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Margin evaluation of in-vessel melt retention for small IPWR

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ABSTRACT

In this paper, the safety margin of IVR (in-vessel melt retention) for small IPWR IP200 (integrated pressurized water reactor) is evaluated by numerical simulation. The thermal hydraulics and core degradation are modeled by SCDAP/RELAP5 code to provide initial conditions for the IVR. Meanwhile, the lower head behaviors are modeled by the finite element code COUPLE to present the dynamic evolution of molten pool with detailed temperature distribution. The transient analyses of thermal load firstly focus on the progression of corium solidification and external cooling, and then analogize to the IVR studies of other IPWRs to discuss the impacts which caused by the inherent design features of IP200. Besides, the differences between FIBS steady model and SCDAP transient model are discussed in terms of the heat transfer governing equation to summarize the benefits of transient calculation. In order to explain the calculation rationality, the result of maximum surface heat flux is also validated with the dimensionless data of related experiment. Finally, the mass composition of molten pool and the gap thermal resistance of inner wall are selected for parametric sensitivity analyses to assess the conservatism of maximum heat flux. For the quantitative conclusions, the low coolant storage of IP200 makes the core degradation very fast. The duration is about 9500s and the maximum temperature of liquid corium is close to 2900 K. The initial inner heat of molten pool is very high that the transient heat flux can get approximately 195% above the steady value. At the moment of maximum thermal load, the peak heat flux reaches 0.46 MW/m^2, still lower than the local CHF. The lowest safety margin locates at the bottom angle and corresponding q/CHF is 0.65. The present work can provide references for the safety design of small IPWR.

1. Introduction

IVR-ERVC (in-vessel retention via external reactor vessel cooling) is widely adopted in the advanced PWRs as a crucial measure for severe accident management. Ensuring the surface heat flux of lower head lower than the local CHF (critical heat flux) is a conservative criterion for the effectiveness of IVR (Pham et al., 2012). A hot topic of current study is the transient heat transfer of molten pool, which is a key mechanism to determine the thermal margin of IVR.

Many experimental studies are contributive to explore the above heat transfer mechanism, but the relevant conclusions still have deviations that cannot form a unified theory. These deviations mainly come from the different explanations of internal natural convection, dynamic solidification and thermal stratification (Gaus-Liu et al., 2010; Pham et al., 2013; Zhang et al., 2016a, 2016b). Similarly, given the mechanism experiment is the basis of numerical calculation, the deviations should also exist in different numerical models that may influence the empirical relation of convective heat transfer, the heat transfer governing equation on solid-liquid interface and the boundary assumption of metal layer. That means, the models of IVR will be influenced by many uncertainties in mechanism, as well as the credibility of different calculations can hardly be evaluated with a uniform criterion. However, even numerical calculation is less credible than experiment, it still becomes the main method for the margin evaluation of IVR, since numerical calculation is usually carried out for the specific reactor that can cover more comprehensive considerations to make the conclusion more targeted and practical.

Jin (Jin et al., 2015) uses MELCOR code to evaluate the safety margin of IVR for APR1400 reactor. Reactor features and accident sequences are both considered in the calculation. A two dimensional model of heat transfer is used to describe the molten pool, and three boiling modes are considered in the external cooling of lower head, which to improve the simulation accuracy. The advantage of such integrated analysis code (Gencheva et al., 2016; Wang et al., 2014; Jiang et al., 2018a) (such as ASTEC, SCDAP/RELAP5, MAAP) is that the multiple phenomena of severe accident can all be covered to reveal their interactions. However, given a lot of uncertain parameters will also be introduced in the multiple models, the parametric sensitivity analysis should be conducted to get the most conservative result. In the sensitivity calculation of Jin's study, the maximum deviation of heat

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Nomenclature

CHF	Critical heat flux
ERVC	External reactor vessel cooling
FIBS	Final Bounding State
HX	Heat exchanger
IPWR	Integrated pressurized water reactor
IVR	In-vessel melt retention
LBLOCA	Large break loss of coolant accident
k	Thermal conductivity of solidified crust
σ	Thickness of solidified layer
T_L	Liquidus temperature of molten corium
R	Effective radius of the molten region
β	Coefficient of volumetric expansion
f(θ)	Factor that varies with angular position
OTSG	Once-through steam generator
PRHR	Passive residual heat removal
PSS	Passive safety system
PWR	Pressurized water reactor
RPV	Reactor pressure vessel
SBLOCA	Small break loss of coolant accident
SBO	Station blackout
q_v	Volumetric heat generation of corium
h_m	Heat transfer coefficient of inner natural convection
h_{fus}	Latent heat of fusion of corium
Q	Effective radius of the molten region
ν	Kinematic viscosity
α	Thermal diffusivity

