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# MANAGING WATER ADDITION TO A DEGRADED CORE[a]

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## ABSTRACT

In this paper we present information that can be used in severe accident management by providing an improved understanding of the effects of water addition to a degraded core. This improved understanding is developed using a diagram showing a sequence of core damage states. Whenever possible, a temperature and a time after accident initiation are estimated for each damage state in the sequence diagram. This diagram can be used to anticipate the evolution of events during an accident. Possible responses of plant instruments are described to identify these damage states and the effects of water addition. The rate and amount of water addition needed (a) to remove energy from the core, (b) to stabilize the core or (c) to not adversely affect the damage progression, are estimated. Analysis of the capability to remove energy from large cohesive and particulate debris beds indicates that these beds may not be stabilized in the core region and they may partially relocate to the lower plenum of the reactor vessel.

## 1. INTRODUCTION

Preventing severe accidents or mitigating their consequences requires implementation of strategies to add water to cool the core. However, under certain degraded core conditions, adding water may lead to enhanced hydrogen production, changes in core geometry that complicate recovery, pressurization of the system resulting from steam generation, steam explosion, or recriticality of the reactor core if unborated water is used. Therefore, plans for managing water addition to a degraded core must ensure that undesirable effects of water addition are understood so that: (1) these effects can be minimized and an accident can be terminated at the earliest possible stage, and (2) plant personnel can be better prepared to deal with plant responses that appear contrary to desired outcomes when water is added during a core degradation transient. The approach presented here provides information to enhance this understanding.

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## 2. APPROACH

The approach used here to gain an improved understanding of the effects of water addition to a degraded core revolves around a sequence of core damage states. Simplified descriptions and results of rough estimates of parameters associated with degraded cores are used to illustrate the steps of the approach. These steps are summarized below.

First, a diagram showing a sequence of core damage states is developed for severe accidents. Core states in the sequence where the core would have distinct responses to water addition include: (1) pre-damage heatup of the core, (2) fuel rod ballooning and bursting, (3) rapid oxidation of zircaloy, (4) debris bed formation, and (5) core relocation to the lower plenum. Temperatures and times of occurrence are estimated for the events in the sequence.

Second, evaluations are performed to characterize the responses of plant instruments to degraded core conditions and to adding water to a degraded core. Innovative uses of instruments to diagnose core conditions are also explored. In this paper, discussion of instrument responses will be limited to instruments available in pressurized water reactors.

Third, bounding estimates for energy removal from degraded cores by water addition are given. These estimates yield the minimum rate and amount of water addition to a degraded core that would not adversely affect subsequent evolution of an accident. In addition, the minimum rate and amount of water to successfully remove energy from or stabilize the core are also given. These rates and amounts of water addition are compared with plant capabilities.

Fourth, critical heat removal boundaries are determined for expected geometries of core degradation. The geometries include those of cohesive as well as particulate debris beds. These boundaries indicate that for certain bed parameters, adding water to the core cannot prevent their heatup and, consequently, relocation of molten core materials to the lower plenum of the vessel should be expected.

## 3. SEQUENCE OF CORE DAMAGE STATES

Although the details of core damage progression depend on plant design and specific accident scenarios, severe fuel damage experiments and the TMI-2 accident [1,2] show that unmitigated core damage follows a sequence of broadly defined, distinct core damage states.

Figure 1 shows a conceptual diagram of the sequence of core damage states for a small-break loss-of-coolant accident (LOCA). The damage sequence starts with core uncovery and ends with relocation of molten core materials to the lower plenum of the reactor vessel. The stages of core damage progression corresponds to a temperature scale from approximately 600 K

| Time After Scram (TMI-2) (min) | Temperature (K) | Core State | Effect of Water Addition |
|---|---|---|---|
| 110 | 600 | Core uncovery | Recovery |
| < 135 | < 1100 | Pre-damage heatup | Pressure increase then decrease, temperature decrease, recovery |
| 135 | 1100 | Ballooning and bursting | Pressure increase then decrease, temperature increase then decrease, recovery |
| 145 | 1500 | Rapid oxidation | Pressure increase, hydrogen production, temperature increase then decrease, possible recriticality (unborated water), possible recovery |
| 150 - 210 | > 1700 | Debris bed formation | Pressure increase, hydrogen production, possible recriticality (unborated water), collapse of upper core, possible recovery, possible quiescent response |
| 225 | > 2800 | Relocation to lower plenum | Pressure increase, hydrogen production, possible steam explosion, possible recriticality, particulate bed formation |

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Figure 1. Sequence of core damage states.

(coolant saturation temperature) to over 3100 K (melting point of $UO_2$). The approximate times associated with the damage states in the TMI-2 accident and potential effects of water addition at each stage of core damage progression are also shown in the sequence diagram.

Pre-Damage Stage

In a small-break LOCA with no emergency core coolant injection, core uncovery generally begins approximately an hour after the initiation of the break. If the reactor coolant pumps are not running, the upper part of the core will be exposed to a steam environment and heatup of the core will begin. However, if the coolant pumps are running, the core will be cooled by a two-phase mixture of steam and water, and heatup of the fuel rods will be delayed until almost all of the water in the two-phase mixture is vaporized. The TMI-2 accident showed that operation of reactor coolant pumps may be sustained for up to approximately two hours to deliver a two-phase mixture that can prevent core heatup.

