Thermal and Mechanical Margin to Failure of Lower Head with COASISO During a Severe Accident

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ABSTRACT

In this paper the efficiency of the external vessel cooling is estimated in terms of thermal and mechanical margin to failure of lower head during a severe accident in the nuclear power plant. Relevant models and correlations are critically reviewed and assessed in terms of their capabilities and uncertainties in estimating the thermal margin to potential failure of the vessel on account of the critical heat flux (CHF) and the mechanical margin in terms of the time to fracture calculated by means of Larson-Miller parameters. Results show that the thermal margin is considerably reduced at the top than is at the bottom of the vessel. In particular, the metal layer focusing effect decreases the thermal margin when the heat split fraction of the heat transferred downward in the oxide pool is small. Results also indicate the effect on the CHF of the initial subcooled condition, mass flow rate and pressure of the external coolant and the gap size between reactor vessel and the external cooling structure. This paper additionally examines the effect on the actual heat flux from the reactor vessel of the two-dimensional conduction heat transfer, the existence of the cylindrical part and the melting process. Sensitivity analyses on the mechanical margin reveal that the pressure in the reactor vessel and the thinned vessel wall by the melting process both tend to shorten the time to rupture of the vessel.

INTRODUCTION

A wide spectrum of management strategies were proposed to cope with a nuclear reactor severe accident. As a viable means to ensure adequate cooling of the decay heat generating debris bed and the retaining vessel wall, the so-called IVR-EVC (in-vessel retention through external vessel cooling) appears to draw a keen attention from the nuclear safety community. The Corium Attack Syndrome Immunization Structures Outside the vessel (COASISO) are being developed at the Seoul National University as prospective in-vessel retention devices for a next-generation water reactor in concert with existing ex-vessel management measures [1]. As quantitative analysis as may reasonably be performed is prerequisite to estimating the thermal and mechanical margin of the reactor vessel wall containing the exceedingly high temperature core material when the IVR-EVC design is considered in the next-generation reactors. Despite its potential consequences, however, the effect on the thermal margin of the multidimensional conduction heat transfer in the vessel wall and the condition of the ex-vessel coolant was not properly accounted for in previous studies [2,3,4.5]. Nor the consequence of the thinning vessel due either to melting or to ablation was explicitly considered in Park and Dhir [6]. In this study we are particularly concerned with determining the thermal and mechanical margin to potential failure of the Korean Next Generation Reactor (KNGR) vessel lower head.

Yoon and Suh [2] estimated the efficiency of the external vessel cooling by the thermal margin in terms of the critical heat flux ratio (CHFR) defined as the ratio of the CHF to the actual heat flux from the reactor vessel. The CHF was calculated by Cheung et al's [7] model. The forced convection effect was only crudely considered by slightly modifying Cheung et al's model. Their results indicated the higher thermal margin at the bottom region because more heat was being transferred to the top region relative to the bottom region by means of the natural convection in the molten debris pool. The results also showed that more heat could be removed by forced convection and subcooled boiling versus natural convection and saturated boiling of the external cooling water.

Kim and Suh [3] also estimated the efficiency of the external vessel cooling per the CHFR. The CHF was calculated from Rouge et al.'s [8] correlation by means of the postulated local condition. The results indicated a higher thermal margin at the bottom than at the top of the vessel on account of the natural convection within the hemispherical molten debris pool in the lower plenum. The information obtained from this study will serve as the backbone in identifying the maximum heat removal capability and limitations of the IVR-EVC technology called the COASISO in this study.

Park and Jeong [4] calculated that thermal margin for external reactor vessel cooling in a large advanced light water reactor (ALWR). They chose Steinberner and Reineke's [9] Nusselt number (Nu) for the upward natural convection and Theofanous et al's [5] Nu for the downward convection, respectively. They also cited the correlation based on the Mini-ACOPO experimental data to determine the angular heat flux distribution and obtained the CHF at the outer surface of the lower head using Theofanous et al. [5] correlation developed from the ULPU-2000 configuration II experiment. Their results showed that the CHFRs were 1.27 and 1.64 depending on which correlation was used at the highest angle of the debris, i.e. $\theta=85^{\circ}$ measured from the bottom of the vessel.

Theofanous et al. [5] estimated the integrity of the vessel during a severe accident by experiments on the natural convection in the molten pool and the CHF on the outer vessel wall. Thermal and mechanical analyses of the reactor vessel were carried out especially concerning the metal layer focusing effect.

