CRBRP STRUCTURAL AND THERMAL MARGIN
BEYOND THE DESIGN BASE

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ABSTRACT

Although Hypothetical Core Disruptive Accidents (HCDAs) are not Design Basis Accidents for the Clinch River Breeder Reactor Plant, extensive assessments of HCDA consequences have been made. Prudent margins beyond the design base have been included in the design to further reduce the risk to the public from highly improbable occurrences. These margins include Structural Margin Beyond the Design Base to address the energetics aspects and Thermal Margin Beyond the Design Base to address the longer term thermal and radiological consequences. The assessments that led to the specification of these margins are described, along with the experimental support for those assessments.

INTRODUCTION

In the design of the Clinch River Breeder Reactor Plant (CRBRP), Hypothetical Core Disruptive Accidents (HCDAs) are not Design Basis Accidents since the postulated initiators of HCDAs have been identified and the design features necessary to prevent their initiation have been incorporated into the design. Even though this position has been accepted by the Nuclear Regulatory Commission (NRC), extensive assessments of HCDA consequences have been made. These assessments indicate that the likely consequence of an HCDA would be a non-energetic partial to whole core meltdown.

To further reduce the risk to the public from highly improbable occurrences, prudent margins beyond the design base have been incorporated into the design. These margins are in two categories:

Structural Margin Beyond the Design Base (SMBDB)
Thermal Margin Beyond the Design Base (TMBDB)

The SMBDB considers the energetics aspects of HCDAs and assures that the reactor coolant boundary would accommodate the short term consequences of an HCDA. The TMBDB considers the longer term thermal aspects of HCDAs and assures that the plant containment would appropriately mitigate the radiological consequences. These areas are discussed in this paper.

STRUCTURAL MARGIN BEYOND THE DESIGN BASE (SMBDB)

A comprehensive search for potential HCDA initiators was made and those potential initiators were categorized in terms of whether they would produce overpower or undercooling conditions. Appropriate initiators were selected in each category for detailed evaluation to determine their potential for resulting in an HCDA. This process led to the identification of two initiators that can be used to evaluate HCDA consequences. These initiators are:

1. Unprotected loss-of-flow, i.e., a coastdown of all three primary loop flows with an assumed failure of both reactor shutdown systems.

2. Unprotected transient-overpower, i.e., a reactivity insertion due to a control rod withdrawal with an assumed failure of both reactor shutdown systems.

The failure sequences associated with these initiators have been evaluated using the current understanding of data and technology important to HCDA evaluations[1,2]. Analyses of the core response have been made assuming significant variations of both data and phenomenology (including combined overpower and undercooling events) to determine the sensitivity of the event sequence to these variations. The potential for energetics[3] resulting from an HCDA has been assessed. The following conclusions were reached:

(a) The best estimate of the progression of an HCDA is a non-energetic termination with partial to whole core involvement (i.e., melting),

(b) Significant deviations in data or phenomenology from current analytical models and experimental data must be invoked to lead to energetic termination of the HCDA progression, and

(c) The Structural Margin Beyond the Design Base capabilities provided in the CRBRP would accommodate the loadings for a large fraction of HCDA progression paths that involve even extreme variations of data and phenomenology.

Although the best estimate prediction of Hypothetical Core Disruptive Accidents results in negligible energetics, margin requirements have been specified to accommodate substantial energetics that encompass a wide spectrum of more pessimistic assumptions of data and phenomenology. These requirements are based on the assumption of an HCDA which would result in the expansion of a high pressure fuel vapor bubble in the core. This bubble has an initial average temperature of 4800°K and, if expanded to one atmosphere, would produce an energy of 661 MJ. The equation-of-state defining the characteristics of the bubble is a pressure-volume relationship and was used as the source in the hydrodynamic/structural two-dimensional analysis using the REXCO-HEP computer program[4] to assess the reactor system dynamic structural response. Figure 1 provides an example of the load transient, showing the force under the reactor vessel closure head. The large increase in load at approximately 70 milliseconds is a result of the impact of sodium with the closure head.

Using the predicted pressures at the vessel nozzle locations as boundary conditions (e.g., Figure 2) the resulting transients in the systems connected to the reactor vessel were determined. A typical pressure transient in the intermediate heat exchanger is shown in Figure 3. The results of these calculations were used to define the Structural Margin Beyond the Design Base (SMBDB) requirements. Other SMBDB requirements were derived from geometry considerations (i.e., the need for minimum clearances) and leakage considerations (on the reactor closure head and pump seals).