Ballooning and Bursting

In the absence of a two-phase mixture going through the core or of water addition to the core to compensate water boiloff, the fuel rods in a steam environment will heatup at a rate between 0.3 K/s and 1 K/s [3]. In less than half an hour, the peak core temperature would reach 1100 K. At this temperature, the zircaloy cladding of the fuel rods may balloon and burst. This is the first stage of core damage.

Cladding ballooning may block a substantial portion of the flow area of the core and restrict the flow of coolant. However, complete blockage of the core is unlikely because not all fuel rods balloon at the same axial location. In this case, sufficient water addition can cool the core and stop core damage progression.

Rapid Oxidation

The next stage of core damage, beginning at approximately 1500 K, is the rapid oxidation of the zircaloy by steam. In the oxidation process hydrogen is produced and a large amount of heat is released. Above 1500 K, the power from oxidation exceeds that from decay heat [4,5] unless the oxidation rate is limited by the supply of either zircaloy or steam.

If water is added to the core during this stage, steam generation will be rapid because of the high rate of heat transfer from the core materials to the incoming water. In the upper part of the core where the oxidation of zircaloy has been steam-starved before water is added, the addition of water to the core will provide steam for additional oxidation. If the sudden revival of oxidation in the upper part of the core releases energy at a rate that is higher than the rate of heat transfer to the water, the temperature there will escalate. This could happen when the temperature of the rods is high or when the oxide layer on the surface of the cladding is thin; both conditions contribute to high rates of oxidation.

Rapid and sufficient amounts of water addition to the core will quench the core and stop core damage progression. However, if the addition of water is slow or intermittent, or if the core is not completely covered with water, the core will heat up to the next stage of degradation.

Debris Bed Formation

When the temperature in the core reaches about 1700 K, molten control materials [1,6] will flow to and solidify in the space between the lower parts of the fuel rods where the temperature is comparatively low. Above 1700 K, the core temperature may escalate in a few minutes to the melting point of zircaloy (2150 K) due to increased oxidation rate. When the oxidized cladding breaks, the molten zircaloy, along with dissolved $UO_2$ [1,7] would flow downward and freeze in the cooler, lower region of the core. Together with solidified control materials from earlier down-flows, the relocated zircaloy and $UO_2$ would form the lower crust of a developing cohesive debris bed.

If water is added to the core at this stage, steam and hydrogen invariably will be produced. It has been estimated that, in the TMI-2 accident, one-third of the hydrogen generation during the entire accident was produced within a few minutes after a coolant pump delivered water to the core at 174 min into the accident, at which time the peak core temperature is believed to have exceeded 1700 K [8]. As a result, the pressure of the primary system will rise. Because of loss of control materials in the upper part of the core, recriticality may also be a concern if the incoming water contains little or no boron to absorb neutrons.

If sufficient water is added to the core, the top surface of the molten pool will solidify to form a crust and the fuel rod remnants above the pool may be shattered to form a particulate bed, as happened during the TMI-2 coolant pump transient.

If a particulate bed formed in the upper part of the core is relatively deep or composed of relatively small particles, water may be prevented from penetrating the bed. After dryout, cooling of the particulate bed by steam inside the bed is inefficient and the particles comprising the bed will eventually melt. Melting of the particles will add to the growth of the cohesive debris bed.

If the cohesive bed is thin and small in radial extent, water addition may gradually cool the bed and the progression of core damage may be terminated. Water addition to a large cohesive bed will generally have little effect upon its subsequent evolution. The interior of a large cohesive bed will continue to heat up and melt until only a thin crust remains. Failure of the crust, either mechanically or by meltthrough, would lead to the relocation of the enclosed molten core materials to the lower plenum.

Relocation to the Lower Plenum

In scenarios of small-break LOCAs, there is generally a pool of water in the lower plenum of the vessel at the time of core relocation. Release of molten core materials into water always generates large amounts of steam. If the molten stream of core materials breaks up rapidly in water, there is also a possibility of a steam explosion. During relocation, any unoxidized zirconium in the molten material may also be oxidized by steam, and in the process hydrogen is produced. Recriticality also may be a concern if the control materials are left behind in the core and the relocated material breaks up in unborated water in the lower plenum.

In the TMI-2 accident, progression of core damage was terminated with the relocation of approximately 20 metric tons of core material into the lower plenum of the vessel. The material partially broke up to form a particulate bed and was quenched by water in the lower plenum. If the relocated material is much in excess of 20 metric tons, it may not be quenched by water in the lower plenum. The unquenched, relocated core materials may eventually cause failure of the vessel. The possible failure modes of the vessel are not discussed in this paper.

