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Subject: Corium Protection for Lower Drywell Sump

Enclosed are the details of the conceptual design for the corium shield. The shield is design to prevent the flow of molten core debris into the lower drywell sumps. This package pro-ides a detailed description of the calculations used to size the shield. Both the short term and long term challenges are considered. A sample calculation is provided to demonstrate the feasibility of the concept. This package is also being provided to the ACRS in preparation for the meeting on August 19.

Sincerely,

Carol E. Buchholz

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ATTACHMENT 7B

This material was submitted to the Staff on August 7, 1992. This information will be incorporated into the ABWR SSAR at a future date.

D. Prevention of Molten Debris Ingression into Lower Drywell Sump

D.1 Issue

During a hypothetical severe accident in the ABWR, molten core debris may be present on the lower drywell (LD) floor. The EPRI ALWR Requirements Document specifies a floor area of at least 0.02 m^2/MW_{th} to promote debris coolability. This has been interpreted in the ABWR design as a requirement for an unrestricted LD floor area of 79 m^2.

The ABWR has two drain sumps in the periphery of LD floor which could collect core debris during a severe accident if ingression is not prevented. If ingression occurs, a debris bed will form in the sump which has the potential to be thicker than the bed on the LD floor. Debris coolability becomes more uncertain as the thickness of a debris bed increases.

The two drain sumps have different design objectives. One, the floor drain sump, is designed to collect any water which falls on the LD floor. The other, the equipment drain sump, collects water leaking from valves and piping.

D.2 Proposed Design

A protective layer of refractory bricks - a corium shield - could be built around the sumps to prevent corium ingression. The shield for equipment drain sump would be solid except for the inlet and outlet piping which would go through its roof. The shield for the floor drain sump would be similar except that it must have channels at floor level to allow water which falls onto the LD floor to flow into the sump. The height of the channels would be chosen so that any molten debris which reaches the inlet would freeze before it exited and spilled into the sump. The width and number of the channels would be chosen so that the required water flow rate during normal reactor operation is achievable. A sketch of a concept for floor drain sump shield is shown in Figure 7B-1.

The walls of the equipment drain sump shield (solid shield) only have to be thick enough to prevent the elevated debris temperature from degrading the shield internal structural support. The walls of the floor drain sump shield (channeled shield) must be significantly thicker so that molten debris flowing through the channels has enough residence time to ensure debris solidification.

Both shields would extend above the LD floor to an elevation greater than the expected maximum height of core debris. Thus, no significant amounts of debris will collect on the shield roofs. The solid shield will be placed directly on top of the LD floor. The channeled shield will have refractory bricks embedded into the LD floor beneath the shield to prevent core-concrete interaction involving the molten debris in the channels.

D.4.1 Assumptions

The major assumptions invoked in the analyses and their bases follow.

1. Molten debris enters the channel with negligible super heat.

   Molten debris interacts with structural material (steel, concrete, etc.) and the lower drywell environment as it passes from the vessel, contacts the LD floor and spreads to the shield. This interaction depletes the molten debris of any super heat and can result in eutectic formations. The melting temperature of core debris which has undergone little interaction is approximately 2500 K. Significant interaction with the concrete floor reduces the debris melting temperature to approximately 1700 K.

2. During the freezing process, the temperature profile of the solidified debris rapidly obtains its steady state value.

   This assumption introduces little inaccuracy because: a) the heat conduction coefficient in the solidified debris is significantly larger than that of the shield material, and b) the depth of the solidified debris is considerably less than the height of the shield.

3. Heat transfer within the channel and shield is one-dimensional.

   The height of each channel is much less than its length. The heat transfer in the shield material is low enough that any heat transferred from debris contacting the shield wall outside of the channel does not affect the temperature along the channel until long after a plug has formed. Any heat transfer to the shield material between adjacent channels enhances the debris freezing process.

4. The shield wall acts as a semi-infinite slab with an initial temperature of 330 K during the initial freezing process.

   The properties of shield cause it to be a poor conductor of heat. The penetration depth during the short duration of the freezing process is on the order of a ten millimeters. The small increases in LD temperature prior to the presence of core debris does not significantly alter the shield temperature from its value during normal plant operation.

5. Core debris is not expected to enter the LD until at least two hours after accident initiation. This places decay heat level at approximately one-percent of rated power.