The dynamic loads, such as those in Figures 1 through 3 are required to be accommodated by the reactor coolant boundary components without failure. Stress and strain limits have been developed and are applied to judge the acceptability of the structural analysis results.

Because of the complex nature of the reactor structural response to HCDA loads, particularly in the vessel head region, several scale model experiments have been performed[5]. These have been used to obtain fundamental data to gain an understanding of the vessel head dynamic response, particularly in the area around the head margin-rings, (which couple the three head plugs during the HCDA loading) and directly verify that the reactor structures have adequate margin against structural failure. Five 1/20th scale models have been tested. The first test (SM-1) was a hydrostatic test of the CRBRP reactor vessel head. The subsequent tests (SM-2 through SM-5) were sequenced with increasing complexity and were dynamic tests.

The tests confirmed the conservatism of the methods used to specify the SMBDB loads. In addition, they have resulted in an improved understanding of both the vessel head and reactor system response to these loads. Test SM-1 showed that the most likely head failure mode is neither through local distortion at the margin-ring juncture nor margin-ring rollout. (These were considered possible failure mechanisms prior to the test.) The failure mode was identified as margin-ring disengagement due to doming of the large rotating plug. However, the disengagement was found to occur at very high static pressure ($\sim$1160 psi) that produced deflections much greater than those predicted during HCDA dynamic conditions. From the SM-2 and SM-3 tests, the magnitude and profile of vessel and core barrel deformations and the effect of the Upper Internals Structure on these deformations were obtained. Tests SM-4 and SM-5, the most prototypic of the tests, further confirm that the reactor vessel and the three plug head designs had significant margin against failure with respect to the SMBDB loads. The inclusion of the Upper Internals Structure and the reactor vessel thermal liner significantly reduced the peak strains in the reactor vessel wall. Figure 4 provides an example of the reactor vessel and core barrel deformation, comparing the experimental results to the pre-test analysis. Overall, the test program confirmed that the reactor vessel and head have adequate strength to accommodate the 661 MJ SMBDB loads.

THERMAL MARGIN BEYOND THE DESIGN BASE (TMBDB)

The specification of Thermal Margin Beyond the Design Base requirements considers the thermal loads that could result from an HCDA with whole core involvement. The evaluation of in-vessel margins shows that a potential for penetration of the reactor vessel and guard vessel exists. Consequently, emphasis has been placed on providing margins external to the reactor vessel and guard vessel to assure that the offsite and control room radiological consequences of an HCDA are acceptable.

To evaluate the adequacy of the plant thermal and radiological margins, the release of the entire core, blankets and primary sodium into the reactor cavity was assumed. Requirements have been placed on plant components and structures to assure that containment integrity can be maintained without venting for at least 24 hours after initiation of the event as required by the Nuclear Regulatory Commission.

The features being implemented to provide adequate Thermal Margin Beyond the Design Base are shown in Figure 5. For each of these features, specific design requirements have been developed. As an example, the reactor containment vent system requirements specify:

- Required vent flow rate at a specified pressure, gas density and viscosity
- Aerosol maximum mass flow rate and total mass entering the vent
- Location of the vent point within containment
- Discharge point of vented materials (into the containment cleanup system)

- Elements and compounds entering the vent system
- Gas temperatures and pressures of materials entering the vent as a function of time
- Operational requirements (e.g., manual operation from the reactor control room)

These TMBDB requirements are developed from extensive analyses of the consequences of core melt accidents involving penetration of the reactor vessel and guard vessel. The overall containment analyses are performed using the CACECO computer program[6]. This program permits the overall containment and several cells within the containment to be modelled. Thermal transport between the various structures is considered, as well as mass transport between the cells. The heat sources include the sensible heat of the core, sodium and structures; fuel and fission product decay heat; chemical reaction energy from sodium-concrete interactions, sodium-water reactions, and sodium and hydrogen burning.

The sequence of events and reactions predicted during the HCDA progression was previously described[7] and will not be repeated here. Rather, an overall perspective will be provided and recent progress will be discussed.

The challenge to containment integrity could result from a combination of excessive temperature and pressure or excessive hydrogen. The TMBDB features have been selected to mitigate these conditions. It is important to note that no active features (except for the normal containment isolation system) are required to function for at least 24 hours following a core melt event. Thus, the NRC requirement is met by inherent margins and passive features such as a vent with a rupture disk between the reactor cavity and the upper containment and vents to remove steam released behind the cell liners. Based on these passive features, current analyses indicate that containment integrity could be maintained without venting for times well beyond the 24 hour requirement.

