BNL-NUREG-47179
Conf-920903--2

An Evaluation of the Failure of a PWR Lower Head*

During a Core Meltdown Accident[1]

BNL-NUREG--47179
DE92 010177

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ABSTRACT

This paper presents an analysis of the failure of lower vessel head during a core meltdown accident. The analysis is limited to PWR systems with no penetration tubes attached to the lower vessel head. The case considered is characterized by a small quantity of corium and a relatively slow discharge into the lower plenum. The assumption of the breakup of the jet stream results in the solidifcation of debris particles and the formation of a debris bed thermally attacking the lower head wall. Detailed analyses were performed to determine the debris/water interaction, ablation of the lower head wall, and the time of vessel failure. Parameters which have significant effect on the results were identified. Parametric studies were performed to reflect uncertainties associated with the various phenomenological processes occurring during corium relocation into the lower head.

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* This work was performed under the auspices of the U. S. Nuclear Regulatory Commission.

INTRODUCTION

A lower head failure comparison exercise was specified by the CSNI Task Group in 1990[1]. The objective of this comparison exercise is to achieve a common understanding among CSNI member countries and to further knowledge on the thermal-hydraulic behavior of damaged core materials when they relocate onto the lower vessel head of a reactor during a core meltdown accident. This information is essential to an understanding of the loads on the lower head, its potential failure modes and the impact on containment performance. The CSNI comparison exercise considered both PWR and BWR systems and two cases were defined for each system. Although the CSNI comparison exercise was cancelled in 1991, BNL has completed the analyses for the PWR system. This paper presents the BNL analysis for the PWR Case 1. This case is characterized by a small quantity of corium (about 10 percent of the core inventory of a typical 3000 MW PWR system) and a small breach size (0.15m) in the core support plant.

ANALYSIS

The specification defined by the CSNI comparison exercise for PWR Case 1 is summarized in Table 1. The specification assumes a superheated molten pool with a height of 1 m initially located on the core support plate. With the breach of the support plate, the corium is discharged through a hole of 0.15 m into the lower plenum. Assuming the discharge of corium is driven by gravity force, using the quasi-steady Bernoulli equation, the total discharge time (t_d) and the transient discharge velocity (u) are given by:

$$t_d = \frac{A}{a}\left[\frac{2H_o\left[1-\left(\frac{a}{A}\right)^2\right]}{g}\right]^{\frac{1}{2}} \tag{1}$$

and

$$u = \sqrt{\frac{2g}{1-\left(\frac{a}{A}\right)^2}}\left[Ho^{\frac{1}{2}} - \frac{at}{A}\sqrt{\frac{g}{2\left[1-\left(\frac{a}{A}\right)^2\right]}}\right] \tag{2}$$

in which A and Ho are the cross-sectional area and initial height of the corium pool, a is the area of the breach hole, g is acceleration due to gravity, and t is the time. The above formulae yield a total discharge time of 36 seconds and an initial discharge velocity of 4.4 m/s. The discharge velocity decreases linearly with time and is zero at the end of 36 seconds.

The corium enters the lower plenum in the form of a jet. Our first attempt was focused on the ablation of the lower head by the direct impingement of a jet stream. Using the ablation model at the stagnation point of an impinging jet given by Sandia [2], it can be shown that the contact temperature between the jet and the lower heat wall is about 1270 K; the delay time required to initiate ablation of the wall is about 5 seconds, and the time required for ablation to penetrate half the thickness of the lower head wall (the failure criterion specified for the comparison exercise) is about 11 seconds. The results indicate that if a coherent jet of molten core material can pass through the water pool and impinge upon the lower head, a rapid failure of the lower head at the stagnation point of the impinging jet is expected. However, this model does not agree with the observations of many experiments, such as Sandia's EJET tests [2], ANL's CWTI tests [3], and CCM tests [4] in which a coherent jet was not observed. All these tests involved a long, slender stream of molten corium falling through a deep water pool. A rigorous steam generation accompanied by the breakup of the jet stream and formation of small debris particles was observed during these tests. Thus, it appears that, in the presence of a deep water pool, direct jet impingement is unlikely to occur.

