Review of the Performance Features of Containment Evacuation System in Integral Pressurized Water Reactor

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1. Introduction

SMRs (Small Modular Reactors) are recognized as a very high-profile energy source amid the prediction of an explosive surge in energy demand. Moreover, global trend of net zero emission attracts nuclear energy unexpectedly compared to before. Despite this favor for nuclear power, the incompleteness of SMR design makes the quick deployment hesitant.

Water-cooled reactors are one of the most deployable SMR: actually several water-cooled SMR completed detailed design stage. And many of the water-cooled SMR takes a type of integral pressurized water reactor (iPWR). iPWRs have many merits for the fast deployment in that they can take most of the construction and operation experiences reaching more than 10,000 reactor-years. Nevertheless, iPWR faces new challenges, because all components of the plant are integrated into one large reactor and the reactor containment vessel (CV) is usually extremely small compared to conventional PWR containments.

Fig. 1 is an illustration of i-SMR, a kind of iPWR, which is now under development in Korean nuclear industry. This shows a very small and narrow CV, and the CV is usually maintained as low pressure as achievable. The low CV pressure during normal operation gives some benefit such as less heat loss, and it results in high heat removal rate during LOCA (loss-of-coolant-accident) due to high condensation heat transfer because of low non-condensable gas fraction. The precedingly leading NuScale is also known to maintain very low pressure as much as 0.1 psia during normal operation [2]. The heat loss reduction in NuScale is believed much more than the others, since it is nearly submerged in a reactor pool.

This paper reviews the design performance feature of the containment evacuation system, which is not so friendly because the conventional PWRs do not have such a system and function.

2. Thermodynamic Features of Containment Vacuum and RCS Leakage

2.1 Review of Pressure 0.1psi

iPWR is also a kind of water-cooled reactor, and the thermodynamics is usually related with water. The triple point of water is 611.244Pa, 0.0007052℃. The pressure 0.1psi is nearly 690Pa, and its corresponding saturation temperature is 1.69℃. Thus, it is noticeable that the 0.1psia is very close to triple point. Moreover, it is very difficult to depressurize by condensing the steam, because the lower chiller temperature than 0.0007℃ can have a risk of making ice, which is almost impossible to remove from the CV (See Fig. 2).

Fig. 1. Illustration of i-SMR [1]

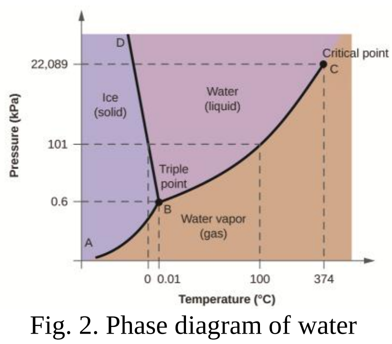

Fig. 2. Phase diagram of water

2.2 Review of RCS Leak Rate

PWR has an inherent feature of coolant leak from reactor coolant system (RCS), so called RCS leak rate. The old conventional PWR usually has 1.0gpm leak rate, and NuScale and some advanced reactors consider 0.5gpm. 0.5gpm in SMR looks very large value considering the very simple design of it.

When the coolant at cold leg condition is leaked into CV of 0.1psia and 200℃ (conservative temperature), assuming complete flashing and evaporation, the 0.5 gpm RCS leak rate is corresponding to 7.28m^3/s in gas form in CV as shown in Fig. 3. It means that the vacuum pump has to remove the gas at the rate of 7.28m^3/s in order to maintain the CV pressure 0.1psi. This flow is achievable if the gas velocity in 2" pipe is 50m/s and if the pipe number is nearly a hundred!

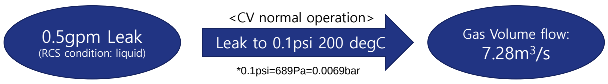

Fig. 3. Volume change to gas flow of RCS leakage

2.3 Analysis of CV Pressurization Considering RCS Leak Rate

As shown above section, 50m/s seems so slow. Followings are selected some important conditions for analysis of vacuum pump performance using MARS code [3]:

- Chamber free volume: 1,500m^3 (This value may be larger than NuScale CV and i-SMR CV)
- Chamber initial condition: 0.1psi, 200℃ (Temperature is conservatively high)
- Heating wall (RV outer wall): 310℃
- Cooling wall (CV inner wall): 80℃
- Pipe size: 2"
- Remove gas velocity: 100m/s (This is very close to choked flow condition. And it cannot be achievable in actual system)
- Stabilizing period: until 20,000sec
- RCS leak rate 0.5gpm: from 20,000sec (The location is assumed bottom of the CV)

As shown in Fig. 4, the chamber is pressurized to 1.0psi (0.068bar) within 35.0minutes. This pressure is very close to the "Not acceptable" region for the RCS leak rate detection in Fig. 5, which is soon discussed.

