REVIEW OF INFORMATION NEEDS FOR DESIGN
OF A MgO CORE RETENTION DEVICE

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Information Needs for Core Retention Device Design and Analysis

Section V of Offshore Power Systems Topical Report Number 36A59 does a creditable job in identifying areas of uncertainty concerning melt/core retention material interactions. The reviewers were able to identify some additional concerns and had comments on items cited in these documents.

Prior to discussing information needed for design of a core retention device, it is important to realize that inclusion of such a device in a power plant would have an impact on the entire course of a hypothetical meltdown accident. For instance, a core

Major conclusions of the review are as follows:

1) The documents submitted for review together do identify most areas of uncertainty. The most important of these, and the additional areas of uncertainty identified by the reviewers, are felt to be:
    - a) crust formation and upward heat flux from the melt,
    - b) exfoliation of brick layers in the retention device,
    - c) thermalhydraulics of the molten core materials,
    - d) mechanism of melt attack on the refractory material, and
    - e) influence of retention device geometry on local refractory erosion.
2) The design and design analysis of the core retention device submitted by Offshore Power Systems places an unjustifiable reliance on the low temperature experience of the steel industry. Other relevant industrial experience does not appear to have been considered.

retention device would greatly reduce the rate of aerosol generation by gas sparging of material from the melt. Substantial reductions of aerosol generation from non-fuel sources would occur. At the same time a variety of heat removal mechanisms available to the melt while in contact with concrete would not be available to a melt within the core retention device. Aerosol generation by vaporization of fission products from this hotter melt would increase. The net result would be a decrease in aerosol generation <u>and</u> a decrease in the rate of aerosol sedimentation within containment. The aerosols within containment would come primarily from fuel sources rather than non-fuel sources as in the case of melt/concrete interactions.

The reviewers did not attempt to identify collateral impacts on meltdown accidents caused by the inclusion of a core retention device. Such determinations can best be done in conjunction with with accident modeling such as that being performed at Battelle Memorial Institute. Attentions were directed, instead, toward identification of design information necessary to meet other goals of a core retention device, namely retardation of ex-vessel melt movement and gas generation.

A) <u>General Comments from the Reviewers</u>

1) The heavy reliance on steel industry experience is not warranted since the temperature ranges involved in steel manufacture (1350 - 1700°C) are on the low end of the melt temperature range expected during a light-water reactor core meltdown accident (1350 - 2600°C). Temperatures cited in the Offshore

Power System report surprised the reviewers since they seemed quite low. During the first day of a melt/concrete interaction melt temperatures fall rapidly from about 2600°C to about 2000°C. For the next five days melt temperatures smoothly decline over the range from 2000°C to 1700°C.

Many of the heat removal mechanisms available during melt/concrete interactions--such as convective heat transport by gas generation and endothermic decomposition reactions of concrete--are not available during melt interactions with core retention materials. The melt temperatures ought then be at least as great during melt/core retention material interactions as those encountered during melt/concrete interactions.

Melt temperature becomes important because at least a portion of the refractory erosion expected during melt/core retention material interaction is due to chemical reaction. Since the rates of chemical reactions are sensitive and non-linear functions of temperature, it is most hazardous to extrapolate encouraging experience at low temperatures to core meltdown situations.

2) Heat generation in the melt and environs was restricted to fission product decay heat. No consideration was given to heat produced by oxidation of metallic phases

of the core melt. Baukal et al.,* have shown that heat due to oxidation of zirconium and chromium in a core melt can be significant in comparison to fission product decay heat. Generation of this heat might be slower--and consequently more prolonged--during melt/core-retention-material interactions than during melt/concrete interactions since gas transport through the melt would be more limited. However, the oxidizing environment of a light-water reactor accident does assure that this chemical heat source will be available.

3) A significant source of industrial experience was neglected in the Offshore Power System (OPS) report--the glass-making industry. Though again the temperature regimes this industry employs are much lower than the core meltdown temperature regimes, the industry has had to deal extensively with oxide melt/refractory interactions.

