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# Estimation of Direct Containment Heating Loads in KNGR Using CONTAIN Code

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## Abstract

*The CONTAIN 1.2 analyses were performed to estimate the containment pressure loading due to DCH in the KNGR containment. Three scenarios, designated as Scenarios V, Va, and VI, were selected as bounding cases of DCH sequence in conformity with the NRC's DCH issue resolution study of Zion plant. Conservative initial conditions in the RCS and the containment before vessel breach (VB) and some phenomenological assumptions were considered. For phenomenological processes that are well understood, a standard methodology for mechanistic models in the CONTAIN code was used, including debris-gas heat transfer, chemical reaction, particle trapping, debris transport, steam blowdown, and hydrogen combustion. Based on the CONTAIN 1.2 calculation results, the maximum pressure and temperature occurred in the case of Scenario Va where the resulting pressure loading in the KNGR containment dome due to DCH was 0.530 MPa. This pressure loading is much lower than the KNGR containment pressure capacity associated with the Factored Load Category allowables of 0.839 MPa, assuring that the KNGR containment is robust to the DCH phenomenon.*

## 1. Introduction

During some severe accidents, meltdown and degradation of the reactor core can take place while the RCS remains at high pressure. Under these circumstances, as the reactor pressure vessel breaches and the molten core debris penetrates the reactor vessel, the core debris would be ejected under high pressure and, subsequently, dispersed into the containment atmosphere. During the process, large quantities of sensible energy from the finely fragmented debris, the chemical energy and the hydrogen are directly transferred to the containment atmosphere. This phenomenon has become known as direct containment heating (DCH).

KNGR has been designed to prevent DCH challenge to the containment integrity by rapid depressurization capability of safety depressurization and vent system (SDVS) to reduce RCS pressure below the debris entrainment threshold. In addition, high pressure severe accident scenarios would develop natural circulation flow within the RCS and consequently induce a hot leg failure, which also results in reducing the RCS pressure to below the debris entrainment threshold. In this paper, however, any operator action to depressurize the RCS or thermally induced hot leg failure were not credited for conservertism.

Three scenarios, designated as Scenarios V, Va and VI, were selected as bounding cases of DCH sequence in conformity with the NRC's DCH issue resolution study of Zion plant [1]. Conservative initial conditions in the RCS and the containment before VB and some phenomenological assumptions were considered. The CONTAIN analyses were performed to estimate the containment pressure loading due to DCH in the KNGR containment. It is the intent of this paper to present the results of the KNGR DCH calculation using CONTAIN 1.2 code [2].

## 2. KNGR Design Features to Mitigate DCH Challenge

To prevent and mitigate HPME/DCH challenge caused by reactor vessel failure at high pressure, the KNGR design is required to provide a reliable depressurization system, and to provide cavity design features to decrease the amount of ejected core debris that reaches the upper containment [3, 4].

The KNGR SDVS serves the rapid depressurization function of the RCS, even in the event that a high pressure meltdown scenario develops and the feed portion of feed and bleed operation can not be established due to the unavailability of the SI pumps. The RCS depressurization analysis for KNGR showed that the RCS can be depressurized below the DCH cutoff pressure, if at least two out of four POSRVs are opened within 1.5 hours after the first automatic lift of a POSRV following a TLOFW event [5].

The KNGR reactor cavity is configured to promote retention of and heat removal from the postulated core debris during a severe accident, thus playing several roles in accident mitigation. Debris retention in the core debris chamber virtually eliminates the potential for significant DCH induced containment loadings. Figure 1 shows a schematic of the KNGR reactor cavity design. The important features of the KNGR reactor cavity include 1) a large cavity volume, 2) a closed vertical ICI shaft, 3) a convoluted gas vent, 4) a large recessed corium debris chamber, and, 6) robust cavity strength. In the design of the KNGR reactor cavity a significant effort has been made to ensure that actual venting to the upper containment either by the ICI shaft or around the reactor vessel (RV) annulus is restricted. The presence of seal table prevents upward corium discharge through the ICI shaft. Similarly, obstructions associated with the shield plugs, the RCS piping and the permanent refueling pool seals serve to restrict the flow through the RV annulus. Thus the primary steam exits via a convoluted pathway above the top of the core debris chamber and into a cavity access area and out through louvered vents under the regenerative heat exchanger room. As a consequence the dominant hot steam and fine debris carryover path will be to the lower compartment of the containment where most of the debris will be trapped before entering the upper compartment.

