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AN ANALYSIS OF MOLTEN-CORIUM-INDUCED FAILURE OF DRAIN PIPES IN BWR MARK II CONTAINMENTS*

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ABSTRACT

This study has focused on mechanistic simulation and analysis of potential failure modes for inpedestal drywell drain pipes in the Limerick boiling water reactor (BWR) Mark II containment. Physical phenomena related to surface tension breakdown, heatup, melting, ablation, crust formation and failure, and core material relocation into drain pipes with simultaneous melting of pipe walls were modeled and analyzed. The results of analysis have been used to assess the possibility of drain pipe failure and the resultant loss of pressure-suppression capability. Estimates have been made for the timing and amount of molten corium released to the wetwell. The study has revealed that significantly different melt progression sequences can result depending upon the failure characteristics of the frozen metallic crust which forms over the drain cover during the initial stages of debris pour. Another important result is that it can take several days for the molten fuel to ablate the frozen metallic debris layer - if the frozen layer has cooled below 1100 K before fuel attack.

One of the most important aspects of hypothetical core meltdown accidents in BWRs is concerned with the consequences of reactor pressure vessel (RPV) failure and associated corium release into the primary containment. One potentially important mechanism for pressure suppression pool (PSP) bypass is associated with the failure of drain pipes which penetrate the concrete pedestal floor downward into the wetwell volume. Analyses of this issue were conducted by the Nuclear Regulatory Commission's BWR MARK II and MARK III Parametrics Program at the Oak Ridge National Laboratory for the LIMERICK[1] and WNP-2[2] Mark II containments[3]. Due to space limitations, detailed results are presented only for the LIMERICK Mark II Containment.

PROBLEM FORMULATION

It is obvious that drain failure characteristics will depend on the specifics of a debris pour history, which may be predicted differently depending upon the code used. Results described later in Section 4 are thus presented parametrically so as to be applicable for various debris pours. However, a focussed analysis is conducted thereafter using a debris pour history predicted by the BWRSAR[4] code for a short-term station blackout accident sequence event, as documented in Ref. 3, and summarized in Table 1. As seen from Table 1, the first debris pour up to 6000 seconds after vessel failure consists largely of molten steel and Zircaloy. Thereafter, a mixture of molten UO_2 and Zircaloy is ejected. Debris bed height increase is evaluated under the implicit assumption that the debris ejected from the reactor vessel instantaneously spreads uniformly over the floor. Possible drain failure scenarios for the Limerick containment were postulated as occuring in 3 stages.

Stage 1 is identified as the situation that occurs at the start of the metallic debris-melt attack on the stainless steel drain cover plate. Therein, two cases are identified. For

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Table 1. Debris Ejection History For BWR Mark II Drain Failure Analysis

Cavity Radius, m = 3.03

	Zircaloy		Other Metals		Uranium-Dioxide		Debris Bed		Elapsed
Time (min)	Mass (lb)	Height (m)	Mass (lb)	Height (m)	Mass (lb)	Height (m)	Total (m)	Rise Rate (m/s)	Time (s)
0.00							0		
2.55	0	0	0	0	0	0	0	0.00E+00	
2.75	3499	0.008	7983	0.016	0	0	0.024	4.36E-05	6.00E+02
2.85	12610	0.031	28773	0.057	0	0	0.088	1.06E-04	1.20E+03
3.05	40108	0.097	40820	0.081	0	0	0.178	7.55E-05	2.40E+03
3.45	40108	0.097	40820	0.081	0	0	0.178	0.00E+00	4.80E+03
3.65	40108	0.097	40820	0.081	0	0	0.178	0.00E+00	6.00E+03
3.85	45752	0.111	49444	0.098	14782	0.021	0.231	4.35E-05	7.20E+03
4.05	64273	0.204	107817	0.214	82745	0.119	0.537	2.56E-04	8.40E+03
9.55	112869	0.276	352454	0.700	380184	0.547	1.523	3.42E-05	3.72E+04

Case A either the debris internal energy is not high enough to melt the drain cover plate, or, if significant water is present, debris quenching and crust formation occurs. In this case the drain plate remains intact. In Case B the drain plate melts, and relocates downwards into the drain pipe region, and freezes along the cold walls. The aspect of molten metallic debris seeping through the drain plate cover slots after overcoming surface tension forces is also addressed.