## 4. INSTRUMENTATION SIGNATURES ASSOCIATED WITH WATER ADDITION

The sequence of core damage states provides a framework for understanding the evolution of core damage. However, judicious decision-making during an accident requires exploiting to the maximum extent possible the capabilities of existing plant instruments, possibly including innovative applications beyond their design purposes, to diagnose core conditions that may be evaluated relative to the damage states in the damage sequence. Potential instrumentation signatures, methods for verifying these signatures, and differentiation of outcomes with varying amounts of water addition are discussed in this section.

Pre-Damage Stage

During this stage, the reactor coolant system instruments most useful to operators are the core water level inference system (differential pressure sensors or heated-junction thermocouples), core exit thermocouples, hot leg resistance temperature devices (RTDs), system pressure transducers, source range power monitors, and self-powered neutron detectors (SPNDs).

The water level inference system gives direct measurement of core water inventory. Deviations of the source range monitor signals and the SPND signals from their normal decay curves may be used to substantiate the direct measurement. If water is added to the core during this stage, the operator should see an increase in inferred water level, and an initial drop in system pressure as vapor is condensed by the incoming cold water. System pressure should eventually increase when vapor condensation stops and when the water compresses the vapor volume.

If water is not added at this stage, or is added but is not enough to compensate for the loss through the break, the inferred water level from the differential pressure readings and the source range monitor or SPND signals would continue to decrease. If water is added to the core when the temperature in the upper part of the core has risen sufficiently above the saturation temperature of the water, the temperatures recorded by the core exit thermocouples and the hot leg RTDs may increase as high temperature steam is produced, although the measured temperatures may be somewhat lower than the peak core temperatures due to the mixing of superheated steam and saturated water. In addition to the core exit thermocouples and hot leg RTDs, anomalous currents of SPNDs may indicate heatup of the core. Certain types of SPNDs are known to produce negative currents when their temperature reaches 850 K and then revert to large positive currents at higher temperatures. This initial increase in temperature would be followed by a drop in temperature if the core is recovered.

Ballooning and Bursting

During the cladding ballooning and bursting stage (1100 K), water addition will have a pronounced effect on core exit thermocouple readings. The time-dependent behavior of the interassembly temperature profile may be used as one indicator of the amount of water reaching the core.

If water is added to the core at a rate sufficient to cool the outer parts of the core but not the inner regions, or at a rate that results in an unfavorable flow split due to partial blockage of the core by ballooned rods, readings of thermocouples above regions where cooling is insufficient would stay high, but radial progression in increased thermocouple readings should reverse at some radial position.

If there is sufficient energy exchange between adjacent assemblies during water addition to the core, the whole core will be cooled before the rapid oxidation of zircaloy occurs. All core exit thermocouples should show a pronounced drop in temperature. This temperature drop would indicate that water is cooling the core. Coincident with the drop in temperature, the system pressure should increase (from steam generation), followed by a gradual decrease (from steam condensation) as water fills the core. The SPNDs should also return to normal shutdown readings.

Rapid Oxidation

After reaching this stage, because the temperatures will be outside their operating range, the core exit thermocouples can no longer provide reliable readings. Subsequent diagnosis of core damage states must rely on other instrumentation, such as the pressure monitors and the SPNDs. However, the erratic behavior of the core exit thermocouples may give indication that core damage has progressed beyond the ballooning and bursting stage. Another indication that the core may have reached this stage is the detection of excess radiation in the containment from fission gas released during the cladding bursting stage. It may take five to ten minutes for the released fission gas to migrate from the reactor core to the radiation monitors in the containment. During this time the core may have heated to a temperature that zircaloy can be rapidly oxidized.

If water addition is modest, resulting in the delivery of high quality steam to the upper core for oxidation of initially steam-starved zircaloy that releases energy and hydrogen, a significant, sustained pressure jump would be observed. In general, rapid oxidation of 20% of the cladding will release enough energy to melt the cladding and liquify a substantial amount of fuel. If this happens in the upper half of the core, the total hydrogen production would be approximately 100 kg. If the average temperature of the produced hydrogen is at 1500 K, the hydrogen would pressurize the primary system (volume at 350 $m^3$) by 1.8 MPa (260 psi).

If water is added at a sufficiently high rate, a pressure surge would occur initially after water addition, but, because of only limited energy and hydrogen release before quench, the pressure jump would be lower than in the case with modest water addition and would not be as sustained.

During this stage, control rods (PWRs) or blades (BWRs) are expected to fail, leading to the relocation of liquified control materials. The SPNDs are potentially of use in determining when control materials have slumped to the lower portions of the core. Abnormal readings of the SPNDs could indicate redistribution of control materials, but analysis is needed to distinguish between the effect of movement of control materials and that of water inventory changes. Toward the end of this stage, it would be advisable for the operator to withdraw the movable SPNDs (Westinghouse plants) from the core region to preserve their integrity so they may be used during later stages of degradation.

Debris Bed Formation

If an accident has progressed through the stage where the peak core temperature has exceeded 2000 K, it is likely that a debris bed would have formed in the core from the relocation of liquified materials. This stage may be indicated by the failure of core exit thermocouples, which would show sudden jumps in temperature as new junctions are formed in the core.

