Investigation of the Behavior of TMI-2 Containment Structure for Hydrogen Burn Accidents

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SUMMARY

This paper describes the scoping investigations of the behavior of the containment structure of a Three Mile Island (TMI) Nuclear Station (Unit 2) subjected to postulated hydrogen burn accidents. The main objective of the investigations was to determine the realistic capacity of the containment structure to withstand the levels of pressure and temperature that could result from hydrogen burns of varying severities. The term realistic capacity, as used here, implies the capacity as determined by procedures which eliminate the substantial conservatisms and factors of safety normally used in conventional design approaches.

The paper describes the following main tasks performed as part of this investigation:

- Definition of Design
- Identification of Conservatisms in Design
- Review of Load Functions
- Determination of Preliminary Capacity of the Containment

The basic design criteria, acceptance criteria, and analytical procedures which formed the basis of the original containment design were first briefly reviewed. The conservatisms in the various assumptions and parameters used in the design and analysis of the containment were then identified. The postulated load functions for hydrogen burn accidents used in the evaluation of the containment capacity were then reviewed.

Approximate nonlinear procedures were then used for the evaluation of the preliminary containment capacity for postulated pressure and temperature loads. The results of this evaluation are presented in this paper, including the capacity curves showing the complete behavior of the containment up to failure for increasing pressures and temperatures.

The paper concludes with a discussion of results, conclusions, and recommendations.

1. Introduction

The investigations described in this paper consisted of an evaluation of the behavior of a Three Mile Island Nuclear Station (Unit 2) containment structure subjected to postulated accidental hydrogen burns of varying severities. The main objective of the investigation was to determine the realistic capacity of such type of containment structures to withstand the levels of pressures and temperatures that could result from accidental hydrogen burns.

The following were the main tasks of this investigation:

- Definition of Design
- Identification of Conservatisms in Design
- Review of Load Functions
- Determination of Preliminary Capacity of the Containment

The following is a description of these tasks, followed by discussions, conclusions, and recommendations.

2. Definition Of Design

The purpose of this subtask was to compile, document, and review the basic design criteria, including design loads, load combinations, structural details, analytical techniques, and design procedures, etc., which formed the bases for the containment design. All the information was obtained from the Final Safety Analysis Report (FSAR) (Ref. 1). The following is a brief description of the structural design.

The containment consists of a 160 ft. high (above the base slab) reinforced concrete cylindrical structure supported on a 146 ft. diameter flat circular base slab, a 33 ft. high shallow dome roof, and a transitional ring girder connecting the cylinder with the dome. The cylindrical wall and the dome roof are post-tensioned. The entire interior of the containment is lined with a 3/8 in. to 1/2 in. leak-tight steel liner plate. Figure 1 shows the plan and a sectional elevation of the containment structure.

An equipment hatch and two air lock penetrations are also provided. The containment is designed for an internal pressure of 60 psi. The containment is constructed of a 5000 psi (f'_c) concrete, 60 ksi (fy) reinforcing steel, and 270 ksi (fu) prestressing steel.

3. Identification Of Conservatisms In Design

Identification of various types of levels of conservatisms used in the assumptions and parameters employed in the design of the containment structure was performed. These conservatisms are conventionally used to provide adequate margins of safety against operating and accidental loading conditions. The following were identified to be the main sources of conservatism:

- Load Factors
- Acceptance Criteria
- Code Specified Strength versus Actual Test Strength
- Aging Effect on Concrete Strength
- Concrete Strength Under Combined Stresses

Additional sources of conservatism were found to include sources such as those involving stresss relaxation due to creep in concrete and strength increases due to relatively fast rate of loading.

4. Review of Load Functions

A review of the given load functions was performed. The loads resulting from a hydrogen burn within the containment structure include simultaneously increasing temperatures and pressures. The magnitudes of these loads depend on the percentage of zirconium reaction. The time histories of pressure and temperature for a 100 percent, 75 percent, and 40 percent zirconium reaction are shown in Figures 2 and 3. The 100 percent zirconium reaction case was used for the determination of the preliminary capacity of the containment structure since this was the worst case.