The SNL's correlation for debris impingement, supported by high pressure melt ejection test data, predicts that the KNGR-like cavity design mitigates the DCH effect by limiting the amount of debris leaving the cavity as finely fragmented particles. Application of the correlation to the KNGR cavity geometry results in a prediction that 90% of the corium debris would be de-entrained into the debris chamber and that 10% of the debris could potentially negotiate the turn into the reactor cavity shaft.

## 3. CONTAIN Input and Modeling

For the application to the DCH analysis, the KNGR containment was represented using 12 cell nodalization, and three additional cells were used for the RCS, the containment annulus, and the environment. Figure 2 shows the nodalization of the KNGR containment.

Three scenarios, designated as Scenarios V, Va and VI, were selected as bounding cases of DCH sequence in conformity with the NRC's DCH issue resolution study of Zion plant [1]. Scenario V represents a small break LOCA with repressurization of the RCS by operator intervention. Scenario Va is same as Scenario V except that containment sprays are in operation. Scenario VI simulates a small break LOCA with partial repressurization of the RCS by operator intervention. The methodology to determine the initial conditions in the RCS was directly taken from the Zion DCH study, but the KNGR specific data were used for the evaluation. The initial conditions in containment were determined from the MAAP4 calculation. For phenomenological processes that are well understood, a standard analysis methodology for mechanistic models in the CONTAIN code [6] was used. In particular, the models in CONTAIN 1.2 for debris-gas heat transfer, chemical reaction, particle trapping, debris transport, steam blowdown, and hydrogen combustion were used.

The initial mole fractions of air, steam and hydrogen in the containment atmosphere were calculated assuming that total moles of nitrogen and oxygen remain unchanged from the normal operating condition and total hydrogen moles is equivalent to the zircaloy oxidation ratio. For the major uncertain parameters, such as the fraction of zircaloy oxidation and melt masses in the RV lower plenum at VB, the upper 1% extreme values were taken from the probabilistic distributions.

User-supplied source tables were specified to simulate the debris dispersal phase of a high pressure melt ejection event. It was conservatively assumed that 100% molten debris was introduced into the trapped bin in all scenarios. The fraction of the entrainment to the trapped debris was considered as 100% for Scenarios V & Va, but 85% for Scenario VI. The coherence between the debris and the steam, and their dispersal rate were determined by side calculation. The coherence ratio ($R\tau$) was externally evaluated using the Pilch methodology [7], which resulted to be 0.273 for Scenarios V & Va and 0.568 for Scenario VI. The steam blowdown time ($t_b$) was determined from the steam blowdown flowrate which was taken from the stand-alone MAAP4 analysis, which was 9.12 seconds in Scenarios V & Va and 7.54 seconds in Scenario VI. Therefore, the entrainment time ($t_e$) was determined to be 2.49 seconds for Scenarios V & Va and 4.28 seconds for Scenario VI. The slip factor, which is the ratio of the velocity of the gas phase to the velocity of debris phase, was set to be 5.0 in the cells inside the reactor cavity, and 1.0 for other cells. The same slip ratios were assumed for all debris fields. Trapping of entrained debris was not considered in the reactor cavity. However, in all other cells, the it was considered using the TOF/KU trapping model.

The combustion of hydrogen by deflagration was conservatively ignored, since the deliberate burning of hydrogen before VB does not contribute to the peak loads during the DCH. Therefore the diffusion frame burning (DFB) and the autoignition are the only processes considered. The threshold temperature for DFB from upstream cell was set to be 400 K in the containment dome and 1000 K for other cells. The auto-ignition temperature of pre-existing hydrogen was set to be 950 K.

For the generation of steam blowdown source, the RV was modeled as a separate cell. The actual volume of RCS is 454 $m^3$. The steam mass was adjusted to make the steam density correspond to the initial condition, which resulted in 31,664 kg for Scenarios V & Va and 9,089 kg for Scenario VI. The RV hole size was specified to be 10% of the RV lower head diameter.