Stage 2 is identified as the phase in which the existing Zircaloy-steel layer that may have partially crusted (over the drain cover) is subjected to a stream of molten UO_2 or a eutectic composition of UO_2 and Zircaloy in the second debris pour.

Finally, stage 3 accounts for the probable situation where the molten fuel melts the Zircaloy-steel layer (formed during stage 2) and thereafter attacks the drain pipe region. This is also the situation when significant core-concrete-interaction (CCI) occurs, accompanied by non-condensible gas generation which tends to stir the molten mixture.

The above mentioned scenarios cover most of the important aspects of the core debris attack of the drain pipe region under consideration.

MODELING OF CORIUM-DRAIN INTERACTION

Various mathematical models and related computer programs that have been set up to analyze BWR Mark II debris-drain interactions are described in this section.

Exact Analytical Solution for Simultaneous Melting & Freezing of Semi-Infinite Slabs in Intimate Contact - Neumann Problem

Consider a solid plate in direct contact with hot liquefied debris material. If the melting temperature of the plate is lower than that of the debris, both plate melting and debris solidification (i.e., crust formation) may occur simultaneously. Based upon experiments conducted with simulant materials, Podowski and Lahey[5] observed that the liquefied plate material (of lower density than the debris) would percolate upwards through the cracks in the crust to the debris pool surface, so that the debris pool remains in contact with the solid plate. Assuming that the plate and molten debris are thick (i.e., their thickness is greater than their respective thermal boundary layers), the propagation of plate melting and the buildup of debris crust was approximated by a one-dimensional "semi-infinite" conduction model.

Details regarding the conduction equations, and accompanying boundary conditions can be found in Ref. 5.

The model described above has been coded as the STEF program. This code proved particularly useful for the modeling of stage 2 scenarios as described earlier, where molten fuel (i.e., UO_2 or UO_2-Zr eutectic) attacks a layer of less dense material (i.e., Zircaloy-steel mixture) that was ejected earlier and may have frozen. Interestingly, codes such as CORCON[6] simply assume that the molten fuel debris gets instantaneously relocated to the concrete surface without accounting for the time delay involved. Such was the case in the analysis presented in Ref. 3. On the contrary, the mechanistic model in STEF described above calculates both the amount of fuel crust that would form, and the relative timing associated with the potential fuel-concrete attack.

The 2DKO program[7] for Analysis of Two Dimensional Melting and/or Freezing in Two-Material Structures

The model used in the 2DKO computer code accounts for 2-D phenomena related to simultaneous heat transfer and phase change (melting/freezing) between hot liquids and relatively cold solids. Various applications include the melting of a solid structure when in contact with a continuously delivered melt, melting of a solid plate subjected to an impinging jet of hot liquid, and the melting of a vertical wall in contact with a liquid pool. The 2DKO model has been validated against experimental data, and showed good agreement[7]. This code was considered particularly useful for the present analysis of drain failure, since it allows for transient debris deposition on a plate.

An additional validation of the 2DKO code model was conducted by comparing against results of a one-dimensional (1-D) heat transfer model developed using the HS and CVH modules of the MELCOR[9] code. A sample problem was set up to evaluate the transient thermal response of a two-slab system consisting of molten Zircaloy on a cold steel plate representing the initial stage of debris pour described earlier. For MELCOR calculations, the specific heat capacity of each material was increased by an appropriate amount over a small temperature range near the material's melting temperature, to account for the latent heat of fusion. Transient temperature profiles generated by the two models were in good agreement with one another. Coupled with validation against experimental data, this verification exercise gave confidence in the use of 2DKO for analyzing pertinent aspects of the BWR Mark II inpedestal drain failure problem.

The PLUG program for Analysis of Core Debris Relocation within Drain Pipe

The PLUG computer program was written to evaluate core debris relocation (i.e., plug-type flow) within a drain pipe with simultaneous debris freezing and possible tube melting. The program utilizes mathematical models reported in Ref. 10. Figure 2 provides a schematic representation of the physical configuration for freezing penetration of a moving molten debris fluid in a channel, combined with channel melting. The time period between the passage of the fluid's leading edge and the beginning of wall melting is referred to as the melting delay time, t_m, whereas the time required for the crust buildup at the entrance region to cause complete blockage is designated as t_c. Both t_c and t_m need to be evaluated externally, or known previously. PLUG also calculates thermal and hoop stresses in the frozen debris crust, and compares them to the critical failure stress at the drain pipe melting front. This allows one to obtain an indication of crust collapse, and re-entry of molten core debris into the channel. The model predictions were compared by Best et al.[10] against data obtained from experiments involving molten UO_2 flow from a reservoir into narrow channels. Good agreement was observed. Furthermore, PLUG program evaluations for a sample problem were verified against hand calculations.