   Core debris will not enter the lower drywell before about two hours for any credible severe accident, see ABWR SSAR section 19E.2.2.

6. The decay heat generation in the debris is negligible compared to the rate of latent heat generation during the freezing process.

This assumption was verified during the analysis.

7. The thermal conductivity and thermal diffusivity of debris in solid and liquid phases are the same.

D.4.2 Initial Freezing of Molten Debris in Channel

If the floor drain sump shield fulfills its design objective, a debris plug will form in the channel before molten corium has a chance to traverse the channel and reach the sump. Molten debris enters the channel at a significantly elevated temperature (2500 K to 1700 K) compared to the shield wall (~ 330 K). The walls absorb heat from the debris because of the large temperature difference. Since the debris contains negligible super-heat, any heat loss by the debris results in freezing. Freeze fronts start at the channel walls and move toward the center of the channel. The leading edge of the freeze front will stay at the melting temperature of the debris. The freezing process is symmetric about the centerline of the channel because the same amount of heat is transferred through each wall while they are behaving as semi-infinite slabs. The channel walls behave as semi-infinite slabs during the freezing process because the heat conduction rate through the wall material is low compared to the release rate of latent heat. A sketch of the freezing process is shown in Figure 7B-2.

a) Freezing Time

The temperature profile in the crust, assuming it quickly reaches its steady state shape, is (Reference 1)

$$T_c(x) = \frac{\dot{q}L_c^2}{2k_f}\left(1 - \frac{x^2}{L_c^2}\right) + \frac{T_s - T_{f,m}}{2}\frac{x}{L_c} + \frac{T_s + T_{f,m}}{2} \qquad (7B\text{-}1)$$

where
- $T_c(x)$ is the temperure within the crust
- x is the crust coordinate measured from the crust centerline
- $\dot{q}$ is the heat density of the crust
- L_c is the half - thickness of the crust
- k_f is the thermal conductivity of debris
- T_s is the interface temperature between the wall and debris
- $T_{f,m}$ is the melting temperature of debris .

The energy balance at the freeze front is

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1. Frank P. Incropera and David P. DeWitt, *Fundamentals of Heat and Mass Transfer, 2nd Ed.*, John Wiley and Sons, 1985, pp. 85-6.

$$q''_{lh} = -k_f \frac{dT_c}{dx}\bigg|_{x=-L_c} \qquad (7B\text{-}2)$$

where q''_{lh} is the laten heat flux.

The latent heat flux is

$$q''_{lh} = \frac{dx_c}{dt}\rho_{cm}h_{lh} \qquad (7B\text{-}3)$$

where
- x_c is the crust thickness
- t is time
- ρ_{cm} is the density of debris
- h_{lh} is the debris latent heat of fusion.

Combining these two equations, evaluating the temperature gradient and rearranging yields

$$\frac{dx_c}{dt} = \frac{1}{\rho_{cm}h_{lh}}\left[\frac{k_f}{x_c}\left(T_{f,m} - T_s\right) - \dot{q}\frac{x_c}{2}\right]. \qquad (7B\text{-}4)$$

This is a non-linear, non-homogeneous, first-order differential equation. Before effort is expended to solve it, the relative magnitudes of the terms containing the crust thickness will be determined to see if either one dominates.

The initial interface temperature between the wall of the channel and the debris can be approximated by assuming both the debris and the shield wall behave as semi-infinite solids. The resulting temperature will be somewhat less than the actual interface temperature because the freezing process will force the crust to stay closer to its initial temperature than it would if it were an semi-infinite solid body only experiencing conduction. The contact temperature between the debris and the channel wall assuming semi-infinite bodies is (Reference 1)

$$T_s = \frac{T_{f,m}\sqrt{(k\rho c)_{cm}} + T_i\sqrt{(k\rho c)_w}}{\sqrt{(k\rho c)_{cm}} + \sqrt{(k\rho c)_w}} \qquad (7B\text{-}5)$$

where
- c is specific heat
- cm represents debris material properties
- w represents wall material properties.

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1. Glen E. Myers, *Analytical Methods in Conduction Heat Transfer*, Genium Publishing Corp., Schenectady, NY, 1987, p. 202

Using the debris properties found in the ABWR SSAR Table 19E.2-17 (Important Parameters for Steam Explosion Analysis) and representative wall properties found in Table 7B-1, the interface temperature is estimated to be 1390 K.