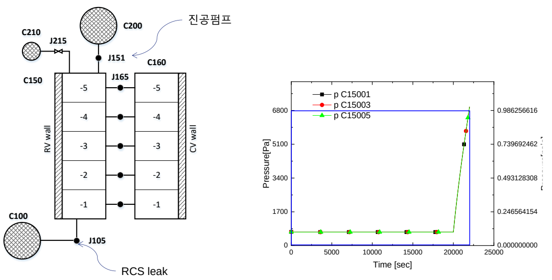

Fig. 4. Analysis of Vacuum Pump Performance (Modelling Node and Result)

3. Review of NuScale Design

3.1 Review of Containment Evacuation System and CV Internal Pressure

The FSAR (Final Safety Analysis Report) section 9.3.6 "Containment Evacuation System (CES) and Containment Flooding and Drain System (CDFS)" deals with this system. But, there is no description on the CV normal internal pressure 0.1psi. Rather, the operation pressure is described in the FSAR section 6.2.1 "Containment Functional Design". In the FSAR Table 6.2-1 the internal CV pressure of normal operation is set 0.1psi.

3.2 Review of RCS leak rate detection design

The FSAR section 5.2.5 "Reactor Coolant Pressure Boundary Leakage Detection" and the FSAR 5.2.5.1 "Leakage Detection and Monitoring" describe the RCS leak rate detection and acceptability using the CV pressure and the reactor pool temperature as shown in Fig. 5.

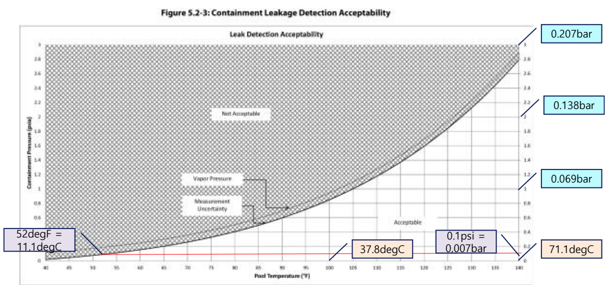

Fig. 5. NuScale's Leakage Detection Acceptability using Containment Conditions

It seems that all the leak is evaporated and the CES condenses the steam to measure the leak rate. Thus, if the CV pressure is lower than the saturation point for given temperature with sufficient margin, the evaporation is not complete and the leak detection is difficult, i.e., unacceptable condition of CV.

One noticeable description in the FSAR is that the 1.0gpm leak rate results in the 0.1 psi pressurization of CV within 1 minute. It looks very rapid pressurization to threaten the plant operation.

3.3 Review of Reactor Pool

A reactor pool is placed outside CV and plays a role of ultimate heat sink (UHS). This pool temperature is believed to affect much the CV internal temperature. The pool temperature in horizontal axis in the graph of Fig. 5 is this pool temperature. The FSAR Table 9.2.5-1 specifies the pool temperature limits as 65˚F-110˚F (18.3℃-43.3℃), together with normal operating temperature 100˚F (37.8℃). Corresponding saturation pressure of 110˚F is 1.275psi (0.0879bar). This pressure can be quickly reached after around 13 minutes according to section 3.3 above.

3.4 Review of Technical Specification

NuScale published generic Technical Specification (TS). In the TS section 3.6, which is related with containment, there is no limiting condition of operation (LCO) on the CV internal pressure. For the reactor pool, there is also no LCO in spite that the FSAR section 9.2.5 specifies the pool temperature limits as discussed in section 3.3 above.

However, in the TS section 3.4.5 RCS operational leakage is limited, which seems corresponding to the FSAR section 5.2.5

3.5 Review of Initial Condition of Accident Analysis

In the FSAR Table 15.0-6 the CV initial pressure is described as 0-3psi. This value seems to consider the uncertainty of the CV pressure maintenance and non-condensable gas from the RCS.

3.6 Estimation of CV Normal Temperature

The accident analysis results in the FSAR section 15.4 and 6.2 provide the graphs of CV temperature in case of accidents. The initial temperature seems over 110˚F~245˚F (43.3℃ ~ 118.3℃).

4. Alternative Method for Vacuum

4.1 Complete Evaporation Analysis

One important function of the containment evacuation system is to detect the RCS leak rate accurately. This function is conducted by evaporating all the liquid water in the CV. The evaporated steam is carried into the condenser in the containment evacuation system, and is condensed to measure the inflow rate.