Table 1 presents the summary of the initial conditions of three scenarios for KNGR DCH analyses.

## 4. Results of the CONTAIN Calculations

The CONTAIN calculation results for the transient pressure, temperature, hydrogen combustion, and debris carryover to the dome compartment are summarized in Table 2 and shown in Figures 3 through 6.

Figure 3 shows the comparison of containment dome pressures as a function of time after VB for three scenarios. This figure shows that the peak loads of the containment dome pressure are predicted to occur at approximately 10 to 15 seconds after VB, after which time the pressure decreases because of heat losses to the surrounding structures. The maximum peak pressure occurred in Scenario Va which resulted in 0.530 MPa. Figure 4 shows the gas temperatures predicted in the containment dome. The maximum peak temperature also occurred in Scenario Va where the peak dome temperature was 1170 K.

Hydrogen burning is shown in Figure 5. This figure is used to demonstrate the DFB and the autoignition since the deflagration burning by igniters was intentionally precluded in the code simulations. One can see that, in Scenarios V & VI, most hydrogen burning occurred during the entrainment period when the hydrogen burned by a continuous diffusion flame as it flows into the upper compartment. However, in Scenario Va, the hydrogen burning continued until the end of simulation, which is the result of autoignition process. This is confirmed by the fact that Scenario Va is the only case that the gas temperature in the containment dome reached the threshold temperature (950 K) for autoignition, as shown in Figure 4.

Figure 6 shows the fraction of the dispersed debris that enters the upper compartment, where it can exist as entrained in the atmosphere or trapped on the surfaces. Most of the debris carryover occurred during the entrainment period. The fraction of debris carryover is 21.5% in Scenarios V and 13.2% in Scenario VI. These values are comparable to the fraction of the flow area directly going up to the upper compartment to the total flow area exiting from the reactor cavity, that is about 15%.

## 5. Conclusion

The DCH pressure loading for the KNGR containment was estimated for three scenarios of high and intermediate pressure sequence, using the CONTAIN 1.2 code. Based on the results of the estimation, Scenario Va was assessed to be the most bounding case where the peak pressure and temperature in the containment dome increased to 0.530 MPa and 1170 K, respectively. In this estimation, almost complete debris dispersal from and no debris trapping in the reactor cavity were assumed that is very conservative considering the convoluted design of the KNGR reactor cavity. Also, hydrogen burning of pre-existed hydrogen due to autoignition was also considered within the DCH time scale. However, by the existence of the subcompartment volume, total fraction of the debris that was entrained to the upper compartment was limited, and the resulting pressure loading due to the DCH process in the KNGR containment was very low, compared to the KNGR containment pressure capacity associated with the Factored Load Category allowables of 0.839 MPa. Therefore, it can be concluded that the KNGR containment is robust to the DCH phenomenon.

## 6. References

[1] NUREG/CR-6075, "The Probability of Containment Failure by Direct Containment Heating in Zion", SAND 93-1535, Supplement 1, Sandia National Lab., December 1994.

[2] CONTAIN 1.2 Code Manual, "A Computer Code for Severe Accident Containment Analysis", Sandia National Lab., April 1993.

[3] SECY93-087, "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor (ALWR) Designs", US NRC, April 2, 1993

[4] Korean Utility Requirements Document, Rev. 0, KEPCO, June 1998

[5] J.W. Park, et. al., “Optimization of SDS Valve Opening Time for the Prevention of HPME/DCH in KNGR”, Power Engineering, Volume 33, 1998

[6] "Direct Containment Heating Models in the CONTAIN Code", SAND 94-1073, Sandia National Lab., May 1995.

[7] Pilch, M., et al., "Heat Transfer During Direct Containment Heating", Advances in Heat Transfer, Vol. 29, Academic Press, 1997.