The debris energy generation density can be found by assuming a decay heat level and a total amount of corium. The density is

$$\dot{q} = \frac{Q_{dh}\rho_{cm}}{m_{cm}} \tag{7B-6}$$

where Q_{dh} is the decay heat level

m_{cm} is the total mass of corium, 285 Mg.

Evaluating this two hours after accident initiation (decay heat level equals approximately one percent of rated power) yields

$$\dot{q} = 1.5 \times 10^6 \ MW.$$

The two terms inside the brackets in equation 7B-4 can now be evaluated. For a channel height of 1 cm ($x_{c,max}$ = 0.5 cm) and a debris melting temperature of 1700 K, these values are

$$\frac{k_f}{x_c}\left(T_{f,m} - T_s\right) = 1.86 \times 10^6 \ W/m^2$$

$$\dot{q}\frac{x_c}{2} = 3.8 \times 10^5 \ W/m^2.$$

Therefore, the term containing the temperature difference across the crust is much larger than the one containing the heat generation rate. The temperature profile in the channel system ignoring energy generation in the debris is shown in Figure 7B-2. Equation 7B-4 can be simplified to

$$\frac{dx_c}{dt} = \frac{k_f}{\rho_{cm} h_{lh} x_c}\left(T_{f,m} - T_s\right) \tag{7B-7}$$

Solving this equation with the initial condition that $x_c(t=0) = 0$, reveals

$$x_c = \sqrt{\frac{2k_f\left(T_{f,m} - T_s\right)t}{\rho_{cm} h_{lh}}}. \tag{7B-8}$$

This equation can be rearranged to determine the time required to freeze debris in a channel of height H_o. The freezing time is

$$t_{freeze} = \frac{H_o^2 \rho_{cm} h_{lh}}{8k_f\left(T_{f,m} - T_s\right)} \qquad (7B\text{-}9)$$

b) Interface Temperature, T_s

The interface temperature between the debris and the channel wall can be determined by equating the heat flux from the crust to that which the crust can absorb. The heat flux from the crust is

$$q''_{crust} = -k_f \left.\frac{dT_c}{dx}\right|_{x=x_c/2} \qquad (7B\text{-}10)$$

which evaluates to

$$q''_{crust} = \frac{\dot{q}x_c}{2} + \frac{k_f}{x_c}\left(T_{f,m} - T_s\right) \qquad (7B\text{-}11)$$

As shown previously, the temperature difference term dominates the energy generation term in this equation for small channel heights. Therefore, the crust heat flux can be simplified to

$$q''_{crust} = \frac{k_f}{x_c}\left(T_{f,m} - T_s\right) . \qquad (7B\text{-}12)$$

Inserting the expression for x_c in equation 7B-8 and rearranging yields

$$q''_{crust} = \sqrt{\frac{k_f \rho_{cm} h_{lh}\left(T_{f,m} - T_s\right)}{2t}} . \qquad (7B\text{-}13)$$

The heat flux absorbed by the channel wall can be approximated by that which a semi-infinite solid body can absorb. This flux is (Reference 1)

$$q''_w = \frac{k_w\left(T_s - T_i\right)}{\sqrt{\pi \alpha_w t}} \qquad (7B\text{-}14)$$

where α_w is the thermal diffusivity of the wall material .

Equating 7B-13 and 7B-14 produces an equation governing the interface temperature. It is

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1. Incropera and DeWitt, *op. cit.* p. 203.

$$\frac{T_s - T_i}{\sqrt{T_{f,m} - T_s}} = \left(\frac{\pi k_f \rho_{cm} h_{lh} \alpha_w}{2k_w^2}\right)^{1/2} \qquad (7B\text{-}15)$$

Solving this equation for T_s using the quadratic formula yields

$$T_s = \frac{-(c_o - 2T_i) \pm \sqrt{(c_o - 2T_i)^2 - 4(T_i^2 - c_o T_{f,m})}}{2} \qquad (7B\text{-}16)$$

where co represents the square of the right hand side of equation 7B-15.

Negative solutions of this equation are physically impossible. For a $T_{f,m}$ of 1700 K and a T_i of 330 K, the interface temperature is 1560 K. Similarly, the interface temperature is 2180 K for $T_{f,m}$ = 2500 K and T_i = 330 K. The other solutions to equation 7B-15 were negative which is physically impossible.