The analysis was then directed to the assumption of jet breakup caused by the hydrodynamic instability due to the interaction betwee the superheated corium jet and the saturated water. The observed ranges of jet breakup length and particle size were used as input parameters to the analysis. Heat transfer from corium to water by film boiling and radiation were used to estimate the steam generation rate. For the unbroken section of the jet stream, Bromley's correlation [5] of film boiling on vertical surfaces was used:

$$h = 0.943\left[\frac{K_v^3\ g\ (\rho_\ell-\rho_v)h_{fg}}{L\nu_v(Tc\ -\ Tsat)}\right]^{\frac{1}{4}} \tag{3}$$

For the fragmented particles, the Farrahat and Haifawy correlation {[6] and [7]} for film boiling on spheres was used:

$$h = 0.75\left[\frac{K_v^3\ g(\rho_\ell-\rho_v)h_{fg}}{D\nu_v(Tc-Tsat)}\right]^{\frac{1}{4}} \tag{4}$$

In the above two formulae, K, ρ, ν, h_{fg} are the thermal conductivity, density, kinematic viscosity, and latent heat of vaporization, respectively. The subscripts υ and ℓ refer to the steam and water, respectively. The length L is the length of the unbroken section of the jet stream, and D is the diameter of the particles.

The thermal radiation between corium and water is expressed by the radiation heat flux:

$$q_{rad} = 5.669\ x\ 10^{-8}\ F\ (Tc^4\ -\ Tsat^4) \tag{5}$$

where F is the radiation exchange factor and is given as:

$$F = \frac{1}{\frac{1}{\epsilon_c} + \frac{1}{\epsilon_w} - 1} \tag{6}$$

The emissivities of corium and water are denoted as ϵ_c and ϵ_w, respectively.

The heat removal by film boiling and radiation cause the solidification of the debris particles and the removal of a large portion of the sensible heat as observed in the experiments [4]. The solidified particles were assumed to move downward at the terminal velocity:

$$V = \sqrt{\frac{4gD\ (\rho_c\ -\ \rho_\ell)}{3\ f\ \rho_\ell}} \tag{7}$$

in which the friction coefficient, f, is taken as 0.44 for a turbulent flow regime [8].

A porous debris bed is assumed as the solidified particles settled on the lower head. The porosity of the debris bed is assumed to be an input parameter. The depth of the debris bed increases during the corium relocation period. The depth (an important characteristic length) is about 0.7 m at the end of corium relocation (36 seconds) for an assumed porosity of 0.4.

The corium/water interaction in a debris bed involves complicated two-phase fluid counter flow. Considerable research has been performed to determine the maximum heat flux leaving the top surface of the bed, i.e., the dryout heat flux which determines the debris bed coolability and the steam generation rate. Yang and Pratt

[7] have compared the various debris bed models and incorporated the zero-dimension Lipinski model ([9], [10]) into the MARCH code. This model is also adopted by the SCDAP/RELAP5 code [11] for the computation of debris bed behavior in the lower plenum. Therefore, the Lipinski model was used in the present analysis. The model considers both laminar and turbulent flow in a porous medium with a volumetric heat source. The flow is governed by inertia, gravitational acceleration, and capillary forces. The heat flux is expressed in complex mathematical form and is not presented in this paper. However, the model shows that the heat flux is governed by several parameters: particle size, bed porosity, bed depth, fluid properties, and turbulent and laminar flow permeabilities. Among these parameters, only the particle size and porosity are input values and are included in the parametric studies of this work. The bed depth is determined by the transient corium relocation model, and the permeabilities are computed by the recommended correlations.

The radiation heat flux expressed in Equations (5) and (6) is included in the debris bed model to take account for the radiation heat exchange at the top surface of the bed. The water emissivity in Equation (6) is replaced by the emissivity of structures after the overlying water pool is depleted. The structural emissivity is included in the parametric study to simulate the uncertainties of the thermal radiation calculation.