DRAIN FAILURE ANALYSIS

The simulation capability developed was used to analyze the BWR Mark II drain pipe regions for their response to attack by core debris. The analysis was conducted in two steps: (1) code calculations over a range of parameters covering the estimated conditions for the Limerick BWR containment, and, (2) application of results of parametric evaluations to analyze the possible sequence of events leading to drain failure. These two steps are described subsequently.

General Parametric Evaluations

The parametric calculations are described in five stages as follows:

Surface Tension Breakdown Evaluations and Analysis. The consequences of surface tension breakdown, and melt entry into the drain pipe through the slots in the drain cover plate for the Limerick containment (Figure 1), were addressed. Assuming negligible contribution from momentum transfer of debris as it settles around the slot, or hole, and ignoring melting or crust formation, a force balance yields, Hc = S x Pw / (rhod x g x Ac), where, Hc is the critical height of molten debris, S is the surface tension of debris material, Pw is the wetted perimeter of the opening, rhod is the density of debris material, g is the gravitational acceleration, and Ac is the cross-sectional area of the opening. Using this relationship it was found that the critical height of molten debris for a variety of conditions is quite often in the several millimeter range.

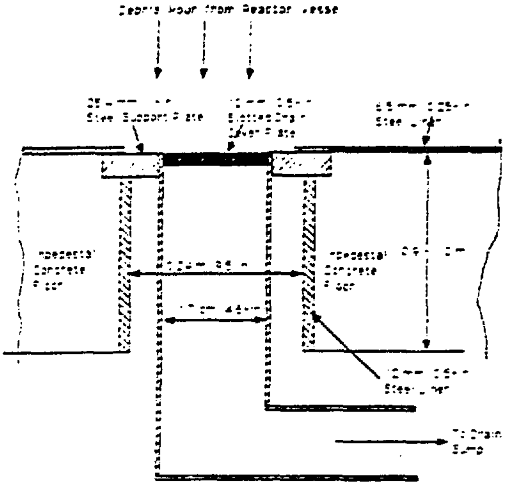

Figure 1. Schematic of Inpedestal Drain Pipe Region for Limerick BWR Mark II Containment

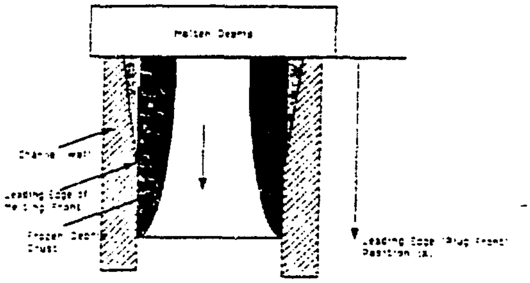

Figure 2 Schematic Representation of Molten Debris Plug Flow Model Characteristics

A thermal analysis using the 2DKO code indicated that it takes less than a second for molten metallic debris to freeze and plug the slots or holes in the drain pipe region, under various boundary conditions. Further, based upon BWRSAR results depicted in Table 1, it would require tens of seconds for several millimeters of molten pool head to form for surface tension breakdown to occur. Hence, for all practical purposes it can be assumed that no significant melt drainage will occur at the start of metallic debris pour.