5. Determination of Preliminary Capacity of the Containment

The information developed in the previous tasks was used to make a preliminary assessment of the realistic capacity of the containment structure to withstand a hydrogen burn accident. This assessment of the capacity was based not only on the determination of the loads at which structural failure would likely occur, but also considered the fact that the main function of the containment structure is to provide an essentially leak-tight barrier and shielding against uncontrolled release of radioactivity into the environment. The assessment included an examination of the dynamic characteristics of the containment structure in relation to those of the postulated pressure loads, a review of the behavior of the concrete and steel materials subjected to high temperature loads and the resulting thermal gradients in the containment wall, and the potential failure modes of the containment structure. The different types of potential local failures were, however, not included in this assessment.

Estimates of the dynamic characteristics (frequencies and mode shapes) of the containment structure were developed and then compared against the characteristics of the postulated pressure loads. It was found that the containment structure would respond statically when subjected to the postulated pressure time history.

The next step in the investigation was to make a preliminary estimate of the distribution of temperatures across a tyical segment of the containment wall. For the postulated temperature time history in the containment atmosphere, the transient temperature distributions across the containment wall were computed. The computer program ANSYS was used for the thermal transient aalysis. It was found that the temperatures in the steel liner would be on the order of 100°F to 250°F (depending on the film coefficient used), and the corresponding temperatures in the concrete wall would be about 60° to 70° within the first one to two inches of the thickness of the concrete wall.

The following two sets of load combinations were used for the evaluations described in this paper.

Load Combination 1: $1.0\ D + 1.0\ F + 1.0\ P_a$
Load Combination 2: $1.0\ D + 1.0\ F + 1.0\ T_o + 1.0\ T_a + 1.0\ P_a$

where

D = Dead load of structure
F = Prestress load
T_o = Normal thermal gradient across the wall (during winter)
T_a = Thermal gradient during the accident
P_a = Pressure load during the accident

For Load Combination 1, a series of analyses were performed to determine the behavior of the containment structure due to increasing levels of accidental pressure load, without the presence of thermal load. For Load Combination 2, a series of analyses were performed to determine the behavior of the containment structure due to increasing levels of accidental pressure load in combination with the normal thermal and peak accidental thermal loads.

The capacity of the containment structure was evaluated at the midsection of the cylinder, which was found to be the most critical section on the basis of preliminary calculations performed using the results of the original design analyses. The procedure used for the thermal analyses was developed at EDAC and has been applied to other nuclear containment structures (Ref. 2). In these analyses, the containment wall was divided into 17 layers including concrete, steel liner, reinforcing and prestressing steels. The nonlinear distribution of the temperature gradient across the wall was used for this preliminary analysis. The propagation of cracks in concrete and yielding of steel were traced step-by-step at different levels of pressure.

Curve 1 of Figure 4 shows the various stages in the behavior of the containment structure to increasing accidental pressure load (Load Combination 1), until complete failure of the containment occurs. Curve 2 of the same figure shows the various stages in the behavior of the containment structure to increasing accidental pressure load in conjunction with peak accidental temperature load (Load Combination 2) until complete failure of the containment occurs. It must be pointed out that in the above stress analyses for the computation of the preliminary realistic capacity of the containment structure, it was attempted to eliminate the various sources of conservatisms described previously.

6. Discussion of Results, Conclusions, and Recommendations

As shown in the first curve of Figure 4, the realistic capacity of the containment, for pressure loads acting alone, can be considered to be 190 psi on the basis of this preliminary investigation. Since the containment is designed for a pressure of 60 psi, the margin of safety is roughly a factor of 3.0. As discussed previously, the postulated pressure for a 100 percent zirconium reaction is 115.0 psia (or 100 psi). The margin of safety for this postulated loading condition is roughly a factor of 2.0; therefore, a structural failure would not occur. The second curve in Figure 2 shows that the realistic capacity of the containment, for pressure and thermal loads acting together, can be considered to be 155 psi on the basis of this preliminary investigation. The margin of safety for the combined postulated accidental thermal and pressure loading condition would therefore be roughly a factor of 2.5. For the postulated loading corresponding to a 100 percent zirconium reaction case, the margin of safety would be roughly a factor of 1.5; therefore a structural failure would not occur.

