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Modification of a Two-Cell Equilibrium Model for Predicting Direct Containment Heating

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1. Introduction

Direct containment heating(DCH) can occur in a nuclear power plants if, as the result of a postulated core melt accident, molten corium material accumulates on the lower head of the reactor pressure vessel (RPV) and erupts through a thermally induced rupture. DCH is only of interest if the RPV failure occurs while the reactor coolant system (RCS) is still at elevated pressure. Failure of the lower head of the RPV initiates forcible ejection of molten core materials into the reactor cavity located beneath the RPV. These processes have been referred to high pressure melt ejection (HPME). Figure 1 show a conceptual diagram for HPME/DCH phenomena.

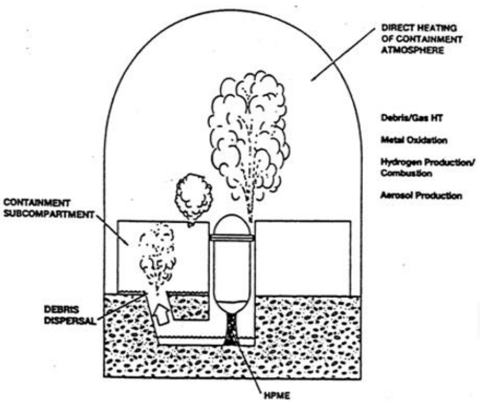

Fig. 1. HPME/DCH Phenomena

The subsequent blowdown of the RCS adds both mass and energy to the containment atmosphere. Some portions of the molten core material ejected into the reactor cavity can be entrained, fragmented, and dispersed into the containment atmosphere. Fragmented debris dispersed from the reactor cavity can dissipate its thermal energy to the containment atmosphere. The metallic components of the dispersed material can oxidize with steam, liberating both energy and hydrogen. The processes will heat the containment atmosphere, possibly to the point at which steam can no longer inert the combustion of hydrogen. Collectively, these processes are termed DCH, which might lead to early containment failure by over-pressurization.

Two-cell equilibrium (TCE) model was developed as a tool to estimate containment pressure by DCH and has been used in calculation of DCH loads for large commercial pressurized water nuclear plants, which have large volume difference between containment and RCS. At the time when TCE being develop, RCS volume effects on pressurization was ignored due to the large volume ratio. However, if RCS volume is comparable to containment and so, the volume effect of the reactor vessel cannot be ignored no more on DCH analysis. In this paper, TCE model regarding contribution of RCS volume to containment pressure was reviewed and a kinds of modification was suggested.

2. Review of Two-Cell Blowdown Model

In general, there are four phenomena in DCH problem that may cause to rapid pressure increase and temperature in the containment; 1) RCS blowdown into the containment, 2) heat transfer between particlized debris and containment atmosphere, 3) exothermic metal-steam oxidation, 4) hydrogen combustion. In this paper, blowdown model among those was reviewed in detail.

2.1 Modification of the blowdown model

The energy gained by the containment atmosphere from blowdown of the RCS is balanced by the energy loss from the RCS.

$$\frac{\mathrm{dU_{g.b}}}{\mathrm{dt}} = -\frac{\mathrm{dU_{RCS}}}{\mathrm{dt}} = \frac{\mathrm{V_{RCS}}}{\gamma-1}\frac{\mathrm{dP_{RCS}}}{\mathrm{dt}} \qquad (1)$$

The blowdown energy can be bounded by assuming that the RCS pressure reduces to the initial containment pressure.

$$\Delta\mathrm{E_b} = -\Delta\mathrm{U_{Rcs}} = \frac{V_{RCS}P_{RCS}^0}{\gamma-1}\left[1-\left(\frac{P^0}{P_{RCS}^0}\right)\right] \qquad (2)$$

The term preceding the brackets represents the total internal energy of the RCS, while the bracketed term represents the fraction of this total that is convected to the containment.