Falling Debris Parametric Evaluations. The 2DKO program described earlier was used to analyze the response of a stainless steel plate to falling metallic debris as predicted by the BWRSAR code (summarized in Table 1). A test matrix of runs made for this analysis is shown in Table 2. A range of effective heat transfer coefficients were estimated for heat transfer between hot and cold surfaces, as shown in Table 2. It was noted from Ref. 3 that the maximum inpedestal drywell temperature reaches a value between 600 K and 700 K. An upper bound of 600 W/m^2-K was thus calculated for the debris surface-to-drywell effective heat transfer coefficient. Due to minimal structural material in the drain pipe, and the atmosphere therein, and to limit the number of code runs and ensuing analyses, the plate surface-to-ambient heat transfer coefficient was conservatively set to zero. The thickness of the plate was for the most part taken as 12.7 mm (0.5-inch) to correspond with the thickness of the steel cover plate in the Limerick inpedestal. However, a parametric study with different plate thicknesses for selected cases has also been conducted. Based upon BWRSAR predictions for the relative combinations of molten Zircaloy and steel, the material properties of the falling debris were derived by weighting the respective properties of Zircaloy and steel with factors of 0.3 and 0.7 respectively. The calculations were performed until 6000 s after the start of debris pour, after which the 2DKO program is not valid.

Results of the various evaluations are summarized in Table 2. It is seen from Table 2 that the steel plate (i.e., drain cover) melting characteristics are not significantly affected by the choice of debris surface heat transfer coefficient. This indicates that the process of plate melting is dominated primarily by heat conduction. It should be noted that for all cases, the steel plate gets completely molten within 1300 s, and that at the end of 6000 s various melt-crust temperature profiles can result.

Debris Crust Ablation Parametric Analysis with the STEF Program. For generality, ten different cases were analyzed with the STEF program. The results are tabulated in Table 3. The plate (i.e., frozen metallic debris) temperature at infinity (i.e., sufficiently far away from the melting front) was tied to the results obtained from the 2DKO falling debris analysis. This temperature was set at the melting temperature of the plate for the case when the metallic debris surface heat transfer coefficient was set to 0 W/m^{2}K

Table 2. Results of Falling Metallic Debris Film Analysis with the 2DKO Program

Case	Plate Thickness (in / cm)	Debris Superheat (K)	Tp (K)	Hd (W/m2-K)	tp,f (s)	Fd / Zd (% / cm)	tp,e (s)	Fd / Zd (% / cm)	Results at 6000 s Falling Debris Temperatures Tc bot (K)	Tc top (K)
1	0.50 / 1.27	0	303	600	547	90 / 5.45	1300	62 / 5.92	1005	592
2	0.50 / 1.27	100	303	600	770	87 / 4.29	1130	54 / 5.51	1060	[illegible]
3	0.50 / 1.27	0	573	500	730	96 / 4.17	1130	63 / 6.43	1019	597
4	0.50 / 1.27	100	573	600	670	95 / 3.29	997	57 / 4.71	1084	[illegible]
5	0.50 / 1.27	0	303	0	547	90 / 5.45	1300	62 / 5.92	1547	1547
6	0.50 / 1.27	100	303	0	770	87 / 4.29	1130	54 / 5.51	1547	1547
7	0.50 / 1.27	0	573	0	730	96 / 4.17	1130	63 / 6.43	1547	1547
8	0.50 / 1.27	100	573	0	670	95 / 3.29	997	57 / 4.71	1547	1547
9	0.375 / 0.95	100	303	600	630	98 / 2.82	860	65 / 4.36	1074	[illegible]
10	1.0 / 2.54	100	303	600	1420	96 / 6.90	2870	95 / 16.97	1048	597

Notes
Tp - Initial Temperature of Plate
Hd - Debris Surface Heat Transfer Coefficient
tp,f - time at which plate first starts melting after attack from metallic debris
tp,e - time at which plate is completely melted
Fd - Fraction of debris that is frozen at time tp
Zd - Height of debris crust at time tp
Tc,bot - Temperature (of debris) at bottom of debris bed at 6000 s
Tc top - Temperature of debris at top of debris bed at 6000 s

Table 3 STEF PROGRAM EVALUATIONS

Case	Debris Material	T_{inf} (K)	Plate Material	T_{inf} (K)	Time to Ablate Plate by [illegible] (s)
1	UO2-Zr	2606	Zr-Steel	1820	1120
2	UO2-Zr	2606	Zr-Steel	1123	876700 (244 hrs)
3	UO2-Zr	2606	Zr-Steel	2098	1250
4	UO2-Zr	3113	Zr-Steel	1820	650
5	UO2-Zr	3113	Zr-Steel	1123	2.44e4 (6.8 hrs)
6	UO2-Zr	3113	Zircaloy	2098	550
7	UO2	3113	Zr-Steel	1820	1650
8	UO2	3113	Zr-Steel	1123	No Plate Melting Possible
9	UO2	3113	Zr-Steel	1423	2.44e4 (6.8 hrs)
10	UO2	3113	Zircaloy	2098	1420