4) The reviewers did not feel competent to address questions concerning mechanical damage to a retention device as a result of debris impacting the device. The reviewers felt that industrial experience cited in the OPS report was particularly pertinent and

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*W. Baukal, J. Nixdorf, R. Skoutajan, and H. Winter, "Investigation of the Relevancy and the Feasibility of Measurement of Chemical Reactions During Core Meltdown on the Integral Heat Content of Molten Cores," BMFT-RS-197, Battele Institut., e.v., Frankfurt am Main, F.R. Germany, June 1977, English translation NUREG/TR-0047, October 1978.

realistic to these questions of mechanical damage. At some point more definitive data than the anecdotal accounts in the OPS report should be made available.

5) The reviewers felt that chemical interactions of oxidic melts with refractory bricks were not adequately treated. Little data are available on this point. Data that are known indicate that assumptions of uniform attack and neglect of melt convection may be seriously in error. The reviewers agreed with the OPS report that the nature of the chemical interactions was a major area of uncertainty.

6) Little data are available concerning melt behavior under conditions of interest. Crust formation over the surface of the melt or other phenomena that would impede upward heat flux from the melt were neglected in the OPS report. The reviewers do not share the OPS confidence that more complete understanding of the surface behavior of the melt could only lead to a greater margin of safety for the retention device. Any reduction in upward heat transfer rate from the melt translates into greater erosion rates of the retention device.

7) The OPS retention device has a minimum vertical thickness of 8 feet 3 inches. It has a minimum lateral thickness of 3 feet 8 inches. Since, to a first approximation, erosion rates in the vertical and lateral directions due to thermal attack are

considered equal, it appears that the sidewalls are the weak link in the design. Lateral penetration, rather than vertical penetration, would be the expected failure mode. Prediction of the failure time must then include the effects of both chemical and thermal erosion by the melt <u>and</u> the effects of material strengths at elevated temperatures.

Data provided by OPS indicate that the core retention device would fail laterally in no more than 60 hours even if only 50% of the decay heat were to go into refractory erosion.

B) Areas of Concern Not Considered by OPS

1) Reflooding of the melt by water was not considered by OPS. OPS did cite unspecified emergency actions should a meltdown accident occur. Deliberate reflooding of the melt could be among these. Reflooding has been indicated by accident analyses (P. Cybulskis, Battelle Memorial Institute, Columbus, Ohio) to be a hazardous undertaking. Reflooding, whether deliberate or accidental, has not been experimentally studied and appears to be an important area of uncertainty.

2) As a corollary to 1) OPS did not consider pressure generation produced when melts contact a water-saturated retention device. Since the MgO bricks described in the OPS report are about 17% porous, they could retain as much as 2030 ft^3 of water. The only design feature

to assure that water does not become entrained in the bricks is a 1/4" steel liner of uncertain description. Vaporization of entrained water could be a significant source of containment pressurization. The reviewers are aware of only a single, scoping, transient experiment in which a high temperature melt was streamed onto a water-saturated brick. (D. A. Powers, Meeting with Experts on the Technology of Sacrificial Materials for Delaying core Melt-Through, August 29-30, 1978, Bethesda, MD) This transient test indicated only relatively smooth vaporization of entrained water.

3) The OPS design of the retention device includes tongue-and-groove bonding of refractory bricks to prevent brick floatation. This design will function satisfactorily only if an entire course of bricks remains intact. Should localized attack penetrate a few bricks, the entire course might exfoliate and float to the top of the pool. This uncertainty adds special emphasis to the uncertainty of localized rather than uniform attack on the refractory.

4) Creep of stressed refractory at high temperatures was not addressed in the OPS study though they provided data for refractory creep at low temperatures (~ 1600°C). Creep of high purity MgO is significant at 1300°C and at lower temperatures for materials of lower purity. Creep rates are exponential functions

of temperature and sensitive to composition.* The core melt places surface bricks in the retention device under loads of about 4 psi. Bricks on the bulkhead walls above the retention device are under loads of about 18 psi. At 2000°C these loads are sufficient to produce significant deformation of refractory structures. Should the bricks be contaminated by solid state diffusion of melt materials into the bricks, even greater creep rates may develop.*

5) The OPS report neglects thermal-hydraulics of the melt. The analysis of MgO erosion is conducted by a thermal ablation model assuming uniform attack on the refractory. The reviewers could find no basis for this assumption. Quite the contrary, available data and industrial experience suggest that localized attack is a major mode of refractory erosion. Some photographs of refractories exposed to glass melts are shown in Figure 1.