**Table 1 Initial Conditions for DCH Analysis**

| Parameter | Scenario | | | Parameter | Scenario | | |
|---|---|---|---|---|---|---|---|
| | V | Va | VI | | V | Va | VI |
| RCS pressure (MPa) | 17.2 | 17.2 | 9 | Initial pressure in containment (MPa) | 0.200 | 0.129 | 0.200 |
| RCS temp. (K) | 700 | 700 | 1000 | Initial temp. in containment (K) | 386 | 329 | 386 |
| Debris temp. (K) | 2800 | 2800 | 2800 | Initial $N_2$ mole fraction | 0.480 | 0.634 | 0.480 |
| RV hole size (m) | 0.47 | 0.47 | 0.47 | Initial $O_2$ mole fraction | 0.128 | 0.169 | 0.128 |
| RCS volume (m) | 454 | 454 | 454 | Initial $H_2$ mole fraction | 0.070 | 0.092 | 0.070 |
| Zr oxidation ratio | 0.55 | 0.55 | 0.55 | Initial steam mole fraction | 0.322 | 0.105 | 0.322 |
| $UO_2$ mass in melt (mt) | 54 | 54 | 67 | Melt ejection fraction | 1.0 | 1.0 | 1.0 |
| $ZrO_2$ mass in melt (mt) | 11.5 | 11.5 | 14.3 | Cavity dispersal fraction | 1.0 | 1.0 | 0.85 |
| Zr mass in melt (mt) | 1.57 | 1.57 | 1.94 | Pilch coherence ratio | 0.273 | 0.273 | 0.568 |
| Steel mass in melt (mt) | 3.07 | 3.07 | 3.72 | Entrainment time (s) | 2.49 | 2.49 | 4.28 |

**Table 2 Results of KNGR DCH Analyses**

| Scenario | Peak Pressure ( MPa ) | Peak Temp. (K ) | Total $H_2$ Burn ( kg )* | Debris Carryover ( % ) |
|---|---|---|---|---|
| V | 0.479 | 788 | 212/257 | 18.8 |
| Va | 0.530 | 1,170 | 512/958 | 17.6 |
| VI | 0.406 | 738 | 192/352 | 11.5 |

* Mass of $H_2$ burned for first 5 seconds / total mass of $H_2$ burned for 30 seconds

