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# Evaluation of in-vessel corium retention through external reactor vessel cooling for small integral reactor

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## HIGHLIGHTS

- We evaluate success criteria of IVR-ERVC for a small integral reactor.
- We perform a thermal load analysis from the corium pool to the outer vessel wall.
- We determine the maximum heat removal rate through the external coolant.
- Thermal margin for the IVR-ERVC is sufficient in the small integral reactor.
- The reactor vessel integrity is maintained during a severe accident.

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## ABSTRACT

A criterion to prevent reactor vessel failure using in-vessel corium retention through the external reactor vessel cooling (IVR-ERVC) of a small integral reactor has been evaluated during a severe accident. A thermal load analysis from the corium pool to the outer reactor vessel wall in the lower plenum of the reactor vessel was performed to determine the heat flux distribution. The critical heat flux (CHF) on the outer reactor vessel wall was determined to fix the maximum heat removal rate through the external coolant between the outer reactor vessel and the insulation of the reactor vessel. Finally, the thermal margin was evaluated through a comparison of the thermal load with the maximum heat removal rate of the CHF on the outer reactor vessel wall. The maximum heat flux from the corium pool to the outer reactor vessel is estimated as approximately 0.25 MW/m$^2$ in the metallic layer, owing to the focusing effect. The CHF of the outer reactor vessel is approximately 1.0–1.1 MW/m$^2$ because of a two-phase natural circulation mass flow rate. Since the thermal margin for the IVR-ERVC is sufficient, the reactor vessel integrity is maintained during a severe accident in the small integral reactor.



## 1. Introduction

The in-vessel corium retention through external reactor vessel cooling (IVR-ERVC) is known to be an effective means for maintaining reactor vessel integrity during a severe accident in a nuclear power plant (Theofanous et al., 1996, 1997; Rempe et al., 2008). This measure has been adopted in low-power reactors of the AP600 and Loviisa nuclear power plants, and in medium-power reactor of AP1000 as a design feature for severe accident mitigation (Esmaili and Khatib-Rahbar, 2004; Dinh et al., 2003, 2004; Scobel et al., 2002; Kymalainean et al., 1997), and in high-power reactors of the advanced power reactor (APR) 1400 and APR$^+$ as an accident management strategy (KEPCO, 1998; Park et al., 2001). It is also adopted in a Korean small integral reactor (The SMART Development Team, 2010) as a design feature for severe accident management. Many studies have been performed to evaluate the IVR-ERVC to prevent a reactor vessel failure (Cheung, 2005; Ha et al., 2012a,b; Park et al., 1994; Yang et al., 1994), but more effort is necessary to verify this severe accident management strategy or its design feature for severe accident mitigation.

A success criterion of the IVR-ERVC during a severe accident for a small integral reactor in Korea has been evaluated to determine the thermal margin for the prevention of a reactor vessel failure. A thermal load analysis from the corium pool to the outer reactor vessel in the lower plenum of the reactor vessel was performed to determine the heat flux distribution. The critical heat flux (CHF) on the outer reactor vessel wall was determined to fix the maximum heat removal rate through the external coolant between the outer reactor vessel and the insulation of the reactor vessel . Finally, the thermal margin for success of the IVR-ERVC during a severe accident in the small integral reactor in Korea was evaluated through a comparison of the thermal load with the

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($m^2$) |
| $c_p$ | specific heat ($J\,kg^{-1}\,K^{-1}$) |
| $C_{sf}$ | nucleate boiling coefficient ($W\,m^{-2}\,K^{-1}$) |
| $g$ | gravity acceleration ($ms^{-2}$) |
| $h$ | heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) |
| $k$ | thermal conductivity ($W\,m^{-1}\,K^{-1}$) |
| $L$ | height of the pool layer (m) |
| Nu | average Nusselt number (=$hL/k$) |
| Pr | Prandtl number (=$\nu/\alpha$) |
| $Q$ | heat generation (W) |
| $Ra$ | Rayleigh number (=$g\beta\Delta TL^3/(\alpha\nu)$), metallic pool |
| $Ra$ | Rayleigh number (=$g\beta QL^5/(\alpha\nu k)$), oxidic pool |
| $q$ | heat flux ($W\,m^{-2}$) |
| $T$ | temperature (K) |
| $V$ | volume ($m^3$) |
| *Greek symbols* | |
| $\alpha$ | thermal diffusivity ($m^2\,s^{-1}$) |
| $\beta$ | thermal expansion coefficient ($K^{-1}$) |
| $\delta$ | thickness (m) |
| $\varepsilon$ | emissivity |
| $\rho$ | density ($kg\,m^{-3}$) |
| $\theta$ | angular position |
| $\sigma$ | Stefan–Boltzmann constant |
| $\nu$ | kinematic viscosity ($m^2\,s^{-1}$) |
| $\Delta T$ | temperature difference between the top and bottom surfaces in the metal pool ($K^{-1}$) |
| *Subscript* | |
| $b$ | bulk |
| $boil$ | boiling point |
| $c$ | crust |
| $c,dn$ | downward crust layer |
| $c,up$ | upper crust layer |
| $l$ | light metal layer |
| $l,b$ | bottom wall of light metal layer |
| $l,bulk$ | bulk of light metal layer |
| $l,t$ | top wall of light metal layer |
| $m$ | melting |
| $max$ | maximum |
| $o$ | oxide pool |
| $o,m$ | melting property in oxide pool |
| $o,max$ | maximum property in oxide pool |
| $o,dn$ | downward property in oxide pool |
| $o,up$ | upward property in oxide pool |
| $s$ | internal structure |
| $sat$ | saturation |
| $w$ | vessel wall |
| $w,in$ | inner wall of vessel |
| $w,out$ | outer wall of vessel |
| *Superscript* | |
| $''$ | per unit area |
| $'''$ | per unit volume |