The most important variables in determining the rate of localized attack appear to be geometry, melt composition, temperature, and *fluid phase* convection. Another uncertainty related to melt hydraulics is whether small perturbations in the refractory

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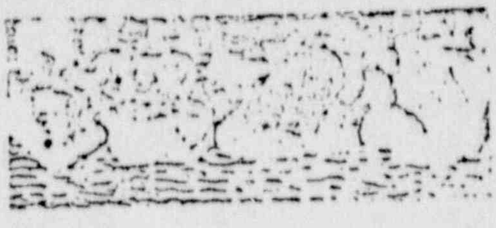
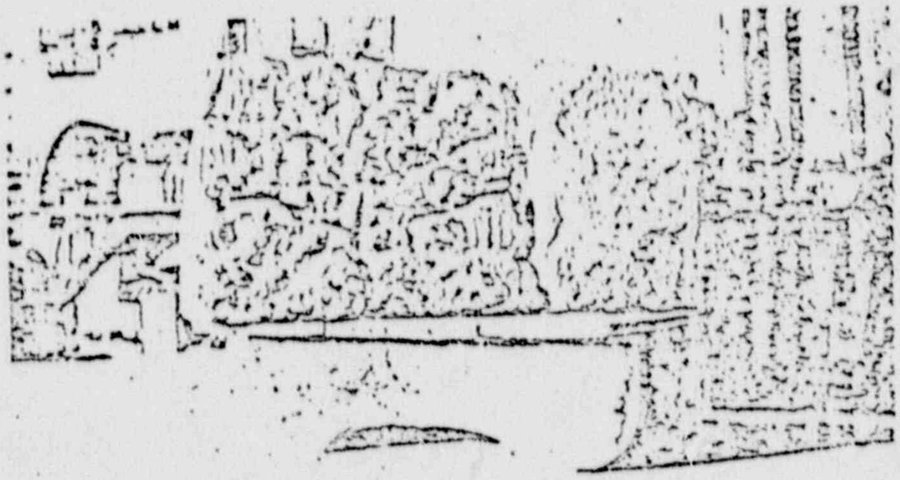
*E. Yasuda and S. Kimura, "High Temperature Creep of Magnesia with Minor Additives," *Proc. Oxydes Refractaires pour Filières Energetiques de Haute Température*, Odeillo, France, June 28--July 1, 1977.

a) Note stepped erosion and enhanced erosion at joints between bricks.



c)

Upward-facing surfaces from which the clay-bearing glass was apparently swept as fast as formed, with the result that active dissolving of the surfaces took place.



b) An Example of Local Attack

These two blocks side by side in service, the face of the right hand block did not crack and showed practically no eating. The face of the left hand block shrunk and cracked badly in use; upward eating started in these defects and practically half the block was dissolved away; side wall blocks, bottle glass tank.

Figure 1a from F. C. Flint and A. R. Payne
J. Amer. Ceram. Soc. 9 613 (1926)

Figure 1b, c from D. W. Ross
J. Amer. Ceram. Soc. 9 641 (1926)

Figure 1. Examples of Chemical Attack on Refractories by Glass Melts

surface grow preferentially or are healed during further attack. Industrial experience suggests that both results are possible.

6) Volumetric expansion of the molten pool is not considered by OPS. Crude calculations by the reviewers indicate that the expansion is not likely to be significant if no additional material falls from the reactor pressure vessel or the bulkhead walls into the molten pool. The effective volume change associated with heating a 17% porous brick from 25°C to melting and assuming a volume change on melting of +5% (exact value is not known) is only +0.6%. However, if steel from the lower head of the pressure vessel is added to the melt, the melt volume would increase by at least 24%. Oxidation of metal phases in the pool or collapse of bulkhead walls would further expand the pool to the point that little safety margin would exist in the core retention device.