Since this temperature is higher than the value for two semi-infinite solid bodies coming into contact, the dominance of the temperature difference term in equations 7B-4 and 7B-11 should be reverified. The heat generation and temperature difference terms for a interface temperature of 1560 K and channel half-height of 0.5 centimeters are

$$\frac{k_f}{x_c}\left(T_{f,m} - T_s\right) = 8.4 \times 10^5 \ W/m^2$$

$$\dot{q}\frac{x_c}{2} = 3.8 \times 10^3 \ W/m^2.$$

Even though the dominance is not as great as before, the temperature difference term is still significantly greater than the heat generation term and the assumptions made previously are still valid.

D.4.2 Required Channel Length to Insure Freezing

The propagation rate of the freeze front was determined in the previous section. This allowed determination of the time to completely freeze the debris in a channel of specified height. A simple approximation of the channel length required to provide this residence time is the product of the initial molten debris velocity and the freezing time. This approximation would predict shield dimensions considerably larger than actually required. A more realistic channel length can be obtained by considering the reduction in channel flow area as debris freezes. In the remainder of this section, the following parameters will be determined: a) debris velocity at channel entrance ; b) channel area decrease resulting from debris freezing; c) average channel debris velocity; and finally d) the required channel length to insure plug formation at the channel entrance before corium ingression into the sump.

a) Debris Velocity at Channel Entrance

The possibility exists that molten debris will not even enter the channel after it has come into contact with the shield wall. Debris which is spreading across the lower drywell floor will have at least a thin crust formed on its leading edge. If the flow energy of the advancing debris front is not great enough to break this crust and overcome surface tension on the length scale of the channel height, debris will not enter the channel. Unfortunately, the physics of crust formation is not currently understood well enough to support this argument without a great deal of uncertainty.

The entrance velocity will be governed by the height of corium outside of the channel. Assuming that the debris spreads uniformly across the lower drywell floor, the height of debris can be obtained by integrating the volumetric expulsion rate of corium from the vessel divided by the floor area of the lower drywell. A conservative, overprediction of debris depth can be obtained by multiplying the maximum expulsion rate by time and dividing by area. The upper bound of the expulsion rate was shown in section X-2.7.6.2.2 (submitted to the NRC on June 30, 192) to be 6000 kg/sec.

The velocity in the channel without area reduction due to debris freezing can be conservatively overpredicted by ignoring frictional effects. This velocity is

$$v_e(t) = \sqrt{2g\Delta z(t)} \qquad (7B\text{-}17)$$

where v_e is the velocity at the entrance of the channel

g is the gravitational acceleration constant

Δz is the height of debris in the lower drywell .

Expanding debris height yields

$$v_e(t) = \sqrt{\frac{2g\dot{m}_{ves}}{\rho_{cm}A_{ld}}} \qquad (7B\text{-}18)$$

where $\dot{m}_{ves}$ is the maximum ejection rate of corium from a failed vessel

A_{ld} is the floor area of the lower drywell (70 m^2 minimum) .

b) Channel Area Decrease Resulting From Debris Freezing

Since the entrance velocity is assumed to remains constant, the mass flow rate of corium in the channel decreases in time due to the area reduction resulting from debris freezing. A conceptual picture of this area reduction process in shown in Figure 7B-3. Conservation of mass requires that the mass flow rate of corium entering the channel per unit length is constant throughout the channel. The mass flow rate at the entrance of the channel and at the location downstream where the debris front has just arrived is

$$\dot{m}_i(t) = \rho_{cm} v_e(t) H_i(t) = \rho_{cm} v_o(t) H_o \qquad (7B\text{-}19)$$

where $\dot{m}_i$ is the time varying mass flow rate per unit width at the entrance of the channel

H_i is the time varying entrance flow height of the channel

v_o is the time varying velocity at the downstream location in the channel where molten debris has just arrived

H_o is the unobstructed height of the channel .