During this stage of core degradation, the operator may want to attempt to map the axial location of the debris bed using the movable SPNDs if the pressure conditions and the state of the system would allow. (If the thimbles guiding the SPNDs are breached and their interior is exposed to primary system pressure, the SPNDs cannot be moved toward the core against the system pressure. However, the SPNDs may be inserted along unbreached thimbles or along breached thimbles that are later resealed by relocated core materials.) As the SPNDs are inserted into the core, positions where they encounter resistance may indicate the location of the bottom crust of the debris bed. Once the geometry of the high resistance area has been mapped out by the SPNDs, the SPNDs could be withdrawn from the pressure vessel for later use as a diagnostic tool to provide information on core relocation.

For modest water addition at this stage, superheated steam at temperatures comparable to peak cladding temperatures would reach the uppermost regions of the core, resulting in additional zircaloy oxidation and hydrogen generation. The pressure transducers in the primary system should transmit a sharp rise in pressure under these circumstances. The pressure rise would also be sustained for a relatively long period due to the noncondensible nature of hydrogen.

With a high rate of water addition that allows water to reach the top of the core without being completely vaporized, shattering of the oxidized cladding in the upper regions of the core may cause a particulate debris bed to form on top of an existing cohesive debris bed, as indeed happened in the TMI-2 accident when a reactor coolant pump was restarted at 174 minutes into the accident. Even if sufficient water is added to completely cover the cohesive and particulate debris beds, there is no assurance that the beds will not continue to heat up. Once a cohesive bed has reached a characteristic size, the surface area-to-volume ratio will not permit heat removal at a rate sufficient to arrest continued heatup of the bed. Similarly, a particulate bed consisting of sufficiently fine particles, or of sufficient depth, will prevent water from penetrating its interior. Under such conditions, water addition to the core may result in deceptively little response from the instruments.

<u>Relocation to the Lower Plenum</u>

The relocation of core materials to the lower plenum may be indicated by signals from several instruments. First, the source range monitors, located outside of the vessel, may register a sharp increase in signal from neutrons leaking out of the vessel and scattered by concrete around the vessel. Second, back-flow of steam generated by the relocated hot materials into the cold legs may increase the temperature readings of the cold leg RTDs. Third, system pressure may increase sharply due to rapid steam and, possibly, hydrogen production. Fourth, anomalous currents may appear from the lower levels of fixed SPNDs (B&W plants) not damaged earlier in the accident.

For Westinghouse plants, the amount of relocated core mass may be estimated from responses of the movable SPNDs if this system is still capable of functioning. Assuming that the operator has withdrawn the SPNDs from the reactor vessel following mapping of the cohesive debris bed, he may now be able to move the detectors axially outside the vessel. The ability to move the detectors axially could help identify the size of the relocated mass. If a small amount of mass has relocated, for instance, the attenuation of SPND signals as the detectors are moved further away from the lower head should resemble the attenuation characteristics of a point source. If a large amount of mass has relocated, attenuation of signals from axial withdrawal should resemble the characteristics of a planar source.

## 5. ANALYSIS OF ENERGY REMOVAL FROM DEGRADED CORES BY WATER ADDITION

Another element that is crucial to the understanding of the system response during water addition to degraded cores is an analysis of the amount of water that is needed to remove energy from the core and the minimum rate of water addition that would arrest core degradation and bring the reactor to a safe shutdown condition. Again, the sequence of core damage states is useful as a guide in performing such an analysis. Instead of analyzing specific accident scenarios, the core damage states could be used as reference points in determining the required amount and rate of water addition. Results of simplified analysis are discussed in this section. This involves consideration of energy sources, stored heat of degraded cores as a function of damage state, and geometry of degraded cores.

### Energy Sources

The predominant energy source in a reactor after scram is the decay of radioactive materials. Another important energy source in the core is the oxidation of zircaloy by steam when the core temperature exceeds 1500 K. The energy release rate from oxidation can be considerably higher than the energy release rate from decay heat, because oxidation may take place in only few minutes and the energy release during that time interval is approximately equivalent to the energy generated by decay heat in an hour (at 1% full power). Fission heat from recriticality could also be an energy source. However, it will be assumed that administrative controls will preclude the possibility of adding unborated water to the core, so that recriticality will not be a concern.

In a small-break LOCA with no emergency core coolant injection, the reactor core generally would not be damaged until after an hour after scram. Without much loss in accuracy, the decay heat level during core damage progression could be assumed to be at 1% of full operating power [9]. For full power operations at 3000 $MW_t$, the decay power is enough to vaporize 20 kg/s of water at saturation. Or, in terms of decay heat removal from the core, a 20 kg/s addition of water to the core would remove the decay heat when the temperature of the core is still near or slightly above the saturation temperature of the water. This is within the injection capacity (650 gpm, or approximately 40 kg/s) of one high pressure injection (HPI) pump, assuming that most of the injected water would go through the core. If the full-capacity operation of the HPI fails to stop the core temperature from rising, either the core has progressed beyond the pre-damage stage, or most of the injected water has failed to reach the core.