Park and Dhir [6] investigated the effectiveness of flooding the cavity of a pressurized water reactor (PWR) in preventing vessel melt-through in case of melting and relocation of the core material in the vessel lower head. Two-dimensional transient and steady-state analyses were carried out including heat loss by radiation to the upper regions of the reactor vessel and the unwetted portion of the vessel lower head. The effect of internal circulation in the molten core material on heat transfer at the bounding walls was determined by extending the correlations used in their study. Radiative heat transfer from the molten pool to the surrounding structures was also included in the analysis.

MODEL DESCRIPTION

Problem Statement

Figure 1 schematically shows the COASISO hemispherical shell structure for heat removal from the reactor vessel lower head considered mainly and uniquely in this study in assessing the IVR capability. The basic factors influencing the thermal margin calculation are the amount of heat to be transferred downward from the debris pool, the angular variation of local heat flux from the downward surface, and the amount of removable heat by the external cooling of the vessel. The first two factors arise from the natural convection within the molten pool of debris, the metal layer focusing effect and conduction heat transfer while the last factor results from the heat removal capability of the injected or flooded water outside the reactor vessel lower head. The information is readily available in the literature for the first two factors. The CHF values are calculated for the last factor utilizing Theofanous et al.'s [5], Rouge et al.'s [8] and Cheung et al.'s [7] correlations.

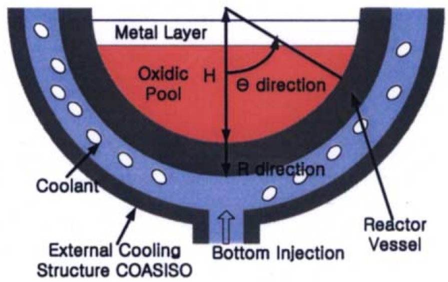


Figure 1 Schematic Diagram for COASISO

Table 1 presents relevant correlations and the cases in the calculation of thermal margin. Temperature distribution from the first three factors of thermal margin and Larson Miller parameter referenced from Stickler et al. [10] was used for calculating time to fracture. The sensitivity analysis on mechanical margin is performed about the pressure in the vessel and thinned thickness of the vessel by the melting process.

Table 1 Correlations and Cases Considered in This Study

Natural Convection Correlation	Angular Heat Flux Correlation	CHF Correlation	Mass Flow Rate (kg/s)	Initial Subcooling (K)	Test Pressure (MPa)	Gap Size (m)
Theofanous et al. [5]	Theofanous et al. [5]	Theofanous et al. [5]	25	0	0.12	0.05
Mayinger et al. [11]	Park & Dhir [6]		50*	80*	0.2*	0.10
Kelkar & Patankar [12]	Suh & Henry* [15]	Rouge et al.* [8]	100		0.3	0.15*
Theofanous et al.* [13]	Asfia & Dhir [16]	Cheung et al. [7]				
Bonnet & Seiler [14]						

* Reference case

Thermal Load

To estimate the thermal margin, the amount of heat transferred to the vessel from the internal pool must be determined a priori. The amount of heat source is determined from the decay heat, which is dependent on the reactor vessel shutdown time, the amount of heat transferred downward by the natural convection, and the angular variation of the downward heat flux. In this study the decay power of 26 MW was chosen in the molten pool given by Park and Jeong [4] based on the MAAP4 output for LL-3 sequence at 2.42 hr.

Five correlations in Table 1 for semicircular or hemispherical geometry were chosen considering the reactor vessel lower head geometry. The downward heat split fraction was calculated utilizing the natural convection correlations for the downward heat transfer versus the upward heat transfer. In this study, the correlation of the experimental data is necessary for the heat transfer coefficient varying with the local position. Several investigators proposed correlations based on the experimental data in Table 1. Metal layer focusing effect is estimated by means of three energy balances. The heat transfer upward from the oxide pool is equal to the oxide pool transmitted to the metal layer. It is also equal to the sum of the heat transferred to upper surface and the vessel wall. The heat transferred to the upper surface is the same as the radiation heat transfer from the upper surface. The method for calculating the thermal load referenced from Theofanous et al. [5] was adopted in the previous studies [2,3,4,5]. Figure 2 shows the values of the heat split fraction according to the different natural convection correlations listed in Table 1.