C) Areas of Concern OPS Treated as Adequately Understood

1) The model for MgO erosion used by OPS was a simple thermal energy balance using the classical steady state ablation formulation. Heat flux applied to the refractory surface was treated as simple fractions of the fission product decay heat (see I-A-1 above) and were independent of the thermalhydraulics of the melt. The model neglected any chemical component attack on the refractory. The model

consequently assumed that the refractory must be heated to a critical melt temperature before it was eroded. The reviewers could not ascertain the basis for the OPS confidence that this simplified model of refractory erosion was verified.

2) The tongue-and-groove construction used for assembling the core retention materials does appear adequate to prevent brick floatation provided:
   - -- all bricks remain in place and exfoliation of the brick layers cannot occur (see I-B-3 above).
   - -- the tongues do not shear due to thermal or mechanical shock.

3) Thermal shock of refractory bricks is most definitely an area of uncertainty. All tests to date involving prototypic melts deposited on MgO bricks have been of a transient nature. In every case the bricks suffered catastrophic fracture after the melt solidified. Because of the transient nature of the tests, it is not known whether the fracturing was due to surface cooling of the bricks or delayed heating of the brick interior.

4) Upward heat flux from the melt is an area of uncertainty. Crust formation, or spalled refractory floating on the melt surface will depress the melt surface temperatures and consequently the upward heat flux. Heatup of walls and reactor internals above the melt will also depress upward heat flux. Any reduction in

upward heat flux results in more heat being available for ablation of the core retention material.

5) MgO-basaltic concrete interactions were not addressed in the OPS report. These interactions may occur at the bulkhead wall coated with 4" MgO bricks. Once basaltic concrete under this coating reaches 1100°C it will begin to melt and the MgO coating will lose its structural integrity. (See also Section I-B-4.) Molten basaltic concrete will be free to flow into the core melt pool and to attack the core retention material.

D) <u>Areas of Uncertainty Considered by OPS</u>

The reviewers agreed with the listings of uncertainties presented in the OPS report. These areas need not be discussed further here. The reviewers felt, however, that there might be some misunderstanding of oxide chemical attack by liquid oxides--sometimes termed "slag-line" attack or "flux-line" attack. Chemical attack is mass transport dominated erosion of the refractory--as opposed to the heat transport dominated erosion considered in the OPS report. Dissolution as opposed to ablation of the refractory occurs because of favorable free-energy relationships among constituents of the melt/refractory system. The rate of dissolution is given by expressions of the form:

$$\text{rate} = k_o(C,T)\ \exp\ (-E(c)/RT)\ [C-C_S(T)]$$

where T = temperature

C = fluid phase composition

C_S = saturation composition of the fluid

K_o and E = kinetic parameters dependent on temperature and fluid composition

R = universal gas constant

Chemical attack is important because it can occur at low temperatures (even in the solid state) and it can be responsible for non-uniform attack.

The rate of attack is very sensitive to temperature. Because of the non-linear nature of the rate expression, it is difficult to extrapolate data from low temperature experiments to predict high temperature behavior. Further, the above rate expression refers only to the <u>net</u> dissolution of refractory. Erosion of solid refractory can occur even when the net rate is zero, provided precipitation of refractory-containing species from the fluid phase occurs. When these precipitated species are of low density--like MgO--and can be swept out of the system--say by floating to the top of an immiscible phase overlying the attacking fluid--this zero net rate dissolution is quite likely.

Iron oxides frequently arise in discussions of refractory attack since they form low melting species with most refractory oxides. However, chemical attack on refractories is not restricted to iron oxides.

Iron oxides are especially important in discussions of light water reactor accidents since these accidents involve high temperature molten steel in very oxidizing environments. Rates of steel oxidation in these conditions can be quite high unless the steel is covered by a reasonably thick, viscous slag layer. (See also Section I-A-2.)

Photographs of refractories subjected to chemical attack shown in Figure 1 illustrate the non-uniform nature of chemical attack. Certainly one of the uncertainties that must be addressed in core retention device design is whether vertical or horizontal surfaces are more grievously affected by chemical attack.