The energy release from the oxidation of 1 kg of zircaloy is 6.5 MJ. At 1800 K, oxidation of 20% of the original thickness of the cladding starting from an unoxidized state would take 150 s; at 2000 K, 30 s [4,5]. (For 20% oxidation of the cladding, the remaining zircaloy would have melted and liquified substantial amounts of fuel. The parabolic oxidation rates would no longer apply.) If the cladding in the upper half of the core is oxidized uniformly at such rates, the energy release rates from oxidation are approximately 100 MW and 500 MW, respectively. At such high powers, the minimum rates of water addition that would result in having not all the water vaporized would be approximately 70 kg/s and 350 kg/s, respectively, assuming that heat transfer to the water is limited to vaporizing the water at saturation. These rates of water addition are close to, or higher than the capacity of the high pressure injection pumps (two pumps at 650 gpm each, or a total of approximately 80 kg/s). Although these water addition rates to remove energy from oxidation are conservative estimates (it has been assumed that water addition will not diminish the oxidation rate), it may be advisable to consider starting the reactor coolant pumps to deliver additional water to the core from the cold legs, or to depressurize the system to allow accumulator discharge, or low pressure injection.

## Stored Heat

The amount of stored heat depends on the core damage states. The stored heat of a core at different stages of degradation, as characterized by a temperature scale, is shown in Table 1. The amount of stored heat is defined to be zero at 600 K, and the temperature in the core is assumed to be uniform. Changes in specific heats due to changes in core composition (zirconium to zirconium dioxide) and heats of fusion are included in the calculation of the stored heat.

Table 1. Stored heat of a degraded core as a function of core temperature

| Temperature (K) | 600 | 1200 | 1700 | 2400 | 2800 | 3000 |
|---|---|---|---|---|---|---|
| Stored heat (GJ) | 0 | 24 | 53 | 99 | 149 | 161 |

If the core dries out at the end of the first hour after scram, adiabatic heatup of the core from decay heat alone will drive its temperature to approximately 2800 K at the end of the second hour. At temperatures above 1500 K, oxidation of the zircaloy cladding will also add to the stored heat in the core. Incidentally, the amount of heat stored in a core at 2800 K is equivalent to the energy release from the complete oxidation of the zircaloy in the core.

The required rate of water addition to remove stored energy in the core depends on the desired rate of energy removal. Assuming that the top half of the core is at 2800 K and the bottom half at the saturation temperature of the water, the stored energy in the core is approximately 75 GJ. (See Table 1.) This amount of energy is sufficient to vaporize 50,000 kg of water at saturation. If the stored energy is to be removed in an hour, the required rate of water addition to the core is, on the average, approximately 14 kg/s, plus the 20 kg/s that is required to remove the continuing decay heat. (It may be assumed that most of the zircaloy is oxidized, or is alloyed with the fuel, and hence unavailable for rapid oxidation, after the core temperature has reached 2800 K for some time.) Of course, the actual rate of energy transfer from the core materials to the water depends on the temperature and the geometry of the core, and any entrainment of water droplets in the steam produced.

The Effect of Geometry

As discussed in Section 3, several major changes in core geometry occur during core degradation. The core geometry first changes when the cladding of fuel rods balloons at a temperature of approximately 1100 K. The flow resistance in the blocked region of the core will be larger than that in the unblocked region of the core. Consequently, in order to prevent the blocked region from continual heatup, the total rate of flow of water through the core must be above the rate that would prevent core heatup when the rods have not ballooned. Detailed calculations are planned to determine this required enhanced flow. The results of such calculations may also be used as a guide in evaluating core exit thermocouple responses as functions of their radial positions as water is added to the core during the ballooning stage.

A second major change in core geometry is the formation of a cohesive debris bed from the solidification of relocated materials. Because water is prevented from penetrating a cohesive bed, heat is conducted from the interior of the debris bed to its surface if it remains solid, or is convected to its surface if its interior re-melts. Heat loss by a cohesive debris bed occurs only on its surface. Such a mode of heat transfer considerably limits the energy removal rate from the interior of the bed even if the debris bed is immersed in water.

A third major change in core geometry is the formation of a particulate debris bed. A particulate debris bed may form in the core from the collapse of rod remnants in the upper part of the core, often as a result of water addition to the core. A particulate debris bed may also form in the lower plenum of the vessel when molten material in the core drops into a pool of water in the lower plenum. The coolability of a particulate debris bed depends on the ability of water to penetrate the bed. The heat transfer characteristics of cohesive and particulate beds are discussed below in further detail.

## 6. DEBRIS BED CHARACTERISTICS

When core damage has progressed to the stage of the formation of cohesive and particulate debris beds, because the heat transfer rate from the hot debris to water may be quite limited, the rate of water addition to the core may be less important than the total amount of water added to and retained in the core. The following sections describe the results of some analyses that define critical limits of heat removal for both cohesive and particulate debris beds. These limits indicate that, during a severe core damage accident, for certain parameters of the debris beds, the interior of the beds will continue to heat up regardless of water addition. Such heatups may eventually lead to failure of the beds and result in the relocation of core materials to the lower plenum of the vessel.