Reviewing the equation, Eq. (2), the equation reveals that there is a conservative assumption, namely, the RCS pressure reduces to the initial containment pressure. This assumption is reasonable only when a containment volume is much bigger than RCS volume. If the RCS volume is similar to containment volume, the equation gives us more conservative results.

The equation was modified for more general application to DCH problems and was changed as follows;

The containment initial pressure, P^o term in Eq. (2) was replaced with P_{mix}. which is summation of partial pressure of RCS and containment.

$$P_{mix} = \frac{(P_{RCS}^0\ V_{RCS}) + (P^o\ V_{CTMT})}{V_{RCS} + V_{CTMT}} \tag{3}$$

$$\Delta E_b = -\Delta U_{Rcs} = \frac{V_{RCS} P_{RCS}^0}{\gamma - 1}\ [1 - (\frac{P_{mix}}{P_{RCS}^0})]$$

$$= \frac{V_{RCS} P_{RCS}^0}{\gamma - 1}\ [1 - \frac{(P_{RCS}^0\ V_{RCS}) + (P^o\ V_{CTMT})}{(V_{RCS} + V_{CTMT}) P_{RCS}^0}] \tag{4}$$

The modification was implemented in the TCE program model and the results were compared to those of the previous origin version.

2.2 Results

The modified program was applied to two plants. The first one is a commercial pressurized water reactor (PWR) with a large containment volume and the second is a small modular reactor with an integrated RCS. In aspect of pressure build-up due to RCS blowdown into the containment, the big difference exists between those two plants. It is that the volume ratio of the RCS to the containment of the commercial PWRs is very small but is comparable for other innovative plants. Table 1 shows containment and RCS volume for two plants considered in the analysis.

Table I: Typical Geometric Data for PWR and SMR

Items	Commercial PWR	Innovative PlantS
CTMT vol. (m^3)	93,400	1225
RCS vol. (m^3)	493	288
Volume Ratio	~4.2	~190

Table 2: Comparison of the Results

Parameters	Commercial PWR	Innovative Plants			
		Case 1	Case 2	Case 3	Case 4
P^o_{RCS} (bar)	170	172.7	172.7	138.72	138.72
P^o (bar)	2.5	30	50	30	50
$\triangle P_b$ (bar)	*0.62 [0.61]*	*24.5 [16.4]*	*26.7 [15.4]*	*19.7 [12.5]*	*21.5 [11.1]*
P_{DCH}(bar)	*11.4 [11.4]*	*90.9 [82.8]*	*116.1 [104.7]*	*86.1 [78.9]*	*110.8 [100.5]*

There were some analyses to find out the effect of the modified TCE model on the pressure loads and the results are summarized in Table 2.

As expected, there was no contribution to reduction of DCH pressure of the modified program with a big containment. However, the pressure by the blowdown energy in case of comparable RCS volume was reduced dramatically. As shown in Table 2, pressure by RCS blowdown went down by 30 ~50 % after modification of the TCE program and approximately 10 % reduction of total DCH pressure can be achievable through this modification

3. Conclusions

A TCE model for HPME/DCH analysis was reviewed and Some modification was suggested for nuclear plants of which volume ratio of the RCS to the containment can be comparable relatively such as SMRs.

DCH pressure loads were compared for several cases using the program before and after modification and we can find out the modified TCE program can reduce a pressure build-up due to RCS blowdown into the containment considerably.

Further study should be carried out to develop a more sophisticated model.

Nomenclature

$U_{g.b}$: internal energy rate due to RCS blowdown
U_{RCS}: internal energy of RCS gas
V_{RCS}: volume of RCS
γ: C_p/C_v, isentropic exponent of blowdown gas
P^o: initial containment pressure
P^o_{RCS}: initial pressure of the RCS
P_{mix}: sum of RCS and containment partial pressure
V_{RCS}: RCS free volume
V_{CTMT}: Containment free volume
$\triangle P_b$: Pressure build-up by RCS blowdown
P_{DCH}: DCH total pressure

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