(i.e., in the 2DKO evaluations). When the debris surface heat transfer coefficient was taken as 600 W/m^{2}K, the plate temperature at infinity was set at 1123 K (arrived at by taking the arithmetic average of frozen metallic debris crust temperatures over the height of the bed at the end of 6000 s). Cases 1 through 6 in Table 3 consider situations where the molten debris is a eutectic mixture of UO_2 and Zircaloy, either at the melting temperature of the eutectic or superheated up to the melting temperature of UO_2. As seen from the results, depending upon the degree of plate subcooling, the time it takes to completely ablate the approximately 18 cm of frozen crust could be several (i.e., Case 2). As expected, the shortest duration of time for completely ablating the frozen debris layer plate is when the plate temperature is at its melting temperature. Even in this case (i.e., Case 1), it can take close to 20 minutes. Hence it is evident that a significant time can elapse before the molten fuel debris can reach the concrete basemat, and initiate CCI. Finally, as seen from Table 3, the evaluations show that the amounts of debris crust formation and plate ablation are generally much less when the debris is UO_2 alone, rather than a eutectic mixture of UO_2 and Zircaloy. This is attributed in large measure to the significantly lower thermal conductivity of UO_2 compared to the UO_2-Zr eutectic mixture.

__PLUG Program Parametric Evaluations.__ In order to evaluate the parameters t_m and t_c for PLUG calculations, additional 2DKO program runs were made with the debris bed height fixed at a given value equal to the drain pipe channel radius. The plate thicknesses chosen correspond with channel wall thicknesses for the pipe regions in the Limerick and WNP-2 designs respectively. The debris side heat transfer coefficient was set at 0 W/m^{2}K due to centerline symmetry. The heat transfer coefficient for the plate (i.e., tube material) interface with the ambient atmosphere was parametrically varied between 5 W/m^{2}K, and 500 W/m^{2}K. Results of these evaluations are shown in Table 4.

The PLUG program was next used to evaluate the amount of debris flow through channels. Results obtained for the length of debris penetration, crust buildup, and failure, are summarized in Table 4. As can be seen, a significant amount of debris can exit through the drain pipes before the entrance

Table 4. PLUG PROGRAM EVALUATIONS

Case	Debris Material	Superheat K	Tube Wall Thickness (in)	Characteristic hc (W/m2-K)	tc (s) (see Note 1)	tm (s) (see Note 2)	Xc (m) (see Note 3)	Crust Failure	Maximum Unobstructed Amount of Debris Expelled (kg) (see Note 4)
1	Zr-Steel	0	0.25	500	300	No Melting	66	None	About 5500 kg (per drain)
2	Zr-Steel	100	0.25	500	347	No Melting	73	None	About 6000 kg (per drain)
3	Zr-Steel	0	0.25	5	400	70	81	None	About 6800 kg (per drain)
4	Zr-Steel	0	0.50	5	580	284	105	None	About 25,000 kg (per drain) - Limerick Not Applicable for WNP-2
5	UO2-Zr Eutectic	0	0.25	500	435	>> 435	171	None	About 17,000 kg (per drain)
6	UO2-Zr Eutectic	500	0.25	500	> 600	20	214	Yes	Continuous Pour Established; if not- About 80,000 kg (per drain) for Limerick About 21,000 kg (per drain) for WNP-2
7	UO2-Zr Eutectic	0	0.25	5	> 1000	15	305	Yes	Continuous Pour Established at Rates of: About 1200 kg/s (per drain) for Limerick About 300 kg/s (per drain) for WNP-2
8	UO2-Zr Eutectic	0	0.50	5	800	80	214	Yes	Continuous Pour Established; if not- About 80,000 kg (per drain) for Limerick Not Applicable for WNP-2
9	UO2-Zr Eutectic	500	0.50	5	> 5000	40	> 1030	Yes	Continuous Pour Established at Rates of: About 1200 kg/s (per drain) for Limerick Not Applicable for WNP-2

Notes/Assumptions:

1) tc - time it takes for channel entrance to get blocked from freezing debris
2) tm - time it takes for tube wall to start melting after first passage of debris front
3) Xc - maximum unobstructed axial debris plug traverse before channel blockage at entrance
4) Mass of debris ejected evaluated as = debris density x cavity area x Xc
5) Height of molten debris pool is assumed to remain constant

blockage condition is met. Crust failure in drain pipes is also indicated in some cases where significant tube wall melting occurs. In these instances a continuous pour of core debris at high discharge rates may also get established.