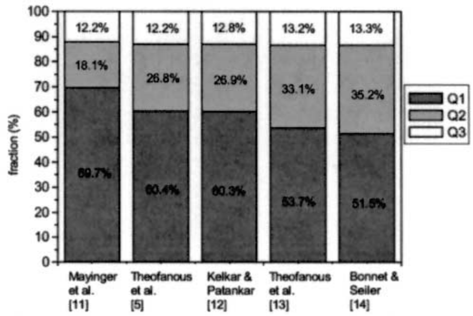


Figure 2 Heat Split Fraction for Different Natural Convection Correlations

Q1: heat transferred from oxide pool to reactor vessel

Q2: heat transferred from metal layer to reactor vessel

Q3: heat transferred from the top of metal layer by the radiation

Two-Dimensional Conduction Heat Transfer

To obtain the local heat flux on the outer surface of the vessel, two-dimensional steady-state conduction equations were solved in spherical and cylindrical coordinates. The boundary condition for the inner surface was the angular variation of the local heat flux. The boundary condition for the outer wall was the nucleate boiling heat transfer coefficient as given by h=20000 W/m^{2}K. The finite difference method was used for solving the differential equations. The thermal conductivity of the carbon steel was taken from Stickler et al. [10]. The thickness of the vessel was 0.15 m. The error of this analysis was within ± 0.001 °C. The local heat flux was determined as follows

$$q''_{act} = h(T_{out} - T_{sat}) \tag{1}$$

Critical Heat Flux

The angularly varying CHF values utilizing the three correlations given in Table 1 generally vary from 0.7 to 1.5 MW/m^2. However, Cheung and Liu's [17] experiments with thermal insulation show that the CHF values are larger than the other experimental values due to the flow mixing and three-dimensional curved surface effects. Unfortunately, however, Rouge et al.'s correlation [8] turns out to be the only one at the moment to be applied to the COASISO structure because this is the one correlation considering the gap size, pressure, inclined angle, local quality and local mass flux in the inclined channel for the downward-facing heated surface. This correlation may not though be applied in the bottom region where the effect of curved surface is prominent and the flow field is unstable with bottom injection. On the other hand the correlation may rather safely be applied in the region where the surface curvature and flow developing effects are diminished. We mainly mention the CHF and the CHFR at the top where the thermal load gets large. Cheung et al.'s correlation [7] can be applied in the limited case of pool boiling without the natural recirculation effect. In addition, Theofanous et al. [5] can be applied for a specific condition of the AP-600 like geometry [2].

Local condition of mass flux and quality for Rouge et al's correlations [8] were respectively calculated by means of the ratio. It was assumed that the thermodynamic quality in the subcooled boiling region was zero. The subcooling effect on the CHF is not explicitly considered in Rouge et al.'s [8] correlation.

Time to Rupture

Creep damage is considered in this study by calculating the time to rupture with Larson-Miller parameter. Larson-Miller parameter is referenced from Stickler et al. [10].

$$LMP = 29.97 - 8.8342 \log_{10}(0.145\sigma) = 1.8T/1000(11 + \log_{10} t_r) \tag{2}$$

The membrane stress σ is calculated as follows [18]

$$\sigma = p_i(r_o + r_i)/4(r_o - r_i) \quad (3)$$

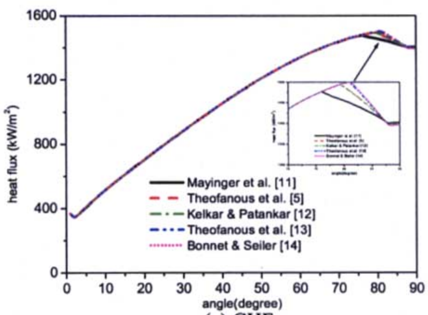
The time to rupture can be calculated from σ in Eq. (3) and the temperature from the thermal load and two-dimensional conduction heat transfer computation.

RESULTS AND DISCUSSION

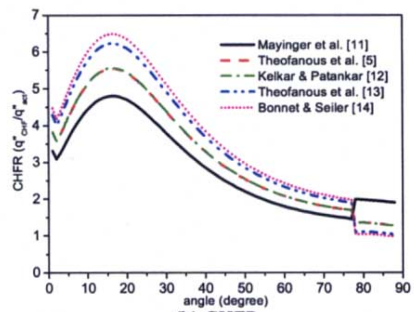
Thermal Margin

The results cover a wide spectrum of sensitivity analyses varying the fractions of downward heat transfer, the correlations for the angular distribution of downward heat flux, mass flow rate, initial subcooled condition, the gap size between the COASISO shell structure and reactor vessel, and the conduction heat transfer in the vessel. If there is no special mention, the parameters are fixed for the reference case in Table 1.