The settling of the fragmented particles during the corium relocation period starts the thermal attack of the lower head wall. It is assumed that the contact between the debris particles and the lower head wall induces a heat flux at the interface and is expressed as:

$$q = h_i \, (Tc - Ts) \tag{8}$$

where h_i is a heat transfer coefficient, Tc and Ts are the corium temperature and the inner surface wall temperature, respectively. The heat transfer coefficient h_i which represents a large uncertainty of the contact conductance is included in the parametric study.

The heating of the lower head wall is computed by the integral heat balance method as discussed by Goodman [12]. Initially, the lower head wall is considered as a semi-infinite body. With a time-dependent heat flux, Equation (8), specified at the boundary and a parabolic temperature profile in the heated layer, the lower head inner surface temperature (Ts) can be determined by:

$$Ts = To + \frac{\delta q}{2K} \tag{9}$$

where To is the initial temperature and K is the thermal conductivity of the wall. The penetration distance of the thermal layer in the lower head wall, δ, is:

$$\delta = \left[6\alpha \int_0^t q \, dt \, / \, q \right]^{\frac{1}{2}} \tag{10}$$

where α is the thermal diffusivity of the wall. After the thermal layer penetrates the entire thickness of the wall, the integral heat balance model is modified to consider the wall as a finite slab. Prior to ablation, the lower head inner surface temperature is determined by the following expression:

$$\frac{d}{dt} \left[Ts - \frac{q \, \ell}{3 \, K} \right] = \frac{\alpha \, q}{K \, \ell} \tag{11}$$

where ℓ is the thickness of the wall. The outside surface of the wall is assumed to be adiabatic.

As the lower head wall reaches the ablation temperature, the integral heat balance model is modified to include a molten layer penetrating into the thickness of the wall. In the analysis, a linear temperature profile is assumed for the molten layer and a parabolic profile for the solid layer. The assumption of a linear profile in the molten layer, a reasonable approximation, greatly reduces the complexity of mathematic calculation as discussed in Reference [12]. The transient ablation thickness (s) is given by:

$$\left(\frac{s}{\ell}\right)^2 + \left[\frac{\alpha \rho L}{q\ell} - 2 - \frac{3KL}{qc\ell}\right]\left(\frac{s}{\ell}\right) + \frac{3K}{\rho c q \ell^2}\int_{t_a}^{t} q\, dt = 0 \qquad (12)$$

in the above equation, ρ, L and c are the density, latent heat of fusion, and heat capacity of the wall, respectively. The time t_a is the time of the onset of ablation. Knowing the ablation thickness, the lower head inner surface temperature is given by:

$$Ts = Tm + q\, s/K \qquad (13)$$

where Tm is the fusion temperature of the wall.

Finally, the average debris bed temperature is computed by the energy balance equation:

$$MC \frac{dTc}{dt} = Q_{dk} - Q_{db} - h\,(1-P)A_s \qquad (14)$$

where Q_{dk} and Q_{db} are the corium decay power and heat removal from the debris bed, respectively. The debris bed porosity is denoted as P and the surface area of the hemispheric section of the debris bed is A_s. Equation (14) is coupled with Equations (8) to (13). For the period of initial thermal penetration and ablation, these equations are solved explicitly with an iteration scheme. For the period between the complete penetration and the onset of ablation, these equations are solved implicitly.

RESULTS

As discussed in the above Section, the analysis involves five input parameters: particle size, jet breakup length, debris bed porosity, debris/lower head heat transfer coefficient, and the radiation heat exchange factor. These parameters represent the uncertainties of the various phenomenological processes in the lower head and are included in eight parametric studies as shown in Table 2. Engineering judgment was used to estimate the values of the parameters used for the base case (Case 1-a).

Base Case

The analysis shows that the interactions among the corium, water, and lower head can be distinguished by five stages. During the first stage, when corium is discharged into the lower plenum, rigorous water boiling takes place due to the sudden increase of contact surface area as the result of corium fragmentation into small particles. At the end of the discharge period (i.e., 36 seconds), about 8.3 percent of the total water inventory (44,000 kg) is vaporized. Consequently, the corium particles are solidified and cooled to about 1210 K. The accumulation of debris particles at the bottom of the lower plenum causes the heating of the lower head wall. At the end of the discharge period, the lower head inner surface is heated from its initial 440 K to about 738 K.