Limerick Drain Failure Analysis

Drain failure was analyzed in a somewhat focused manner using the results of the parametric evaluations, and the BWRSAR debris pour history given in Table 1. Analysis results are depicted in Figure 3, using a flow chart format.

As seen in Figure 3, upon initial debris attack of the drain pipes, surface tension breakdown may or may not occur depending upon the nature of the pour. Even if breakdown occurs, only negligible drainage will result, as was previously demonstrated.

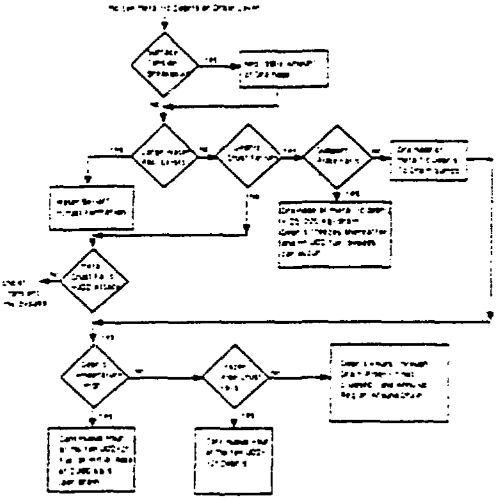

Figure 3. Flow Chart of Events for Inpedestal Drain Failure Analysis in Limerick BWR MARK II Containment

As described below, very different scenarios may take place dependent upon whether or not a significant water pool exists in the inpedestal cavity region.

Significant Water Pool Present in In-Pedestal Cavity Region. In case a significant water pool exists in the inpedestal region, debris freezing from quenching will occur until the water boils off or the metals cool down sufficiently. The degree of subcooling of the metallic debris would clearly depend upon operating conditions. The MELCOR analysis of Ref. 3 indicates that the metallic debris temperature would be lowered to about 1100 K at the end of 6000 s from the start of the debris pour. In any case, it is evident that no significant metallic debris drainage into the drain pipes can occur in this scenario.

Upon ejection of molten UO_2-Zr Eutectic into the inpedestal cavity region, the frozen metallic debris crust may start to ablate. For the likely case where metallic debris has cooled off to about 1100 K, Case 2 (Table 3) results indicate that it may take several days before the entire frozen metallic debris crust layer of about 0.178 m height can be ablated, even if the UO_2-Zr debris does not solidify due to combined heat of radiation and convection to the structural materials in the cavity region. If a UO_2 debris layer is assumed, no metallic crust ablation is predicted (Case 8). From Table 3 it is seen that other relative timings (e.g., 30 minutes for Case 7, to several hours for Case 9) are also possible. These are revealing and important results, since the accident progression is significantly impacted by virtue of the fact that CCI may not occur at all.

Clearly, if the fuel debris does not reach the drain pipe region, no bypass can occur. In the event that the molten fuel debris does reach the inpedestal drain pipe region an indication of the relative amounts of drainage can be obtained from the results of the PLUG program evaluations, Cases 8 & 9 respectively in Table 4. Depending upon the amount of debris superheat, a continuous pour may or may not take place. Significant drainage can be expected in either case. The actual amount of debris expelled may be greater than the amounts indicated in Figure 3, since the simultaneously occurring CCI would tend to remove the entrance blockage, and enlarge drain holes due to radial concrete ablation.