This equation requires that

$$v_o(t) = \frac{v_e(t)}{H_o} H_i(t) \qquad (7B\text{-}20)$$

The entrance flow height is

$$H_i(t) = H_o - 2x_c(t). \qquad (7B\text{-}21)$$

Inserting the relationship for x_c found in equation 7B-8 into this expression yields

$$H_i(t) = H_o - \sqrt{\frac{8k_f\left(T_{f,m} - T_s\right)t}{\rho_{cm} h_{lh}}} \,. \qquad (7B\text{-}22)$$

The product of this equation and the width of the shield channel describes the reduction of channel inlet flow area with time.

c) Average Channel Debris Velocity

The velocity of the leading edge of molten debris in the channel can be obtained by combining equations 7B-20 and 7B-22. It is

$$v_o(t) = v_e(t)\left(1 - \frac{1}{H_o}\sqrt{\frac{8k_f\left(T_{f,m} - T_s\right)t}{\rho_{cm} h_{lh}}}\right) . \qquad (7B\text{-}23)$$

The average velocity of debris between the entrance of the channel and the leading edge of molten corium is

$$\bar{v}(t) = \frac{\int_0^t t v_o(t)dt}{\int_0^t t dt}. \qquad (7B\text{-}24)$$

Evaluating this integral yields

$$\bar{v}(t) = a_o\sqrt{t} - \frac{a_o b_o}{H_o} t \qquad (7B\text{-}25)$$

where

$$a_o = \frac{4}{5}\sqrt{\frac{2g\dot{m}_{ves}}{\rho_{cm} A_{ld}}}$$

$$b_o = \frac{5}{3}\sqrt{\frac{2k_f\left(T_{f,m} - T_s\right)}{\rho_{cm} h_{lh}}}.$$

This is the average velocity of the molten debris into the shield channel.

d) Required Channel Length to Insure Freezing

The channel length required to ensure a plug forms at the channel entrance before debris spills into the sumps is

$$L_{freeze} = \bar{v}(t_{freeze})t_{freeze}$$

$$= a_o t_{freeze}^{3/2} - \frac{a_o b_o}{H_o} t_{freeze}^2. \qquad (7B\text{-}26)$$

D.5 Long Term Ability of Debris to Remain Solid

Initial debris solidification was considered in section D.4. The requirements for keeping the debris in the channel frozen for an extended period of time (at least 24 hours) will be determined in this section. The height of the upper (above the lower drywell floor) shield wall and depth of the lower (below the lower drywell floor) shield wall will be specified.

D.5.1 Upper Shield Wall (Above Lower Drywell Floor)

The roof of the upper shield wall should be free, or at least nearly so, of debris to provide long term cooling to the debris frozen in the channel. No significant amount of debris will splatter on the roof during ejection from the vessel because the

sump is near the periphery of the lower drywell. To prevent any debris from flowing on top of the shield roof, the shield should be taller than the maximum possible debris pool depth in the lower drywell. This requirement is given by

$$H_{uw} \geq \frac{m_{cm,tot}}{\rho_{cm} A_{ld,min}} \tag{7B-27}$$

where $m_{cm,tot}$ is the total amount of corium ,285 Mg

$A_{ld,min}$ is the minimum floor area of the lower drywell, $79\ m^2$.

Evaluating this expression yields

$$H_{uw} \geq 0.33\ m. \tag{7B-28}$$

In the long term (at least minutes after debris solidification), the lower drywell will be filled with either saturated steam or water. Heat transfer from the shield to the environment is less effective when steam is present. Therefore, only steam will be considered in the remained of this analysis. A shield wall sized to perform its function when steam is present will also perform its function when water fills the lower drywell.

The maximum steam temperature in the lower drywell is that of saturated steam at the ultimate containment pressure (180 psig). The steady state heat flux through the upper shield wall is

$$q''_{uw} = \frac{k_w}{H_{uw}}(T_i - T_o) \tag{7B-29}$$

where q''_{uw} is the steady state heat flux through the upper shield wall

H_{uw} is the height of the upper wall

T_i is the temperature of the upper wall in contact with debris

T_o is the temperature of the upper wall in contact with the lower drywell environment.

Natural convection governs the temperature of the wall in contact with the lower drywell environment. The heat flux from the top of the wall can be written as

$$q''_{uw} = \bar{h}(T_o - T_{ld}) \tag{7B-30}$$

where $\bar{h}$ is the natural convection heat transfer coefficient

T_{ld} is the temperature of the lower drywell environment.

The natural convection heat transfer coefficient depends on the Rayleigh number. The Rayleigh number is