The active TMBDB features would only be used to mitigate the longer term (>24 hours) consequences of a core melt event. The annulus cooling system would blow outside air between the steel containment vessel and the concrete confinement and thereby reduce the temperature of these structures. The containment vent system would prevent containment over-pressure. The containment purge system, which draws outside air through the containment after depressurization, would limit the hydrogen concentration to acceptable levels. Finally, the containment cleanup system would remove a high fraction of the vented particulate matter to mitigate the environmental radiological consequences.

Typical predictions of the containment conditions based on operation of these TMBDB features are provided in Figures 6, 7 and 8.

The most important uncertainties in the TMBDB assessments are in the areas of bed dryout and potential penetration into concrete prior to boildry; consequences of sodium-concrete reactions; and hydrogen autocatalytic burning. Numerous papers at this conference relate to these topics. Only a brief assessment related to CRBRP will be provided here.

The particulate bed that would be expected to be formed within the reactor cavity after vessel penetration would have a depth of 3 cm to 9 cm (depending on the amount of blanket material mixed with core fuel) if spread uniformly over the reactor cavity floor. To reach heat fluxes estimated for bed dryout, the bed depth would need to be 2 to 4 times greater than the average depth. This provides margin for non-level beds. In addition, bed leveling has been observed experimentally when a non-level bed approaches a local dryout condition. Consequently, fuel melting into the concrete while sodium is still present in the reactor cavity is not expected.

Although considerable data on sodium-concrete reactions have been developed recently, some uncertainties in predicting reaction rates and penetration depths still exist. For some combinations of conditions, energetic and extensive reactions have been observed. Based on current understanding of the phenomena, a necessary (but not sufficient) condition for energetic reactions is to have the sodium pool saturated with sodium hydroxide. In the TMBDB scenario for CRBRP, sufficient water would not be released from the concrete to saturate the sodium pool with sodium hydroxide until late in the scenario (well beyond 24 hours). At those later times, the hydrogen overpressure (above the pool) would not be sufficient to maintain a high concentration of sodium hydroxide in the pool. Consequently, at no time throughout the TMBDB scenario are conditions predicted that are similar to those that have resulted in energetic sodium-concrete reactions. Nevertheless, further work is in progress to confirm this conclusion.

Criteria to predict when hydrogen would burn autocatalytically have been developed based on extensive experiments at HEDL[8] where ignition and extinguishment characteristics have been determined for a wide range of conditions, including those applicable to the TMBDB scenario. Although the experiments were performed in a small simulated containment volume, similar results were obtained from later experiments (reported elsewhere at this conference) with larger containment volumes by a factor of >1000. Consequently, hydrogen burning, based on the burning criteria, is considered reliable; the hydrogen and sodium vapor exit the reactor cavity through a common planned vent path.

In the earlier TMBDB work, effort was focused on keeping the decay and chemical reaction heat within the reactor cavity. Later studies showed this to be a less than optimal approach, and indicated substantial merit in assuring dissipation of that heat. Thus recent CRBRP efforts have focused on making more effective use of the inherent plant heat sinks during the TMBDB scenario. For example, the design of the reactor cavity and connected cells includes a layer of insulating concrete to reduce structural concrete temperatures in the event of design basis sodium leaks. It has been determined that this insulation could be reduced in some areas and still meet its functional requirements. The reduction permits more heat absorption by the structural concrete during the TMBDB condition and, consequently, less energy is transferred to the upper containment. This work indicates the desirability of taking advantage of the large inherent heat sinks of the plant structures as opposed to attempting to localize the energy of the meltdown products.

CONCLUSIONS

Structural Margin Beyond the Design Base in CRBRP provides capability to accommodate the consequences of an energetic HCDA, even though the expected consequence is non-energetic. Analytic and experimental results indicate that the reactor coolant boundary integrity would be maintained following the dynamic loads.

Thermal Margin Beyond the Design Base in CRBRP provides capability to accommodate the consequences of a core melt event. Through use of the combination of passive features in the short term and active features in the longer term, the assessments lead to the following conclusions:

1. No operator actions with respect to TMBDB features operation would be required during the first 24 hours following a core melt event.

2. Passive features and inherent plant margins ensure that the NRC requirement to maintain containment integrity for at least 24 hours without venting would be met. For example, the containment pressure would not exceed 22 psig during this time.

3. Effective use of the large heat sinks provided by the plant structures (e.g., the pipeway cells adjacent to the reactor cavity) can reduce the challenge to containment integrity, and is probably more beneficial, in the long term, than attempts to retain the heat within the reactor cavity.