maximum heat removal rate of the CHF on the outer reactor vessel wall.

## 2. Design characteristics of integral reactor

In general, an integral reactor has a big reactor vessel size in comparison with other reactors, because the main components of the steam generators, the pressurizer, and the reactor coolant pumps are located inside the reactor vessel. Thus, the lower plenum is large compared with the thermal power.

**Table 1**
Comparison of the main design parameters of the Korean small integral reactor with other plants.

| Design parameters | Small integral reactor | OPR1000 | APR1400 |
|---|---|---|---|
| Core thermal power (MW) | 330 | 2815 | 3983 |
| Fuel ($UO_2$) mass (ton) | 16.8 | 85.6 | 120.0 |
| Mass for active core zircaloy-4 (ton) | 4.7 | 23.9 | 33.6 |
| Bottom head inner diameter (m) | 5.3 | 4.2 | 4.7 |
| Bottom head thickness (cm) | 20.0 | 15.2 | 16.5 |
| Number of ICI nozzle in the lower head | None | 45 | 61 |

Table 1 shows a comparison of the design parameters of the Korean small integral reactor with other plants of the optimized power reactor (OPR) 1000 and APR1400 in Korea. The total mass of the core materials of the Korean integral reactor is smaller than that of the OPR1000 and APR1400, as the thermal power is small. However, the reactor vessel size and thickness of the Korean integral reactor are bigger than those of the OPR1000 and APR1400, because the main components are located inside the reactor vessel. The ICI (In-Core Instrumentation) nozzles are not located in the lower hemispherical reactor vessel of the integral reactor. In general, if these nozzles were to be located in the lower plenum of the reactor vessel, they will affect the evaluation of the IVR-ERVC.

Fig. 1 shows a schematic diagram of the containment for the Korean small integral reactor. The reactor vessel insulator is installed in the reactor cavity. During the IVR-ERVC condition,

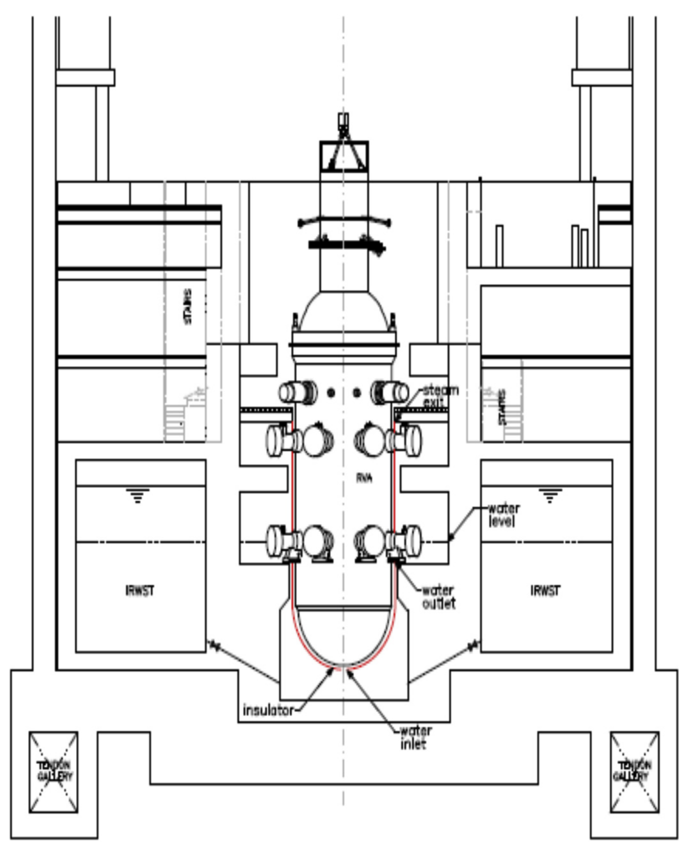


**Fig. 1.** Schematic diagram of the containment for the small integral reactor in Korea.