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TRANSITION PHASE ISSUES

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Hanford Engineering Development Laboratory

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TRANSITION PHASE ISSUES

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ABSTRACT

The safety issues associated with the transition (core disruption) phase of hypothetical LMFBR accidents are identified and discussed. This discussion is intended to serve as a basis for defining future experimental needs to support core disruption analysis, and for defining analytical code developments required to support the licensing process and experimental analysis.

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TRANSITION PHASE ISSUES

I. INTRODUCTION

The transition phase of an accident involves a grossly disrupted core where substantial motion of molten fuel and cladding has occurred. The transition from the intact geometry of the initiating phase and the grossly disrupted state of the transition phase is sometimes called the transition-to-transition phase. The issues discussed in this document are intended to be those associated with the transition phase. However, some issues discussed here may actually be associated with the transition-to-transition phase or the later stages of the initiating phase depending on the different interpretations of the accident sequence.

It should be recognized that the current understanding of the transition phase is primative compared to the initiating phase, and this understanding is changing rapidly as new information becomes available. Therefore, the transition phase issues discussed in this section represent only a preliminary assessment.

Unlike the initiating phase of the accident, where the issues can be related to specific experimental data needs to verify analytical models, the development of analytical models to mechanistically calculate the accident sequence in the transition phase is still in its infancy. Although some specific data needs can be identified, the more important role of experimenters will be to guide the direction of modeling by characterizing the dominant physics for a wide range of possible alternative conditions. It is more important to obtain reasonable representations of these dominant processes now, and to develop more rigorous mathematical models later on as the increased level of understanding permits.

II. PERMANENT FUEL REMOVAL

As the transition phase accident sequence proceeds, axial dispersals of fuel induced by fission gas or steel vapor pressure may be extensive enough to lead to a permanently subcritical configuration. If this subcritical configuration is also coolable, then the accident is terminated. Therefore, a very high priority should be placed on assessing the probability of permanent fuel removal during the early stages of the transition phase.

A. INTRA-SUBASSEMBLY FUEL BLOWDOWN

The most likely path for early permanent fuel removal is through the normal coolant flow path within the subassembly. The ability of molten core materials to penetrate through the above-core fuel pin structure is a key issue which has been extensively investigated both analytically and experimentally. However, good agreement between the analytical models and the experimental data has not been obtained, leading to the conclusion that the mechanisms of freezing and plugging are not yet fully understood.

B. FUEL BLOWDOWN THROUGH OTHER EXISTING OPEN PATHS

As the growing core disruption melts the subassembly duct walls, other paths for permanent fuel removal become available. Two such paths which have been identified are the space between subassembly ducts and control rod subassemblies. The likelihood of fuel penetration between subassembly ducts may be dependent on the particular core design, but the possibility of fuel draining out through control rod subassemblies should be valid for any core design. The potential for achieving a permanently subcritical configuration by fuel removal through these paths should be evaluated.

III. BLOCKAGE CHARACTERISTICS OF FUEL/STEEL MIXTURES

If sufficient fuel removal leading to a permanently subcritical and coolable configuration cannot be achieved, the accident will progress further into the transition phase. At this point, the course of the accident is critically dependent on the nature of the steel or fuel/steel blockages at the top and bottom of the core.

A. COMPLETE VERSUS POROUS BLOCKAGES

The characteristics of the blockages (e.g., location, composition, thickness, porosity) will determine whether the core is completely closed ("bottled") or whether molten and vaporized core materials can escape. The behavior of open and bottled pools are quite different and the correct situation which prevails will have to be established.

B. EFFECT OF ONGOING PENETRATION AND REMOVAL OF CORE MATERIALS

Even if the blockages are not complete, the continual removal of molten and vaporized core materials can eventually seal the remaining flow paths. If these flow paths do not seal, continual removal of the core materials will eventually lead to a permanent subcritical configuration. Then, after the determination of coolability of the subcritical configuration, the accident is terminated.

C. EFFECT OF THERMAL ATTACK ON BLOCKAGES

Even if the blockages are complete initially, continual heat transfer from molten and vaporized core materials can melt the blockages and open up flow paths. The blockage characteristics (e.g., composition, thickness, nuclear heating, etc.) will have a strong effect on whether the blockages are susceptible to thermal attack.

D. EFFECT OF SODIUM PENETRATION

If the blockages are not complete, it might be possible for sodium liquid to leak into the core and interact with molten core materials. This thermal interaction may generate sufficiently high pressures to cause permanent core dispersal.

IV. POOL BEHAVIOR

If early permanent fuel removal and continual fuel removal through incomplete blockages do not terminate the accident, the continuing core disruption eventually results in a pool of molten and vaporized core materials. Initially the pools are contained with their individual subassembly ducts and the motions are very incoherent. As the subassembly ducts melt, coherent core-wide movements become possible. For convenience, the technical issues associated with pool behavior have been arbitrarily subdivided into concerns about pool dispersal, pool collapse, and coherent pool motion.

A. POOL DISPERSAL

Unless most of the original fuel inventory has been removed from the core, it is possible that the remaining fuel might re-configure into critical mass and result in a neutronic power burst. However, recriticality can be prevented if the fuel does not form molten pools but becomes dispersed into a two-phase mixture of fuel and steel.

1. Flow Regimes

The most important effect of the flow regime on boiling pool behavior is the relationship between the void fraction and the relative velocity (slip flow) between the vapor and liquid. Two other effects of flow regimes which will be treated separately later are the pool dynamics and the heat losses to the structure. The void fraction of the flow regime determines the average "boilup" of the two-phase system from which the evaluation of criticality is made. Flow regimes which exhibit higher slip flow velocities are less capable of entraining the liquid and can be considered less dispersive. For a boiling pool, it is important to determine what the realistic flow regimes are and the boilup associated with each flow regime.