The leaked coolant at first flashed, and some becomes gas phase and the other remain as saturated water to evaporate. It is necessary to analyze how much of the saturated water is flashed and evaporated.

<u>Flashing Analysis</u>

The coolant is in RCS condition before leak:

- RCS pressure: 150 bar
- RCS temperature: 280 ℃

The coolant is leaked into the CV pressure in following condition:

- CV pressure: 0.3 bar

The pressure0.3bar rather than 0.1psi is selected for the more realistically achievable target through above discussion.

The leak process is assumed to be isentropic process or isenthalpic process for the conservatively less flashing. Of course, the isenthalpic process yields more steam than isentropic process. Isenthalpic process is believed to be closer to the realistic case. For each process, the resultant calculated are summarized in Table I.

Table I: Flashing Analysis

	Flashed quality [-]	Liquid rate [kg/s]
Isentropic process	0.323	0.0209
Isenthalpic process	0.400	0.0185

<u>Evaporation Analysis</u>

The remained water is assumed to fall down the bottom of the CV and undergo the free convection heat transfer with the CV atmosphere. This heat transfer model is usually based on Ra number, which is proportional to the temperature difference, (T_{CV}-T_s). One temperature (T_{CV}) is CV atmosphere temperature, and the other temperature (T_s) is nono-flashed water temperature.

The none-flashed water temperature is saturated depending on the CV pressure as shown in Fig. 6, where it can be found that the gradient become smaller as the pressure increases. For 0.3 bar CV pressure, for example, the saturation temperature is 69.1℃

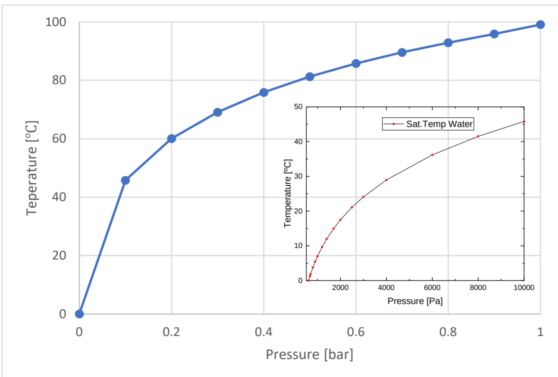

Fig. 6. Saturation curve of water

The calculated Ra number, heat transfer coefficient (HTC), and resultant evaporation rate for the CV temperature 150℃ are provided in Table II.

Table II: Evaporation Rate

CV temp. [℃]	Ra [10^{10}]	HTC [W/m^2K]	Evaporation [kg/s]
150	3.3	2.899	0.000286

If the HTC increases to 6 W/m^2K under affordable condition, the evaporation would be nearly 0.00055kg/s. It is regarded as far smaller value compared to Table II.

4.2 Chilling Method together with Vacuum Pump

This method is to condensed the steam and depressurize the CV. The chiller is specified as follow:

- Install: Outer wall of CV upper part
- Heat transfer area: width 0.1m along the outer circumference (corresponding heat transfer area is 13.34m^2)
- Chiller temperature: 4℃
- Vacuum pump: 100m/s through 4” pipe

MARS was used to analyze as shown in Fig. 7. The RCS leak and chilling start from 0 second, and the pressure reaches equilibrium state nearly 2,450Pa. When the vacuum pump starts additionally, the pressure decreased to be 2,250Pa.

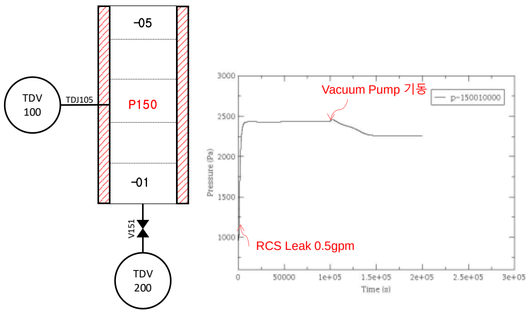

Fig. 7. Chilling Analysis

Chiller is more contributable to the depressurization than vacuum pump. However, the water is to fall to the bottom of the CV, and new facility is necessary to remove the water. And the RCS leak rate detection becomes difficult.

5. Conclusions

This paper reviews the containment vacuum system and relevant features. The CV pressure 0.1psi seems too low pressure to achieve using vacuum pump. The conservative evaporation rate cannot follow up the RCS leak rate. Chilling method seems very powerful method, however it yields another problems such as water removal and RCS leak rate detection. More consideration is necessary for the smart design of the containment evacuation system.

ACKNOWLEDGMENTS

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