The second stage starts when a steady debris bed depth is established at the end of the discharge period. Since the heat removal from the debris bed is higher than the decay power of the corium (5 MW), the debris temperature is predicted to continually decrease.

The third stage starts at about 713 seconds when the core debris is quenched to the water saturation temperature. During this stage, the corium decay power is the only energy source for steam generation. Because of the large water inventory specified by the comparison exercise, a complete water boil-off occurs at about 15,500 seconds (i.e., 4 hours and 20 minutes after the debris has been quenched at 713 seconds).

The fourth stage is characterized by the rapid increase of debris temperature as the result of water depletion. The high debris temperature enhances the thermal attack of the lower head wall. At about 18,970 seconds (i.e., 58 minutes after the water depletion), ablation starts at the wall inner surface.

The fifth stage is the ablation period. The continuous heating of the debris bed by the corium decay power causes the ablation layer to expand into the lower head wall thickness at a rate of 0.52 x 10^{-4} m/s. At about 20,510 seconds (i.e., 26 minutes after the onset of ablation), about 50 percent of the lower head wall is ablated. The failure of the lower head is then assumed. At this time, the core debris temperature is about 2085 K, only 65 K below its fusion temperature. The core debris could re-melt if the wall failure is delayed.

Figures of the above discussed steam generation, water mass, core debris, and lower head inner surface temperatures, and the ablation distance during the five stages are given in Reference [1].

Parametric Study

1. Effect of Particle Size. The analysis shows that a small particle size (0.75 mm in Case 1-b) provides a large total surface area which, in turn, yields a high steam generation rate and lower debris temperature as shown in Table 3. On the other hand, a large particle size (2 mm in Case 1-c) yields a lower steam generation rate and higher debris temperature. However, the particle size has no significant effect on the corium/lower head interaction, except for the timing of major events as indicated in Table 4. The lower head failure time is delayed by about 3 minutes when the particle size is reduced from 1 mm to 0.75 mm (Case 1-b); the failure time is advanced by about 10 minutes when the particle size is increased to 2 mm (Case 1-c).

2. Effect of Jet Breakup Length. An early breakup at 10 jet diameters is assumed in Case 1-d. This early breakup provides a longer cooling time for particles travelling downward at the terminal velocity. Consequently, the debris, as well as the lower head temperatures, are lower than that of the base case at the end of the corium discharge period as shown in Table 3. Similar to the case of small particles, the early breakup of the jet stream has no significant impact on the debris/lower head interaction, except to delay the timing of major events as indicated in Table 4.

3. Effect of Debris/Lower Head Heat Transfer Coefficient. A 50 percent decrease or increase of the heat transfer coefficient is assumed in Case 1-e and 1-f, respectively. As one expected, a lower heat transfer coefficient will reduce the heating of the lower head wall and delay the ablation and failure time. On the other hand, a higher heat transfer coefficient enhances the heating of the wall and causes an early ablation and failure of the lower head wall. Comparisons in Tables 3 and 4 show that the lower head failure time is delayed by about 20 minutes when the heat transfer coefficient is reduced from 1000 to 500 w/m^2-k; the failure time is advanced by about 5 minutes when the heat transfer coefficient is increased to 1500 w/m^2-k.

4. Effect of Radiation Heat Exchange. Radiation heat transfer is an important part of debris cooling and involves a large uncertainty, particularly with respect to the heat exchange with structures above the debris bed after the depletion of water. In the base case, the radiation exchange factor is 0.43 (i.e., the emissivities of corium and structures are assumed to be 0.75 and 0.5, respectively). In Case 1-g, the exchange factor is increased to 0.6 by increase the emissivity of structures to 0.75. This increase of the radiation heat exchange factor reduces the debris temperature. Hence, both the wall ablation and failure are delayed as shown in Tables 3 and 4.

5. Effect of Debris Bed Porosity. The size of the pores in the debris bed controls the quantity of water entering the porous medium and, therefore, affects the debris bed coolability. In Case 1-h, the porosity is reduced from 0.4 to 0.3. The analysis shows that, with a smaller porosity, the core debris cannot be quenched to water saturated temperature. Although the water depletion time is delayed, the reduction of porosity has no significant effect on the lower head ablation and failure as shown in Tables 3 and 4.