4. Controlled venting, purging and annulus cooling would maintain containment integrity above the basemat indefinitely.

5. The containment cleanup system would result in acceptably low radiological dose consequences for an accident beyond the design base (Typical long term doses at the low population zone would be 3 rem to the whole body, 30 rem to the bone and 100 rem to the thyroid. The two hour site boundary doses are less limiting.)

ACKNOWLEDGMENTS

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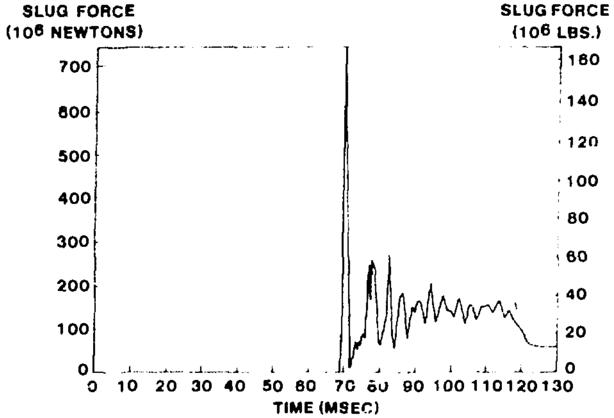

Figure 1. Force on Shielding Under Reactor Vessel Closure Head

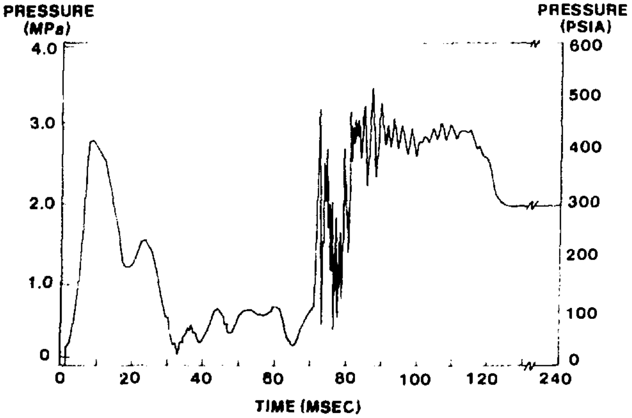

Figure 2. Reactor Vessel Outlet Nozzle Pressure

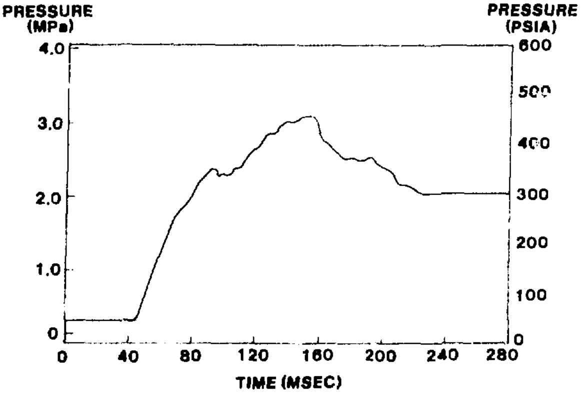

Figure 3. Intermediate Heat Exchanger Tube Pressure

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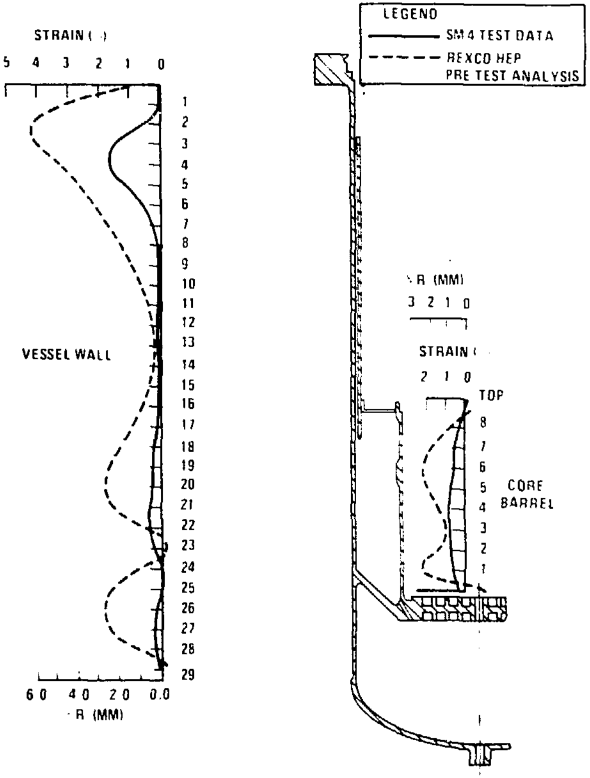
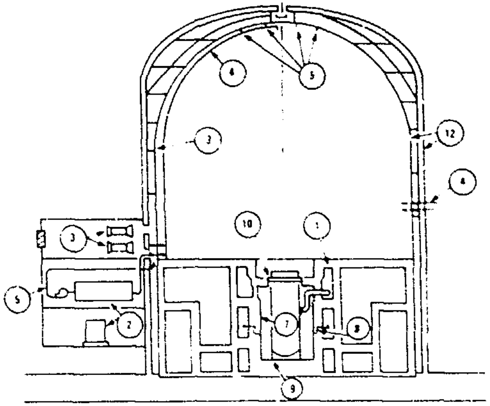


