assuming complete vaporization of the incoming flow, the energy removal capacity would be 20 MW, which is approximately the decay heat generated in the debris.

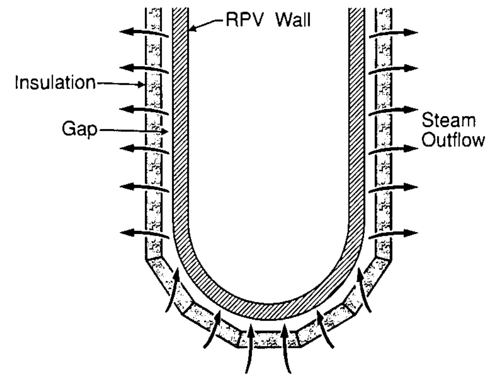

Fig. 13. Water inflow and steam outflow through the gap between insulation panels.

Application of this approach to specific designs must consider the following points.

(1) The insulation configuration is plant specific and needs to be evaluated for each design. For example, some vessels have no insulation on the lower head.
(2) Insulation is removed and replaced for maintenance and surveillance activities. Repeated activity tends to bend the metal edges and open the gaps between the panels. Therefore, the effective loss coefficient for plant insulation can be expected to be less than that used here resulting in a larger water–steam flow rate for the same conditions.
(3) The capability to provide water to the lower head is affected by design specific issues such as a vessel support skirt and whether there are holes in the skirt to relieve the steam produced by the cooling.
(4) The energy which could be transferred to the RPV lower head by the accumulated core debris is likely much less than that generated. Most of the energy would be transferred from the upper debris surface

to the RPV structures and gases. These could, in turn, transfer heat to the cylindrical section of the vessel. Hence, while the capacity to remove 20 MW, or more, may exist, the energy may not be efficiently transported to the appropriate surfaces.

(5) Even if the energy could not be efficiently transferred to the RPV wall, two-phase cooling of the vessel outer surface certainly causes the vessel to retain substantial strength in those regions below 800 K.

(6) If the submergence includes the hot legs and cold legs for PWRs, particularly the hot legs, the heat removal capabilities would be substantially increased. This is due to the thinner wall (compared to the vessel) and the reflux heat removal path between the hot legs and the core.

6. Summary

The heat removal processes associated with the two-phase natural convection boiling energy transfer in the gap between the RPV cylinder and insulation has been evaluated in terms of the water inleakage through the insulation, the two-phase boiling heat transfer for heat removal in the annular gap and for steam venting through the junctions between insulation panels. In this evaluation, it has been assumed that the lower and RPV cylinder are insulated by replaceable panels and that there is no limitation to flow around the vessel lower head other then the insulation. This would need to be evaluated on a plant specific basis since some reactor vessels have a vessel support skirt, which may or may not have holes to allow for water circulation and some reactor vessels do not have insulation around the lower head. The assessment of the two-phase hydrodynamics illustrates that the energy conducted through the reactor vessel wall can be removed by nucleate boiling processes on the RPV outer surface. This is consistent with the limited scale integral tests performed on a simulated lower head with insulation. Lastly, a simplified analysis for the steam venting shows that sufficient steam could be vented through the gaps in the insulation panels even if there were no flow out through the top of the annulus between the vessel and the insulation.

Extrapolation of the separate effects tests for water inleakage to the insulation for a reactor system shows that there would be a greater water leakage flow rate through the insulation and sufficient outflow to venting the steam generated. Consequently, the reactor vessel lower head would be effectively cooled to remove the energy transferred to the vessel wall through the debris crust. This would be a very influential action to both mitigate and terminate the accident progression by retaining the core material in the reactor vessel.

In summary, considerations of the water inflow, the two-phase hydrodynamics and the steam outflow show that submergence of an insulated RPV lower head, and perhaps some or all of the vessel cylinder, has the capacity to remove most or all of the decay heat generated in the debris. Of particular note is that it can retain the strength in the vessel wall by keeping the temperature of a significant portion of the wall (several centimeters) below 800 K. Consequently, should an accident occur, this could be a most effective plant configuration to arrest the accident progression.

Nomenclature

A_c	channel flow area,
A_F	flow area,
A_u	upward facing surface area,
C_d	discharge coefficient,
C_1	empirical constant,
D	hydraulic diameter,
f	friction factor (for turbulent flow $f \approx 0.005$),
g	acceleration of gravity,
G	mass flux,
h	water height,
k_c	thermal conductivity of the molten core debris,
k_s	thermal conductivity of carbon steel,
L	insulation gap length,
L_c	length of channel,
L_l	water submerged gap length,
L_g	gap length for steam venting,
l	debris pool height,
q_d	downward heat flux,
q_u	upward heat flux,
$\dot{q}$	volumetric heat generation,
ΔP	pressure differential,
R	radius of the RPV lower head,
s	channel gap,
x	exit steam quality,
ΔT	superheat within the molten debris pool,
V_{melt}	volume of the molten debris,
W_w	water inleakage through the insulation gap.

Greek letters

α	thermal diffusivity of the debris,
β	thermal expansion coefficient,
δ	wall thickness with a temperature < 800 K,

ν kinematic viscosity of the debris,
ρ_g steam density,
ρ_l water density,
θ (°) inclination angle,
λ latent heat of vaporization.

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