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Quantitative Risk Assessment of MMR Passive Decay Heat Removal System

Eunseo So [a], Man Cheol Kim [a*]
[a]*Department of Energy Systems Engineering, Chung-Ang University, 84, Heukseok-ro, Dongjak-gu, Seoul, Korea*
[*]*Corresponding author: charleskim@cau.ac.kr*

1. Introduction

Recently, new and advanced reactors adopted many innovative concepts to meet the needs of consumers. One of them, KAIST micro modular reactor (MMR) is a supercritical CO_2 (S-CO_2) cooled fast reactor, which can generate 36MWth. MMR is aiming at the operation in remote region with the minimum amount of human action. It has long life core, autonomous load following operation and safety systems without continuous supply of electric power. Especially, it has passive decay heat removal (PDHR) system which remove the heat from the core to the ambient air [1].

Owing to the weak driving force, the reliability of passive systems has many challenges and it has been considered with conservative assumptions. The recent studies devised many methodologies to evaluate the reliability of passive systems in realistic way [2].

The uncertainty for unprotected loss of flow (ULOF) of prototype Gen-IV sodium-cooled fast reactor (PGSFR) was analyzed. Phenomena identification and ranking table (PIRT) and model identification and ranking table (MIRT) was developed to identify the knowledge level and uncertainty parameters of the scenario. The result showed that the safety limits were not exceeded in any samples [3].

To evaluate the reliability of passive systems quantitatively, two approaches were provided; exceedance probability (EP) model and stress-strength interference (SSI) model. The former one was suggested if there is not enough information of the system strength [4].

In this paper, the quantitative risk assessment of PDHR system was performed in a large loss of coolant accident without scram (LLOCAWS) scenario with single failure criterion of PDHR train. The EP model approach with single failure criterion was applied as a feasibility study of the evaluation of the reliability of PDHR system.

2. Background of Analysis

2.1 MMR Safety Systems

MMR has simple safety systems because of its small size and minimum human action. If the reactor is tripped, the active air-cooling system is not involved in the accident mitigation system. Only four safety systems are considered which operates without continuous power supply or human action such as feed valve, venting valve, turbine bypass valve and PDHR system.

Feed valve passively feeds the CO_2 in the inner containment to the primary system when the pressure goes below the containment pressure. Venting valve is located near the core and opened to depressurize the primary system. Turbine bypass valve is opened to prevent the turbine blade from damage. PDHR system is connecting the core and the ambient air with two heat exchangers [5].

The whole system including the turbomachinery is contained in the inner and outer containment as shown in Fig. 1. The inner and outer containment is pressurized at 5MPa and 1MPa respectively.

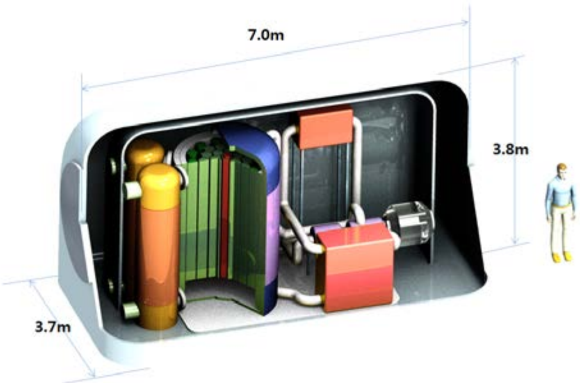

Fig. 1. Layout of KAIST MMR concept design.

2.2 Accident Scenario of PDHR System

The LLOCA is assumed to be 100in^2 and located at the compressor outlet, which has the highest pressure of the primary system. After LOCA occurred, the primary system pressure decreases generating reactor trip signal and PDHR valves open signal. Feed valve is opened when the pressure at the compressor inlet goes below the containment pressure.

In the previous study, transient analyses were performed for LOCA to develop an event tree. The LLOCA and small loss of coolant accident (SLOCA) were analyzed considering the failure combinations of three safety functions, which are reactor trip, feed valve opening, and PDHR system. Among them, the LLOCAWS scenario with one PDHR train showed the highest value of the peak cladding temperature (PCT) 1089.2℃ although it is still under the safety limit 1200℃ [6].