### Energy Removal from Cohesive Debris Beds

Critical heat removal limits (or stability limits) for cohesive debris beds are defined in this study by the thickness of the crusts around the beds. It will be assumed that crusts having thicknesses less than the critical thicknesses are unstable and will fail open to allow the enclosed molten materials to relocate. Steady-state conditions are assumed in the calculations. At the limit, the material enclosed by the crust is assumed to be molten and to comprise 3/4 of the mass of the cohesive debris bed. (In TMI-2, molten interior of the cohesive bed comprised of over 90% of the mass of the bed.) If the decay heat generated exceeds that conducted through the crust, the excess heat will melt part of the crust so that the crust will become thinner and will be assumed to fail.

The critical heat removal limits for cohesive debris beds in Figure 2 are defined by the radii and the thermal conductivities of the debris beds. Two limit curves are shown in the figure, one labeled by a power density of 3.0 $MW/m^3$, which is a typical power density for a bed formed approximately two hours after scram, and another labeled by a power density of 1.5 $MW/m^3$, which is a typical power density for a bed formed approximately 8 hours after scram. These curves delineate the stability limits of cohesive beds having those power densities. For example, if a cohesive bed having a power density of 1.5 $MW/m^3$ is positioned by its radius and thermal conductivity in the figure to the right of the curve characterized by the power density of 1.5 $MW/m^3$, it is unstable; if it is positioned to the left, it is stable.

By probing the core with the movable SPNDs as discussed in Section 4, the operator may be able to estimate the size of a cohesive debris bed. The thermal conductivity of the bed depends on the core oxidation history, but, in general, it falls between the limits of 4 W/m-K and 8 W/m-K. If the core is heavily oxidized, the conductivity will be closer to the lower limit than to the upper limit; if the core is lightly oxidized, the situation is reversed. When a size and a thermal conductivity are assigned to a debris bed, the position of the cohesive debris bed in the stability