Sensitivity analysis was performed for the heat split fraction. Figure 2 illustrates that the larger heat split fraction reduces the heat flux from the metal layer focusing effect. Figure 3(a) show the larger heat split fraction reduces the CHF as expected in the upper region of the oxide pool but the difference in the CHF values at the angular position of the metal layer is very small because of the similar heat transferred from the oxide pool and the metal layer with the five correlations as shown Figure 2. The thermal margin is presented from differing natural convection correlations for the downward heat transfer given the angular variation of the heat flux in Figure 3(b). The result implies that the thermal margin is higher in the lower region than in the upper region of the oxide pool. Despite increase in the removal energy moving from the bottom to the top as the inclination angle increases, the reason for the thermal margin decrease is that the local heat flux increases more rapidly moving from the bottom to the top. Because the smaller heat split fraction increases the heat flux in the metal layer, the thermal margin increases all at once at the angular position of the metal layer.



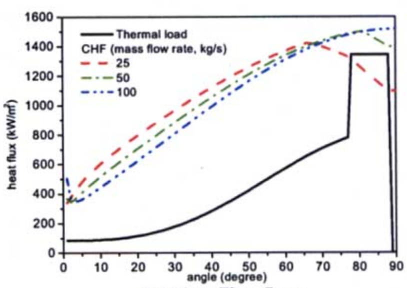
(a) CHF



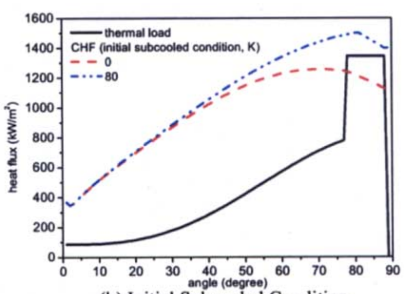
(b) CHFR

Figure 3 Cases for Forced Convective Boiling with Varying Heat Split Fraction

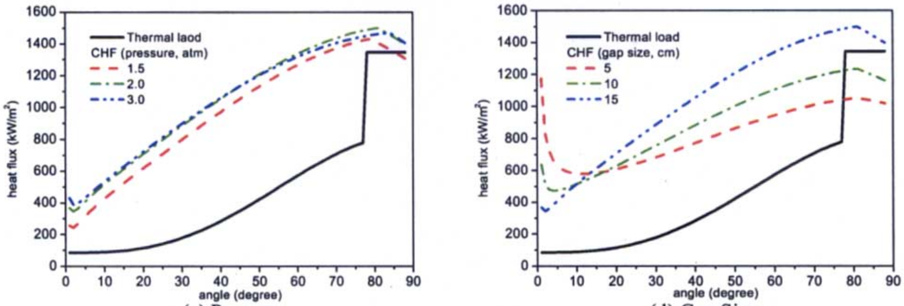
The critical parameters in determining the CHF at the top may be summarized as follows. The large mass velocity decreases the local quality so that the CHF increases at the top as shown in Figure 4(a). The initial subcooled condition decreases the local quality at the top so that the CHF increases at the top as displayed in Figure 4(b). The high pressure of the coolant directly increases the CHF until the decreasing latent heat of vaporization begins to produce the counter effect above a certain limiting pressure. If the initial temperature of the coolant is constant, the higher pressure indirectly increases the CHF due to the larger initial subcooled condition in Figure 4(c). The larger gap size decreases the CHF at the bottom because of the smaller local mass flux, but increases the CHF at the top because of the enhanced natural circulation effect in Figure 4(d).