It also needs to be pointed out that the main function of the containment structure is to provide an essentially leak tight barrier and shielding against uncontrolled release of radioactivity into the environment. The assessment of the capacity of the containment structure should therefore also consider the phenomena associated with various types of conceptual functional failures. On the basis of the results presented in Figure 4, the following table may indicate the internal pressures for these phenomena.

Phenomenon	Preliminary Estimate of Internal Pressure (psi)
Minor Concrete Cracking	~60
Significant Concrete Cracking	~80 - 110
Yield of Steel Liner, Reinforcing Steel and Prestressing Tendons	~140 - 180
Large Displacements, Possible Fracture of Liner, Failure of Reinforcing Steel and Prestressing Tendons	~140+

It was recommended that detailed nonlinear finite element analyses be performed of the containment structure to confirm the capacities determined in this preliminary investigation. Such analyses can also provide more detailed information on the local failures as well as functional failures since the cracking of concrete, yielding of reinforcing and prestressing steels, and yielding of the steel liner can be investigated in more detail. It is also recommended that evaluations be performed of other generic types of containments to investigate their capacities as compared to that of the subject containment for hydrogen burn accidents. In addition, it is also recommended that conceptual modifications be developed for containment structures so that they can stand higher pressures.

7. References

[1] Metropolitan Edison Company, Jersey Central Power and Light Company, Pennsylvania Electric Company, "Final Safety Analysis Report (FSAR) - Three Mile Island Nuclear Station, Unit 2," Docket No. 50-320, 1978.

[2] Chen, M.C., and Kamil, H., "Nonlinear Analysis of Reinforced Concrete Containments Considering the Rotation of Diagonal Reinforcement", Proceedings, Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, November 1980.

[3] "The Response of a TMI-2 Containment Structure to Hydrogen Burn Accidents," prepared by Engineering Decision Analysis Company, Inc. (EDAC) for Nuclear Safety Analysis Center, Final Report, January 1981.