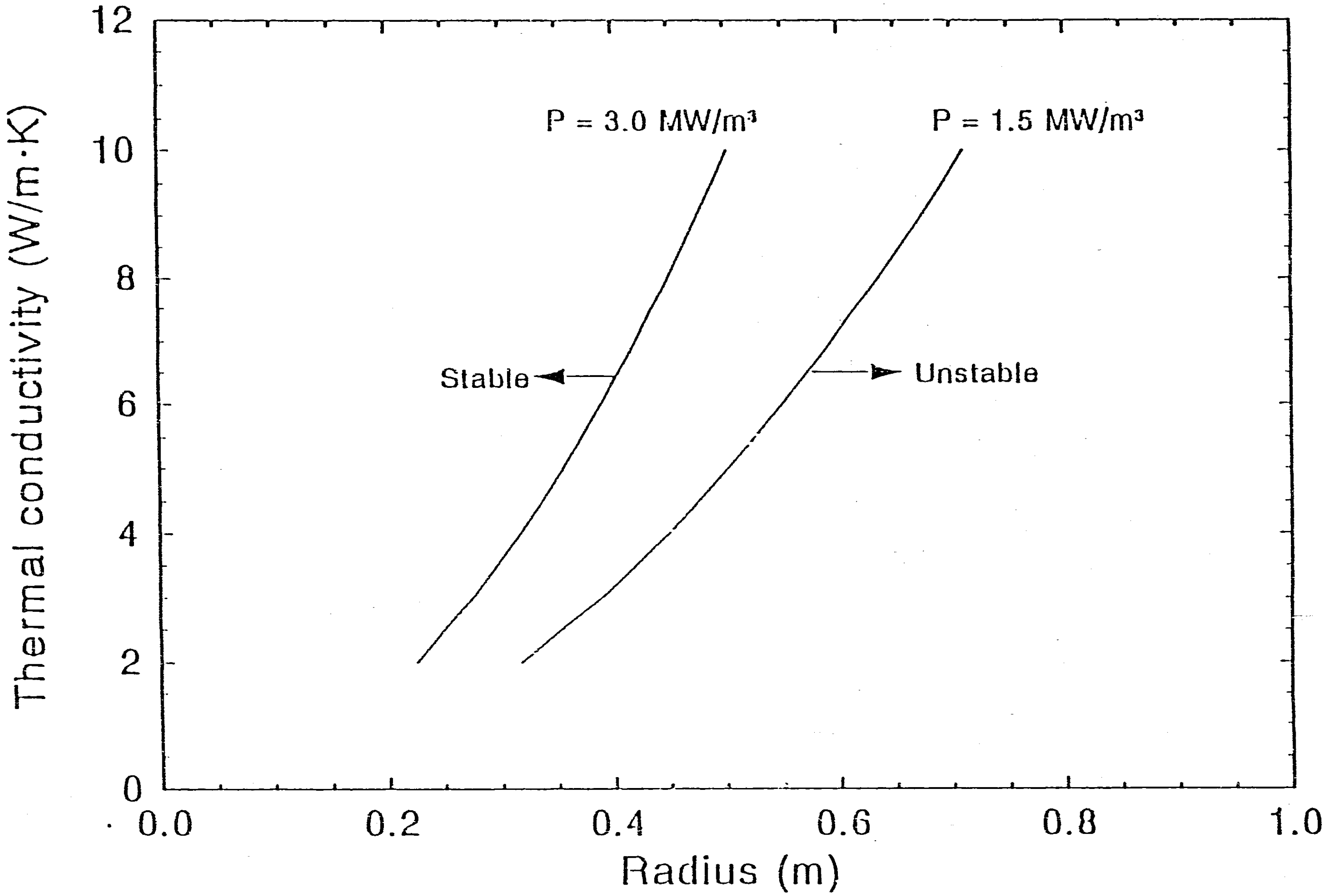


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Figure 2. Power density (P) contours separating stable region from unstable region for spherical cohesive debris beds.

diagram is determined. By examining the position of the cohesive debris bed in the stability diagram in relation to the stability limit contour characterized by its power density (related to time after scram), the stability of the cohesive debris bed may be inferred.

Energy Removal from Particulate Debris Beds

The heat removal rate from a homogeneous particulate debris bed on top of an impermeable plate (e.g., the top crust of a cohesive debris bed) is determined by its porosity, the size of the particles comprising the bed, and the power density in the bed. The Lipinski model [10] is used to calculate the dryout heat flux for particulate beds in one dimension along the vertical direction. Figure 3 shows the dryout limits of particulate debris beds characterized by porosity and particle size at a system pressure of 6.9 MPa. The energy removal diagram for particulate beds is divided into regions of dryout and regions where energy can be removed from the interior of the debris bed by curves labeled by the dryout heat flux.

In the energy removal diagram for particulate debris beds, the dryout heat flux associated with each contour of dryout corresponds to the potential heat flux that can emerge from a particulate debris bed immersed in water. The heat flux could come from several sources. One source is the heat stored in the particles at elevated temperatures. Another source is the decay heat being generated in the debris bed. A third source is the heat liberated from the oxidation of zirconium in the bed when water penetrates the bed. During an accident, the size and characteristics of a particulate debris bed formed in the reactor core cannot be ascertained with existing instruments. However, if a particulate debris bed exists in the core and the interior of the bed can be cooled, steam will be generated when the water added to the core quenches the bed. There will also be a temporary increase in system pressure during the early stage of water addition when there is not yet enough water to condense the steam coming out of the particulate debris bed. If water is prevented from entering the bed, water added to the core cannot quench the bed and there will not be much of an increase in pressure because there will be little steam production.

## 7. SUMMARY AND CONCLUSION

The unmitigated core damage sequence presented in this study consists of: (1) Ballooning and rupture of fuel rod cladding, (2) rapid oxidation of zircaloy by steam, (3) formation of debris beds in the core, and (4) the relocation of core materials to the lower plenum of the reactor vessel. The above sequence of core damage is essentially a temperature sequence, ranging from ballooning of the fuel rod cladding at approximately 1100 K to melting of the $UO_2$ fuel at 3100 K. This sequence of core damage has been used as a guide in discussing the effects of water addition to degraded cores.