3. Quantitative Risk Assessment of PDHR System

3.1 Evaluation Methods

The passive safety systems can be grouped by four categories from A to D [7]. PDHR system can be regarded as category D because it consists of the valves which need an actuation signal to operate. Reactor cavity cooling system (RCCS) for very high temperature reactors (VHTRs) can be considered as category B, which has moving working fluid, but no moving mechanical parts. And it makes the risk assessment of the passive safety systems more complicated.

To evaluate the reliability of passive systems, two approaches were provided such as EP model and SSI model. These approaches can be utilized with single criterion or two failure criteria which are determined by the release level of radioactive materials [4]. Because we cannot specify the strength distribution or two or more criteria in conceptual design, EP model approach with single failure criterion is adopted as a feasibility study of quantitative risk assessment of PDHR system.

The transient analysis code used was General Analyzer for Multi-component and Multi-dimensional Transient Application (GAMMA+) code, which was originally developed by Korea Atomic Energy Research Institute (KAERI) and modified with S-CO_2 data [5,8].

3.2 Quantitative Risk Assessment of PDHR System

The MMR core consists of uranium carbide (UC) fuel and assumed to be at the beginning of life (BOL). As a feasibility study, fuel temperature reactivity coefficient (FTC) and steam mass reactivity coefficient (SMC) were adopted among many uncertainty parameters such as fuel conductivity or heat capacity. It is assumed that it has normal distribution and the uncertainty band and standard deviation is assumed as shown in Table I. Then 100 random samples within the given condition of FTC and SMC were derived by Module for Sampling Input and Quantifying Estimator (MOSAIQUE) [9].

As a result, the PCT of each sample can be drawn as a normal distribution with the mean of 1089.7℃ and the standard deviation of 4.9℃ as shown in Figure 2. There were no sample which exceeded the safety limit of PCT, however the failure probability of cooling performance of PDHR system can be calculated as about 2.055E-6 in this accident scenario.

This probability mans the cooling performance of one PDHR train when the PDHR valve is successfully opened. Unlike RCCS of VHTR, PDHR has moving mechanical parts and needs actuation signal. Therefore, failure probability of both should also be considered to calculate the exact failure probability in this scenario.

Table I: Uncertainty Parameters

	Nominal value	Standard deviation	Uncertainty band
FTC	-0.457 pcm/K	6.352E-4	± 20%
SMC	2.063 pcm/(kg/m^3)	1.344E-3	± 20%

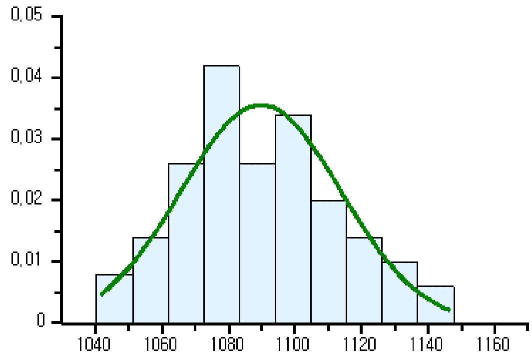

Fig. 2. PCT distribution of LLOCAWS scenario with single failure of PDHR train.

However, as mentioned above, the distribution of the reactivity coefficients is simply assumed value for the feasibility study. Detailed analysis is required for the identification of uncertainty parameters to evaluate the reliability as reasonable as possible.

3. Conclusions

To identify the adaptability of reliability evaluation method used for passive system in different category. Even though PDHR system has moving mechanical parts and needs actuation signal, it is still essential to evaluate the reliability of the natural circulation. In this paper, LLOCAWS with one PDHR train was adopted which has the highest value of PCT among the transient analysis scenarios. Finally, the failure probability of decay heat removal by one PDHR train was calculated.

The result does not tell the failure probability of the whole PDHR system and there are still remaining parts such as mechanical failure, signal failure and so on. It is also the result of the specific scenario and PDHR system may have different failure probability depending on the accident scenario. Moreover, the uncertainty parameters are simply assumed value which means that it does not reflect the uncertainty of natural circulation.

If the quantitative risk assessment including PDHR system is done, MMR may gain insight into the design improvement in the process of the probabilistic safety assessment (PSA).

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