(a) Mass Flow Rate



(b) Initial Subcooled Condition



(c) Pressure (d) Gap Size

Figure 4 Cases For Forced Convective Boiling with Varying Parameters

In this study the results show that the mass flux has the major influence on the CHF while the thermodynamic quality has a decreasing effect on the CHF at the top unless the limiting value is reached above which the CHF may abruptly decrease, and the gap size has the major influence on the CHF due to natural circulation effect. But the change in the CHF is smaller than the change in the thermal load. The CHF value is dependent on the thermal load. The CHF standard deviation are calculated for Rouge et al.'s [8] correlation and the twenty cases of the natural convection, i.e. the combination of the five correlations for the heat split fraction times the four correlations for the angular distribution as listed Table 1. The CHF deviation is about 10 % including the error of the correlation. The standard deviation in the heat transferred downward is about 4.78 %. Whereas that of the angular deviations in the heat transferred at the metal layer is about 9.8 %. Thus it may be concluded that about 15 % is the overall uncertainty obtained from the combination by root-sum-square for the three factors. Figure 5 shows the best estimate, maximum, average, minimum, and the most conservative values of the CHFR for the reference mass flow rate, initial subcooled condition, pressure, and gap size in Table 1. The best-estimate value of the CHFR is obtained from the largest value in the twenty cases of natural convection in the molten pool. The maximum and minimum values of the CHFR cover the range of the total error. The most conservative value of the CHFR results from the case where the CHFR is the smallest value in twenty cases in natural convection at the molten pool. The values were respectively calculated as follows.

$$CHFR_{best} = Max.(CHFR_{i,j}) \tag{4}$$

$$CHFR_{max} = CHFR_{avg}(1+\sigma_{total}) \tag{5}$$

$$CHFR_{min} = CHFR_{avg}(1-\sigma_{total}) \tag{6}$$

$$CHFR_{worst} = Min.(CHFR_{i,j}) \tag{7}$$

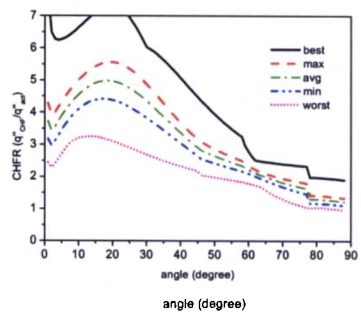
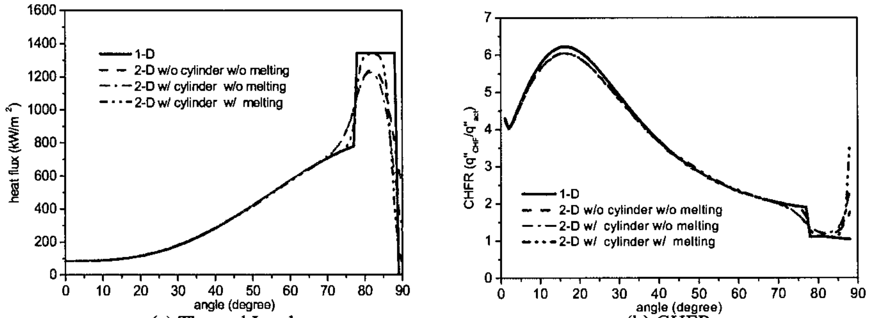


Figure 5 CHFR Uncertainty Band for Various Cases

Figure 6 (a) shows that the cylindrical part has varying degrees of influence on the local heat flux with the angular positions when thickness is 0.15 m. The cylindrical part has little influence on the local heat flux at the bottom. But it tends to decrease the local heat flux on the outer wall at the top. Figure 6 (b) also shows increases in the CHFR at the top because of little effect on the CHF values. Figure 6 also shows the effect on the local heat flux and the thermal margin of the melting. The vessel thickness thins out by the high heat flux at the inner wall so that the effect of two-dimensional conduction heat transfer is decreased. Therefore, the local heat flux at the top with melting and smaller than that without two-dimensional heat transfer as illustrated in Figure 6 (a). Figure 6 (b) shows the same effect on the CHFR. The external vessel cooling of the cylindrical part has the effect of increasing the minimum CHFR.

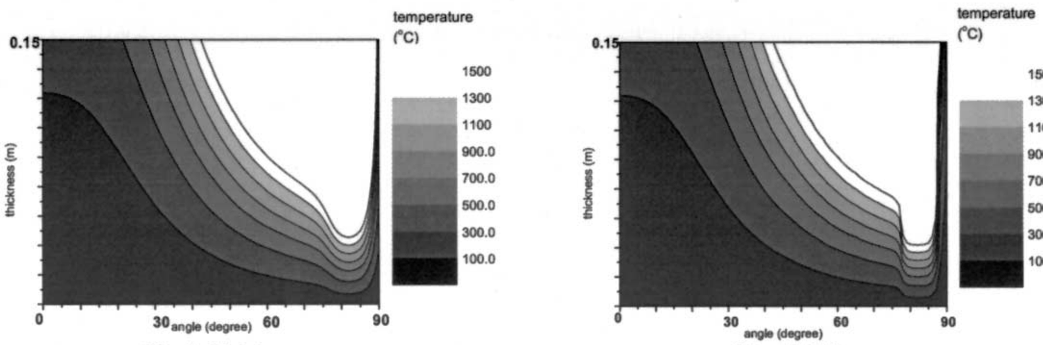


(a) Thermal Load (b) CHFR

Figure 6 Thermal Load and CHFR Values With and Without Cylindrical Part, 2-D Conduction and Melting