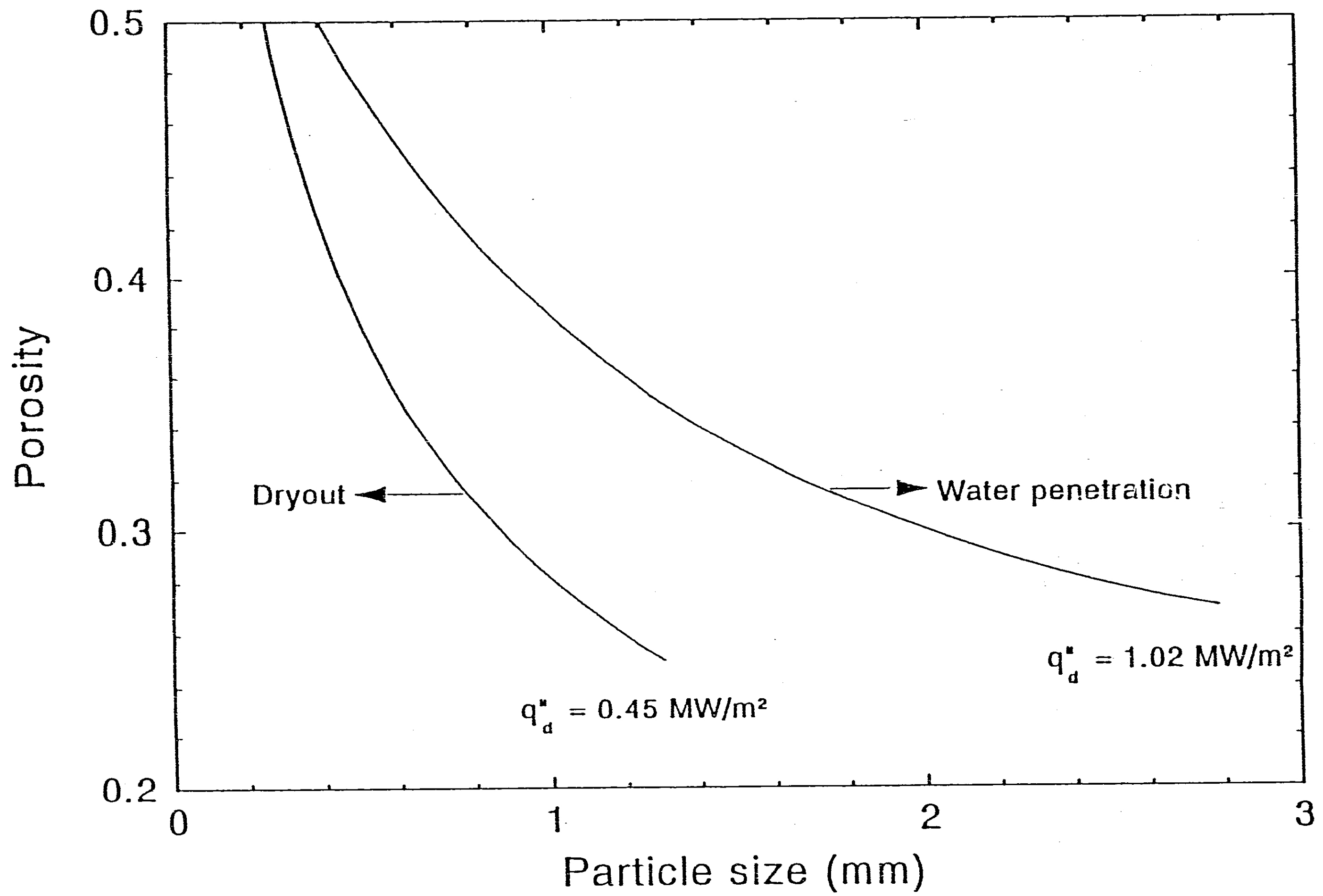


Figure 3. Dryout heat flux contours ($q_d''$) delineating dryout boundaries in the particle size-porosity plane for a one-dimensional particulate debris bed.

At the ballooning stage, core recovery can be assured if enough water is added, and this can be ascertained by a decrease to saturation temperature indicated by the core exit thermocouples.

If enough water is added to the core during the rapid oxidation stage, the subsequent recovery of the core, although also almost assured, will be accompanied by additional hydrogen production. Because temperature measurements would have become unreliable at this stage, confirmation of recovery of the core has to rely on measurements of system pressure and responses of the SPNDs .

Movement of significant amounts of core materials first occur when control rods, or blades, fail. Care must then be exercised that no unborated water is added to the core after the relocation of the control materials lest a re-criticality of the core occur.

If a cohesive debris bed is formed in the vessel from the relocation of core materials, complete energy removal from the interior of the bed cannot be assured even if unlimited amounts of water is added to the vessel. The energy removal from a cohesive debris bed depends on its size, the power density in the bed, and the thermal conductivity of the materials comprising the bed. During an accident, only the size the debris bed may be obtained by probing the core with the use of the movable SPNDs if these instruments are still functioning; information on the other parameters will have to rely on estimates based on accident scenarios. If remnants of fuel rods and unoxidized zircaloy remain above the cohesive bed, flooding the core will lead to rapid generation of steam and hydrogen, and also collapse of the materials to form a particulate bed.

The interpretation of the response of system pressure to water addition after the formation of a cohesive debris bed could be quite counterintuitive. Core materials may be partitioned into a cohesive bed, a particulate bed, and parts that are more permeable to water than the debris beds (intact and partially damaged assemblies). The larger the cohesive and particulate beds, the smaller would be the amount of materials that are more permeable to water. If water addition to the core produces rapid pressure rises, it is more likely the cohesive and the particulate beds are small and energy removal from their interiors can be accomplished. If there is hardly any appreciable rise in system pressure when water is added to the core, the debris beds are more likely to be large and energy removal from them will be minimal. The particulate bed may continue to heat up and melt and the crust of the cohesive debris bed may be thinned to a point that it may fail open to allow the enclosed molten materials to relocate.

Although a broad outline of core damage progression and possible instrumentation signatures at each stage of core degradation have been presented in this paper, much needs to be done to better understand the possible system responses when water is added to degraded cores. First, the effects of water addition at each stage of core degradation must be better quantified as functions of the amount of water added to the core than what has been presented here. These include the temperature distributions at the exit of the core during the rod ballooning stage, the pressure responses during later stages, and SPND responses when core geometry changes. Second, for various accident scenarios, the stages of core degradation should be tied to times after core uncovery. As mentioned in Section 3, core damage could begin in less than an hour after core uncovery when emergency core cooling is unavailable. Oxidation of the zircaloy in the core can rapidly increase the core temperature to over 2000 K in a few minutes. After the rapid oxidation of zircaloy, there is a time interval of tens of minutes to an hour when the core geometry slowly changes from a rod-like geometry to one of cohesive and particulate beds. These estimates of the time intervals need to be refined by code calculations that include heat transfer between the core materials and the coolant in the core. Finally, the consequences of relocation of molten materials to the lower plenum must be considered.

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