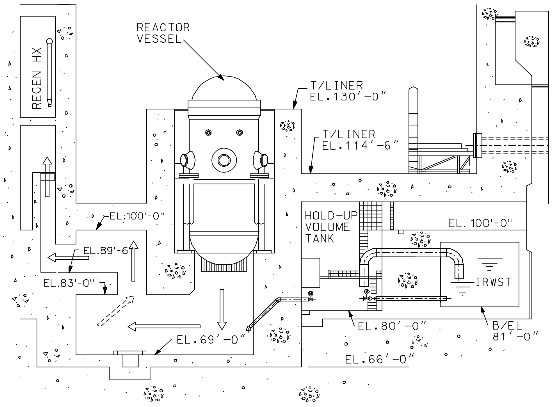

Figure 1 Convoluted Flow Path of KNGR Cavity

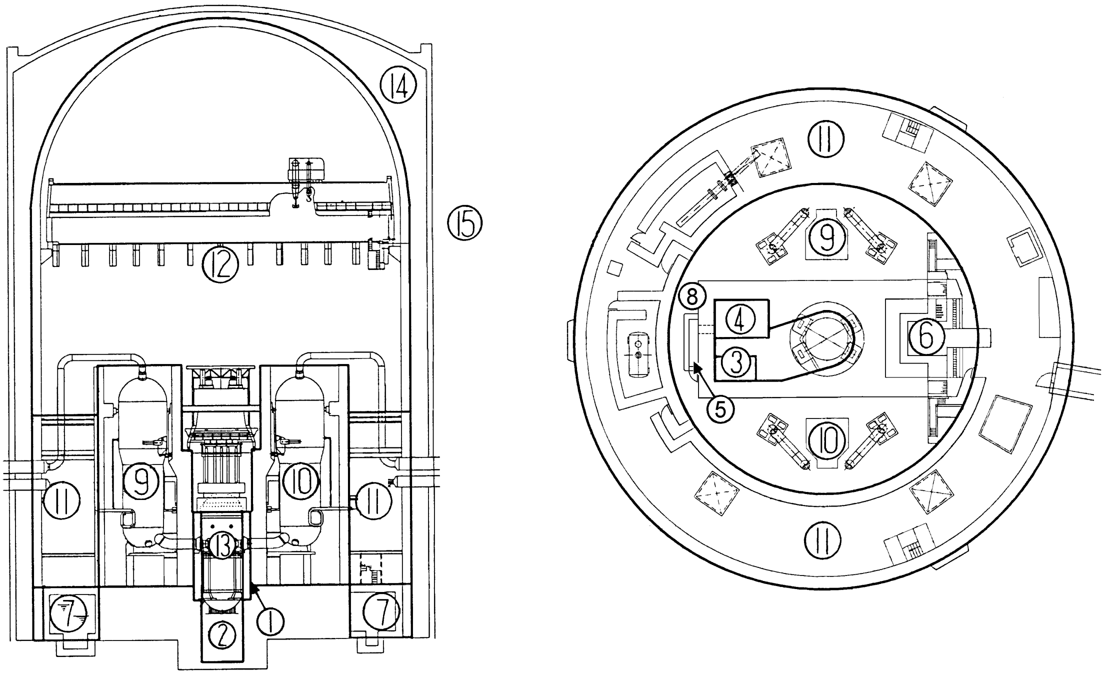

Figure 2 Nodalization of KNGR Containment

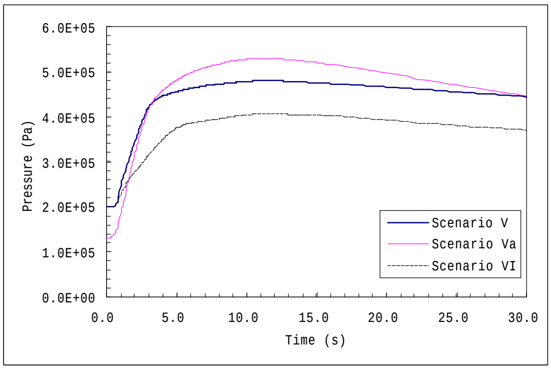

Figure 3 Pressure in Containment Dome

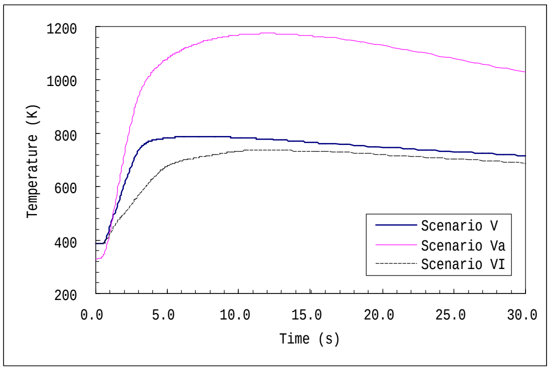

Figure 4 Temperature in Containment Dome

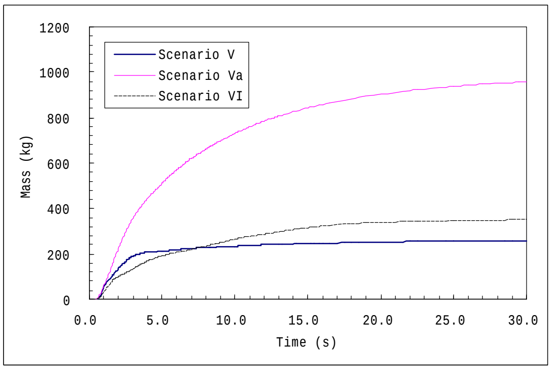

Figure 5 Mass of Hydrogen Burned

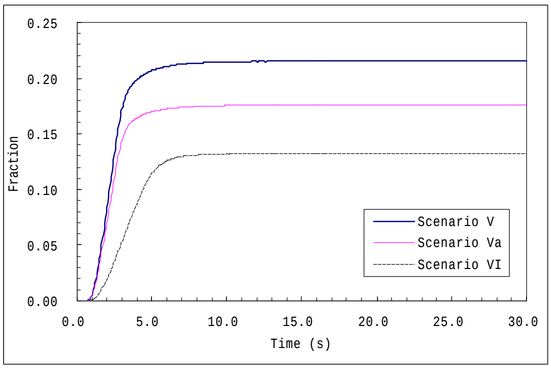

Figure 6 Fraction of Debris Carryover to Dome