flux caused by metal layer thickness can reach 27%. Tusheva (Tusheva et al., 2015) uses finite element code ANSYS to calculate the thermal load of IVR for VVER1000 reactor. In this study, the thermodynamic model of molten pool and the mechanical model of RPV wall are recursively coupled to calculate temperature and stress. Comparing with the finite volume method of integrated code, the advantage of finite element method is that the interpolation calculation requires less continuity to solve the integral in irregular region. Therefore, the non-spherical structure of molten pool and the irregular melting of PRV wall can both be considered in the calculation. However, the result of such high-resolution local calculation is strongly affected by the initial and boundary value, and the initial value still needs to be extracted from the integrated code.

In the complex engineering calculations, different numerical methods are tried to consider the multiple factors, which can provide effective references for the IVR evaluation. But the mainstream trend of these studies is raising the Rayleigh number of molten pool towards higher, which aims to assess the thermal margin of IVR for ultra-high-power reactor. Correspondingly, their analyses of IVR effectiveness only focus on the mechanism phenomenon of high power molten pool, or the design features of high power distributed reactors. However, less studies have been done for the IVR of small power IPWR (integrated pressurized water reactor) at present, and the relevant thermal margin analysis is still lacking.

Park (Park et al., 2013) uses the lumped parameter code MIDAS to perform an IVR estimation for the 330 MW SMART reactor. This study belongs to the steady-state calculation of FIBS (FInal Bounding State) which assumes the molten pool has formed a stable stratification. Thus, the thermal power of molten pool is set to be constant, and the external cooling is simplified as an isothermal boundary of saturated water.

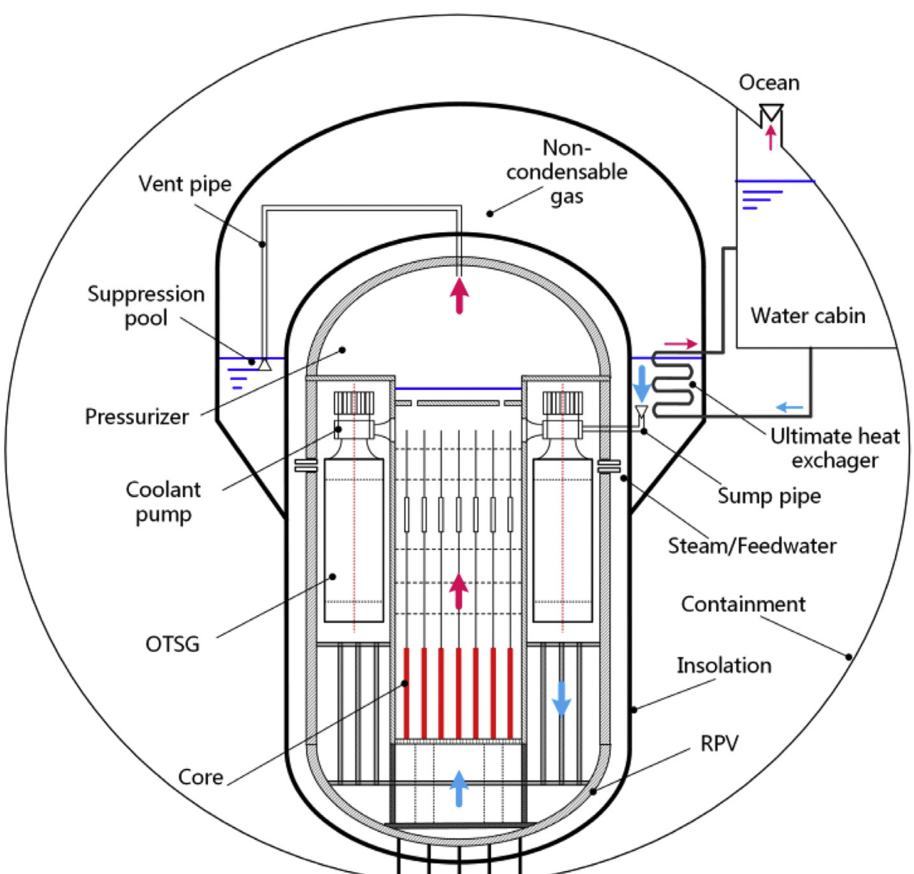

Fig. 1. Structure of IP200 and its PSS.