Figure 4. Scale Model SM-4 Predicted and Experimental Deformation Profiles



SPECIFIC SYSTEMS OR COMPONENTS FOR TMBDB

1. REACTOR CAVITY VENT SYSTEM
2. CONTAINMENT CLEANUP SYSTEM
3. ANNULUS COOLING SYSTEM
4. CONTAINMENT VENT AND PURGE SYSTEM
5. INSTRUMENTATION AND RADIATION MONITORING

SYSTEMS OR COMPONENTS WITH AUGMENTED CAPABILITIES FOR TMBDB

6. DUAL CONTROL ROOM AIR INTAKES (NOT SHOWN)
7. REACTOR CAVITY AND PIPEWAY CELL LINERS
8. LINER VENT SYSTEM
9. GUARD VESSEL SUPPORT
10. REACTOR CAVITY TO HEAD ACCESS AREA SEALS
11. REACTOR CAVITY RECIRCULATING GAS COOLING SYSTEM (NOT SHOWN)
12. CONTAINMENT-CONFINEMENT SYSTEMS (INCLUDING INSULATION)
13. EMERGENCY ELECTRICAL POWER SYSTEM (NOT SHOWN)
14. RCB STRUCTURES (ADDITION OF REINFORCING STEEL)(NOT SHOWN)

Figure 5. Design Features Providing Thermal Margin Beyond the Design Base

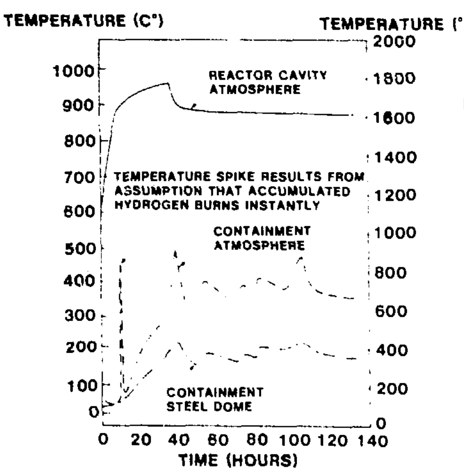


Figure 6. Reactor Cavity and Containment Atmosphere & Containment Steel Dome Temperature

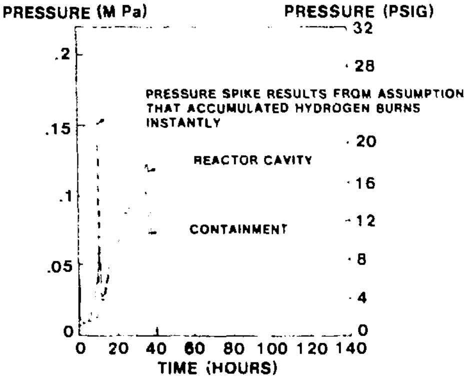


Figure 7. Reactor Cavity and Containment Pressures

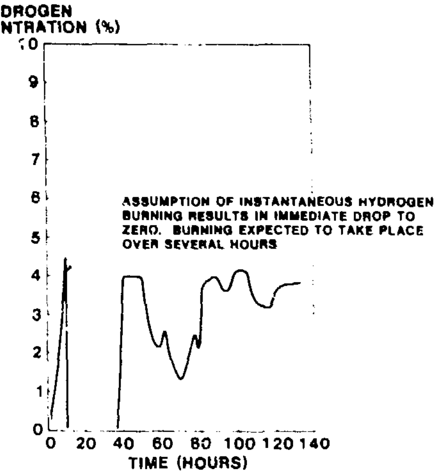


Figure 8. Containment Building Hydrogen Concentration