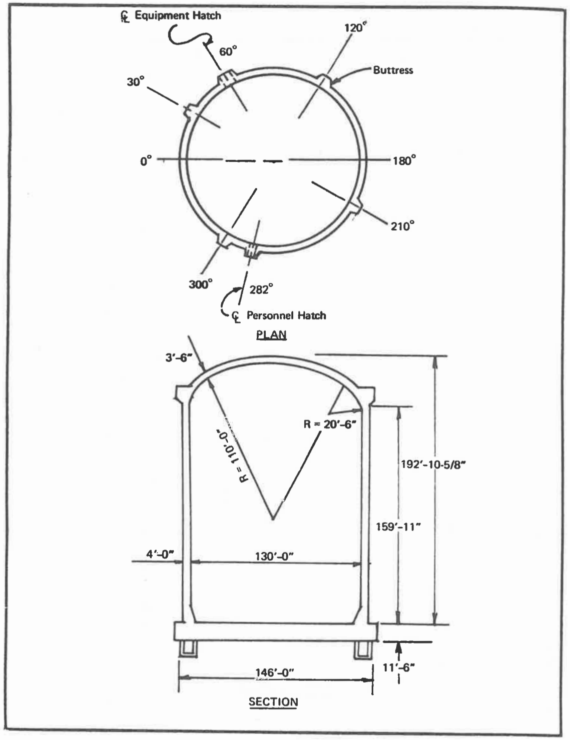

FIGURE 1 PLAN AND SECTION OF THE CONTAINMENT

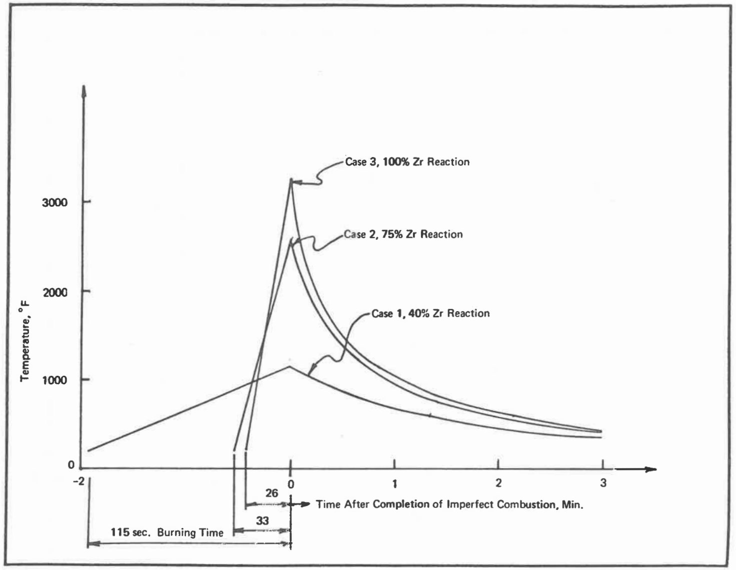

FIGURE 2 CONTAINMENT ATMOSPHERIC TEMPERATURE TIME HISTORIES

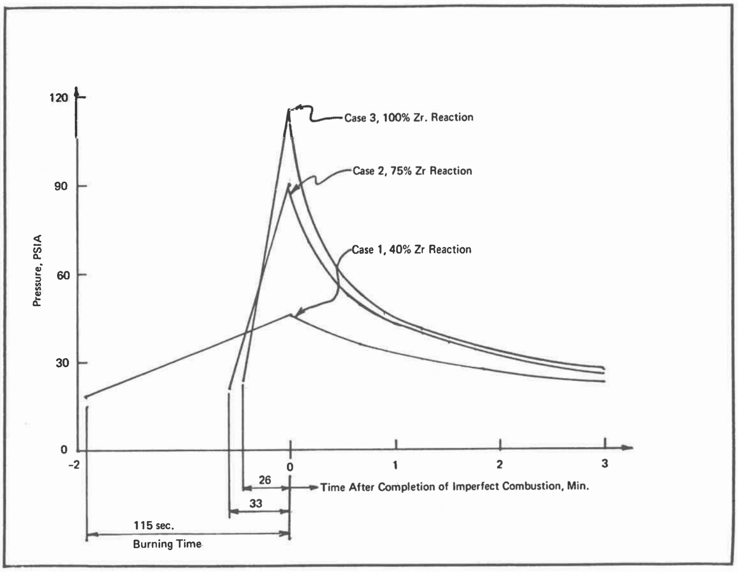

FIGURE 3 CONTAINMENT ATMOSPHERIC PRESSURE TIME HISTORIES

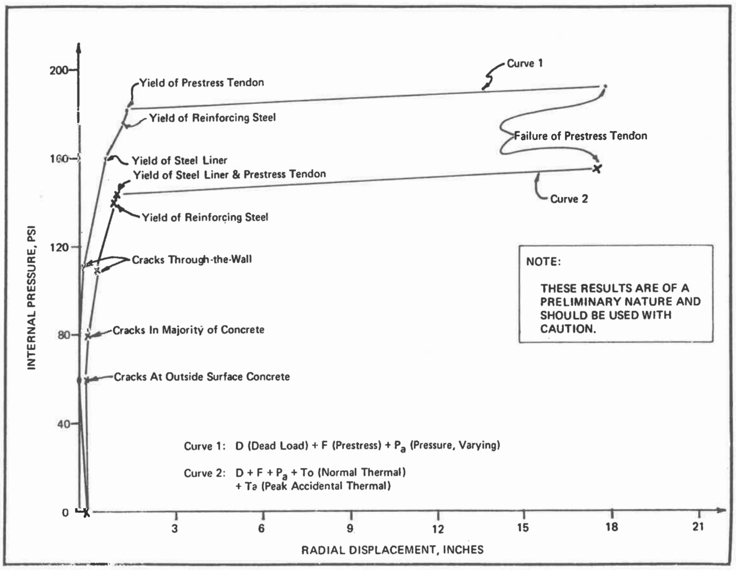

FIGURE 4 PRELIMINARY CAPACITY OF THE CONTAINMENT
(Computed for the Middle Section of Cylinder)