No Significant Water Pool in In-Pedestal Cavity Region. In the absence of a water pool, the 2DKO-based evaluations shown in Table 2 indicate that plate melting can be expected to start in about 10 to 15 minutes from the start of metallic debris pour, at which point in time several inches of debris crust would have formed. Even at the start of plate melting a significant debris crust may have formed. Hence, a qualified conclusion may be drawn that metallic debris drainage will not occur even if the drain cover plate is completely molten. However, a significant amount of concrete degassing may also be occurring simultaneously which may fracture or stir the frozen debris mixture. In case crust failure or bypass do not occur, the 2DKO evaluations (Cases 1 through 4 in Table 2) indicate that at the end of 6000 seconds the entire metallic debris would have crusted based on assumed debris surface-to-ambient heat transfer. The crusted debris temperature would exhibit a temperature gradient ranging from about 600 K at the top of the debris, to about 1000 K at the debris-drain plate region. At the other extreme, where the surface heat transfer characteristics may have been sufficiently degraded (e.g., possibly from the generation of an aerosol cloud layer which blocks radiation heat transfer) only small fractions of the debris would have frozen after 6000 s into the transient. Such a surface condition in unlikely, because no significant CCI can occur during this stage, and because the metallic debris has no significant UO_2 fuel in it. Thus, the formation of dense aerosol clouds above the debris bed to cause adiabatic-type heat transfer surface conditions is not possible.

In the unlikely event of debris crust failure upon drain-cover plate melting, the accident sequence can change significantly. Molten metallic debris above the crust would begin pouring into the drain pipe region. Based upon the 2DKO and PLUG program results (Table 4), it appears that 5000 to 7000 kg (per drain) can be expected to leave the debris bed, and enter the drain sumps as shown in Table 4 for Cases 1 to 3. The metallic melt would freeze before the remaining metallic debris bed above in the concrete pedestal is attacked by the molten fuel debris at the end of 6000 seconds.

Finally from the falling debris analysis for Case 10 (Table 2) it appears that there may be a remote possibility of melting the 25.4 mm (1-inch) thick supporting structure (Figure 1) holding the 0.102 m (4-inch) diameter drain pipe late (i.e., after 2870 seconds) into the transient. From the results of Case 1 through 8 analyses (Table 2), it is evident that this result would hold true even if the debris surface heat transfer conditions were not adiabatic. However, even upon complete melting of the support plate, most of the metallic debris above it would be in a frozen state. Hence, under the assumed conditions, a continuous pour of any significant amount does not appear likely through the opening that may be created. If the support plate were to fail somehow (e.g., from creep rupture or material degradation), and molten metallic debris poured through it, PLUG evaluations (Case 4, Table 4) indicate that up to 25,000 kg (per drain) of debris may pour out before plugging up the channel entrance. If such an event did occur, it would happen about an hour after the first debris pour commenced. Since it does not appear likely that the annulus portion will get plugged up with metallic debris melt, a reasonable pathway does exist for the molten fuel to get ejected out of the inpedestal region after it has ablated the crusted metallic debris.

The progression of the transient after 6000 seconds would essentially remain the same as for the case when a significant water pool exists. However, in the unlikely event the entire drain pipe region (including the annulus) were plugged up with frozen metallic debris, the progression of the molten fuel would be radically different. No fuel can be ejected from the inpedestal region during MCCI for this instance. However, if the annulus region were not filled with frozen debris, the results of melt progression would remain similar to those described previously (i.e., when a significant water pool exists). This indicates that the support plate for the drain pipe in the Limerick containment design can potentially play an important role in preventing early PSP bypass of molten fuel debris.

CONCLUDING REMARKS

Mechanistic models of the combined heat transfer and phase change between either flowing or stationary multi-material corium and the drain pipes have been used in the analysis. These models have been numerically tested and validated against experimental data. Several accident scenarios have been analyzed, including timing, amount and composition of corium released from the RPV onto the containment floor, melt superheat, the effect of water in the in-pedestal cavity region, melt inflow into the drain pipe, pipe heatup and plugging due to crust buildup, etc. in a general manner. The results of these analyses have been used to assess the possibility of drain pipe failure, as well as to estimate the timing and amount of molten corium release to the wetwell. The study has revealed that significantly different melt progression sequences can result depending upon the failure characteristics of the frozen metallic crust which forms over the drain cover during the initial stages of debris pour. Another important result is that it can take several days for the molten fuel to ablate the frozen metallic debris layer - if the frozen layer had cooled below 1100 K.

As a final note it is cautioned that the results presented in this paper are based upon the specific debris pour history predicted using the BWRSAR code, and on the individuals models and assumptions used. Other debris pour histories (predicted by other codes) may cause considerable variations in BWR MARK II containment drain failure characteristics.

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