SUMMARY AND CONCLUSIONS

The PWR Case 1 is characterized by a small quantity of corium and a relatively slow discharge into the lower plenum. The assumption of breakup of the jet stream results in the solidification of debris particles and formation of a debris bed on the lower head. For most cases, the debris is quenched within 7 to 12 minutes and the corium decay power becomes the energy source for water boil-off. Due to the large inventory of water in the lower plenum, it requires about 4 hours to completely vaporize the water. After water depletion, the core debris and lower head wall are heated up rapidly. In about 58 minutes, ablation starts at the inner surface of the lower head wall. The ablation rate is about 0.5 x 10^{-4} m/s. With this ablation rate, the lower head fails in about 26 minutes. Parametric studies, involving the variations of particle size, jet breakup length, debris bed porosity, radiation heat exchange factor, and the corium/lower head heat transfer coefficient, show that under various conditions, the lower head failure time can be delayed by about 10 minutes or advanced by about 20 minutes in comparison with the base case.

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Table 1

Initial Conditions and Material Properties for the PWR System (Case 1)

1.	Initial Condition	
	Mass of corium on the core plate, kg	12,000
	Depth of corium pool on the core plate, m	1
	Decay power*, MW	5.0
	System pressure, MPa	1
	Water inventory, kg	44,000
	Water temperature, K (saturation)	453
	Structure temperature, K	440
	Core debris temperature, K	2,000
	Support plate breach diameter, m	0.15
2.	Properties (Corium/lower head)	
	Fusion temperature, K	2,150/1,700
	Specific Heat, J/kg-K	500/680
	Density, kg/m^3	8,500/7,800
	Latent heat of fusion, KJ/kg	300/275
	Thermal Conductivity, W/m-K	30/30
	Viscosity, Kg/m-s	2X10^{-3}/-
	Surface tension, N/m	0.8/-

* This refers to decay power in debris relocated to bottom head.

Table 2

Summary of Parametric Studies

Case	D, mm	L/D	h_l, w/m^2-k	F	P	Remark
1-a	1	15	1000	0.43	0.4	Base Case
1-b 1-c	0.75 2					Effect of Particle Size
1-d		10				Effect of Jet Breakup Length
1-e 1-f			500 1500			Effect of Debris/Lower Head Heat Transfer Coefficient
1-g				0.6		Effect of Corium/Structure Radiation Exchange Factor
1-h					0.3	Effect of Debris Bed Porosity

Table 3

Results of Parametric Studies

Case	Corium/Lower Head Temperature, K	Maximum Steam Generation Rate, kg/s	Ablation Delay Time, min	Lower Head Failure Delay Time, min	Average Ablation Rate, m/s
1-a	1209/738	102	58	26	$0.52X10^{-4}$
1-b	866/605	116	58	26	$0.52x10^{-4}$
1-c	1988/1044	87	58	26	$0.52x10^{-4}$
1-d	831/592	44	58	26	$0.52x10^{-4}$
1-e	1209/620	102	74	30	$0.45x10^{-4}$
1-f	1209/820	102	54	25	$0.54x10^{-4}$
1-g	1209/738	102	68	31	$0.43x10^{-4}$
1-h	1209/735	99	49	26	$0.52x10^{-4}$

Note:

1. Corium/lower head temperature at the end of corium discharge period.
2. Maximum steam generation rate during the corium discharge period.
3. Ablation delay time = from time of water depletion to the start of ablation.
4. Lower head failure time = time for the ablation of 50 percent of the wall thickness.

Table 4

Comparison of Major Events (Time in Seconds)

Case	Debris Quench	Water Depletion	Ablation	Lower Head Failure
1-a	713	15,500	18,970	20,510
1-b	753	15,660	19,130	20,680
1-c	572	14,900	18,370	19,910
1-d	398	16,710	20,180	21,730
1-e	728	15,480	19,930	21,700
1-f	704	15,510	18,730	20,220
1-g	713	15,490	19,580	21,420
1-h	---	16,770	19,720	21,250

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