2. Pool Dynamics and Stability

Not only is it important to determine whether the average boilup condition is subcritical, but density oscillations associated with dynamic pool behavior need to be assessed to determine the magnitude of reactivity fluctuations.

B. POOL COLLAPSE

For a boiling pool which is dispersed in a subcritical configuration, various mechanisms have been postulated for collapsing the pool and leading to a recriticality.

1. Heat Losses

The nuclear heat generation of the fuel provides the necessary energy to vaporize the steel and give pool dispersal. However, if heat losses to the structure are too high, not enough energy for steel vaporization will be available for pool dispersal.

2. Fuel Crust Stability

It has been postulated that molten oxide fuel in contact with the steel structure would form a protective fuel crust. The low thermal conductivity of the fuel crust and the small temperature difference between the fuel melting point and the steel boiling point would then limit the heat losses to the structure. If a protective fuel crust is not formed, the temperature driving force for heat losses would be considerably higher: the difference between the melting point of the structure and the steel boiling point. Therefore, it is important to determine whether the protective fuel crust on the structure will be stable.

3. Vapor Condensation Limits

Although it is desirable that heat losses to the structure surrounding the pool be minimized to provide more energy to vaporize the steel, a heat sink above the pool is necessary to condense the steel vapor. If the vapor condensation is limited (e.g., by non-condensible gases), then the pool will pressurize to a higher temperature level with resulting higher heat losses.

4. Pressure Equilibration in Pools

If the vapor condensation goes to zero, the pressures and temperatures equalize and the two-phase pool collapses.

5. Duct Melt-In

It has been postulated that the rate of subassembly duct melting can be high enough that the mixing of newly-melted material into the pool can quench the pool. Also, addition of in-core blanket material can dilute the fuel. Such concerns arose from scoping calculations, and this mechanism for pool collapse should be evaluated by integration into a consistent mechanistic model.

6. Boundary-Induced Pool Stratification

There appears to be a tendency for cold core materials to collect on the outer radial periphery of the core due to heat losses to the structure, condensation, and power-induced gradients. This material drains down the outer periphery in a boundary layer losing energy to the structure in the process. This refluxing liquid flow eventually reenters the pool below the bottom of the boiling region. Thus, boiling penetration to the bottom of the pool is prevented. Depending on the thickness of the all-liquid layer at the bottom of the pool, the probability of a critical configuration needs to be evaluated.

7. Fuel-Steel Separation

The lighter steel will exhibit a tendency to rise above the heavier fuel, thus leaving the source of energy for steel vaporization and losing the ability to entrain the fuel. Although the dynamic pool behavior will insure some penetration and mixing of the steel into the heat-generating fuel region, the degree of fuel-steel separation and its effect on the potential for pool collapse needs to be evaluated.

8. Effects of Matrix Fission Product Gas

During the growing core disruption, it is possible that fission gases could become entrapped in the core region, particularly in the case of a bottled pool. These fission gases can limit the boilup of the two-phase pool by providing a volume which has to be compressed and also by limiting vapor condensation at the upper surfaces. The probability of having to consider fission gases needs to be evaluated.

9. Loss of Volatile Precursors

Part of the heat generation in the fuel results from decay products which are volatile. Separation of the volatile precursors might substantially reduce the heat generation rate and the potential for boilup. The magnitude of this reduction should be evaluated.

C. COHERENT FUEL MOTION

During the time that a two-phase pool exists, it is possible for coherent pool motions to cause a recriticality. Several mechanisms for coherent pool motion have been identified.

1. MFCI Pressure-Driven Recompaction

When the upper blockages fail, molten and vaporized core materials can be expelled upward through the above-core fuel pin structure and contact liquid sodium. If an energetic MFCI occurs, the pressurization may be sufficient to reverse the motion of the expelled core materials and drive it back into the core. Such a core recompaction could lead to a severe recriticality. For oxide fuel, such concerns have been alleviated by theoretical models which show that a large-scale energetic MFCI is not possible and by upper plenum injection experiments using thermite reaction products. For carbide fuel, the same models indicate that an energetic MFCI is theoretically possible.

Further analytical and experimental studies should be performed to determine whether an energetic MFCI is possible under the expected accident conditions. Alternatively, analytical studies can be performed to show that mitigating factors will reduce the consequences even if an energetic MFCI occurs.

2. Build Up of Sloshing Fuel Motion

The sloshing behavior of two-dimensional pools has been investigated analytically. Although the calculated behavior is generally dispersive, oscillatory-type motions eventually result in neutronic power bursts. Unfortunately, the results are highly dependent on the imaginative conditions which are postulated. These types of analyses should be continued to identify the various sloshing modes and to determine how more realistic conditions would act to mitigate or prevent the consequences of these sloshing modes.

3. Sudden Failure of Intra-Pool Structural Barriers

The individual subassembly ducts restrict coherent radial fuel motion during the initial stages of the boiling pool development. As these ducts melt through, their failure can cause sudden core-wide movements with possibly severe recriticality consequences. Such situations should be considered in the course of parametric analytical studies.

4. Sudden Vaporization

The penetration and vaporization of liquid sodium, or the theoretical possibility of superheating the steel before vaporizing, could cause sudden core-wide movements with possibly severe reactivity consequences.

V. FINAL TERMINATION

If early permanent fuel removal does not terminate the accident, and if severe recriticalities from pool collapse or coherent fuel motions do not cause an energetic disassembly, the accident will probably end benignly by gradual melting of the blockages and eventual dispersal of core material. With all of the possible modes of transition phase behavior considered up to this point, it is difficult to envisage the conditions under which the accident will be finally terminated.

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