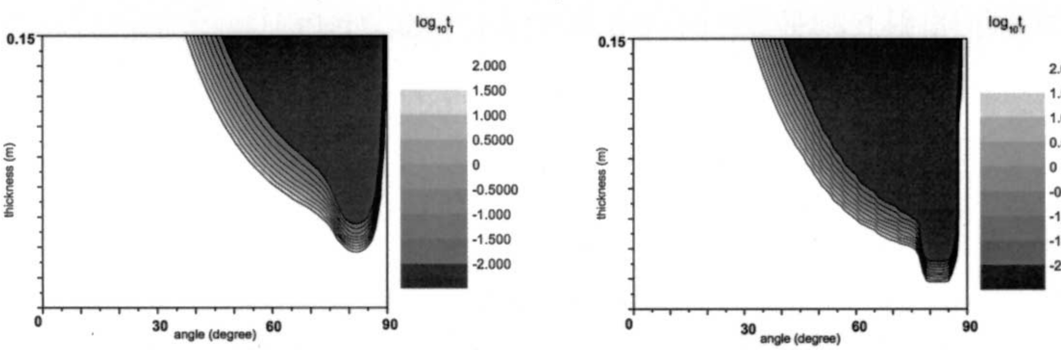
Mechanical Margin

Sensitivity analyses on mechanical margin by the time to rupture were performed for the internal pressure and melting process. The reference internal pressure is 0.3 MPa because of the LBLOCA accident in thermal load calculation. The others are 2 MPa, which is the boundary pressure between high pressure accident and low pressure accident, and 10 MPa. Figure 7 shows temperature distributions with and without melting. The vessel wall thinned by melting reduced the diffusion of thermal load to the cylindrical part so that the molten volume is larger with melting than without melting. Figure 8 shows the distribution of common logarithms of time to rupture. Because of larger molten volume and thinner wall without melting than with melting, the node where common logarithms of the time to rupture are less than 1.5 is closer to the outer vessel with melting.



(a) w/o Melting (b) w/ Melting

Figure 7 Temperature Distributions With and Without Melting



(a) w/o Melting (b) w/ Melting

Figure 8 Distributions of Time to Rupture With and Without Melting

CONCLUSION

Main conclusions from this study may be summarized as follows. First, the natural convection in the oxide pool is the utmost important parameter in determining the CHFR. Especially the heat split fraction from the oxide pool turns to be the main parameter because of the sudden increase of the actual heat flux by the metal layer focusing effect on top of the debris bed. However, existing experimental and numerical studies appear to yield rather differing results judging from considerably large standard deviations for the variation to have a significant impact on the computed CHFR. Therefore, further study is needed to fully test and comprehensively theorize the natural convection in the molten pool. Second, Rouge et al.'s correlation did not unfortunately cover the local subcooled condition and the curved surface. Experiments are needed for the CHF to take the effect of the downward-facing curved surface into consideration. Third, two-dimensional conduction heat transfer in the vessel increases the minimum CHFR though the thinning vessel wall by the melting process. Last but not least, the thinning vessel wall by the melting process increases the membrane stress so that the time to rupture is shortened around the outer wall. Mechanistic analysis is required for the melting process.

NOMENCLATURE

$CHFR$	= critical heat flux ratio
$CHFR_{best}$	= best estimate CHFR
$CHFR_{i,j}$	= CHFR of the various cases
$CHFR_{max}$	= maximum CHFR
$CHFR_{min}$	= minimum CHFR
$CHFR_{worst}$	= the most conservative estimate CHFR
h	= nucleate boiling heat transfer coefficient
LMP	= Larson Miller Parameter
p_{in}	= internal pressure in the vessel
q''_{act}	= actual heat flux or thermal load
q''_{CHF}	= critical heat flux
r_i	= inner radius of the vessel
r_o	= outer radius of the vessel
T	= temperature of the node in the vessel
T_{out}	= temperature of the outer surface
T_{sat}	= saturated temperature of water
t_f	= time to rupture
σ	= membrane stress [MPa]
σ_{total}	= total standard deviation of CHFR

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