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A Quantitative Accident Sequence Analysis for a VHTR

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1. Introduction

The Very High Temperature gas-cooled Reactor (VHTR) is one of the six technologies classified by the Generation Ⅳ International Forum as a high-energy heat source for nuclear hydrogen generation. In Korea, the basic design features of VHTR are currently discussed in the various design concepts.

Probabilistic risk assessment (PRA) offers a logical and structured method to assess risks of a large and complex engineered system, such as a nuclear power plant. It will be introduced at an early stage in the design, and will be upgraded at various design and licensing stages as the design matures and the design details are defined. Risk insights to be developed from the PRA are viewed as essential to developing a design that is optimized in meeting safety objectives and in interpreting the applicability of the existing demands to the safety design approach of the VHTR [1].

For this reason, an accident sequence analysis for VHTR was conducted. This paper shows the results and insights of the analysis which will be needed to assure the safety of the design.

2. Methods and Results

2.1 Methodology

A PRA model for VHTR will be structured somewhat differently than the traditional Level 1-2-3 model for a light water reactor (LWR) PRA for several reasons. There is nothing comparable to a Level 1 PRA for VHTR, because there is no plant state comparable to 'core damage frequency' and 'large early release frequency' as defined for an LWR [2]. Thus, it is needed to implement a new PRA procedure for VHTR, as shown in Fig.1.

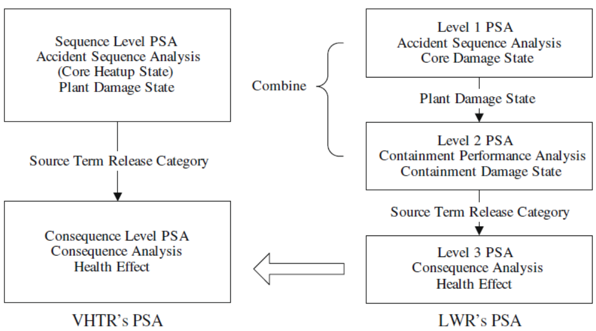

Fig.1. A tentative PRA procedure for VHTR comparing with LWR's PRA [3]

This paper deals with the sequence level PRA in Fig.1, which is similar to a combination of Level 1 and Level 2 PRA. The end states of accident should be defined according to the release categories of radioactive materials, which are called a source term release category in the typical PRA [3]. Therefore, two release categories, namely SR for small release and LR for large release were defined for this study. As VHTR is in the design stage where various configurations are under consideration now, a concept design of VHTR that is shown in Fig.2 was used for the analysis.

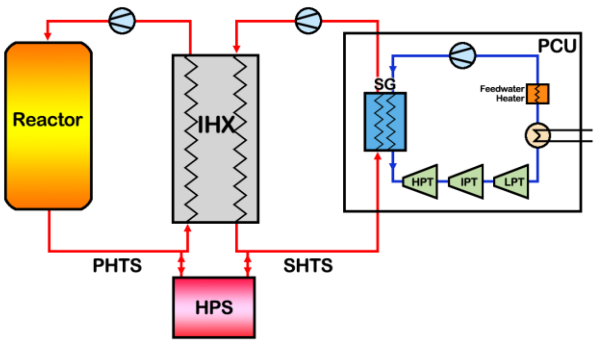

Fig.2. A concept design of VHTR used for the analysis

2.2 Initiating Events Selection

Master Logic Diagram (MLD) was used to identify possible initiating events occurring in the VHTR, and ensure to a high degree of the completeness of the analysis. Possible initiating events were selected through the MLD method which addressed systems and structures which are required to maintain control of radionuclide release. Possible initiating events were defined based on three function failures: failure of control heat generation, failure of decay heat removal, and failure of chemical attack control.

The possible initiating events were screened and then grouped into four initiating events categories. For the quantification of initiating events frequencies, the fault tree analysis was used. The reliability data used for the fault tree analysis were compiled from operating experience in LWR or HTGR operating experience and risk analysis. The four initiating events categories that are going to be analyzed and their frequencies are shown in Table I.

Table I: Initiating events categories and frequencies

Category	Frequency (/RY)	Error Factor	Source
Loss of Helium Pressure Boundary	5E-4	3.2	[4]
Loss of Secondary Heat Transport System	1.621E-2	5.0	Fault Tree
Water Ingress	2.7E-5	5.0	[5]
Transients	1.47	3.8	[4]

2.3 Accident Sequence Analysis

Accident sequences from the 4 initiating events were modeled using the event tree analysis. There are several important safety systems for the accident sequence analysis. Heat Transport System (HTS) is a forced circulation core cooling system generating the steam to drive the turbine. HTS is divided into Primary Heat Transport System (PHTS) for primary cooling and Secondary Heat Transport System (SHTS) for secondary cooling. Shutdown Cooling System (SCS) is a forced circulation core cooling system removing core residual and decay heat when reactor trips and the HTS is unavailable. Reactor Cavity Cooling System (RCCS) is a passive air cooling system, external to the reactor vessel, which removes core residual and decay heat when reactor trips and both the HTS and the SCS are unavailable. Although the primary purpose of the Helium Purification System (HPS) is to control chemical impurities in the helium, the HPS efficiently removes both gaseous and metallic fission products from the helium at a rate determined by the gas flow rate through the purification system [5]. Thus, depressurization using HPS is necessary to reduce the amount of environmental release of radioactive materials when the RCCS fails. Table II shows the safety systems used in the headings in the event tree and their failure probability.

Table II: Safety systems and failure rates

Safety System	Failure Probability	Error Factor	Source
Reactor Trip	5.106E-6	5.0	[4]
Shutdown Cooling System	7.240E-3	5.0	Fault Tree
Reactor Cavity Cooling System	1.107E-4	1.2	[6]
Helium Purification System	1.030E-2	5.0	[4]
Steam Generator Isolation	3.919E-8	5.0	Fault Tree
Primary Relief Valve	3.0E-2	3	[5]
Loss of Secondary Heat Transport System	1.621E-2	5.0	Fault Tree

2.3.1 Loss of Helium Pressure Boundary (LHPB)

Helium leak from break in the helium pressure boundary results in the containment pressure rise endangering the plant due to depressurization of primary system through opening. Also, forced cooling effectiveness decreases. Fig.3 shows the event tree for this event.

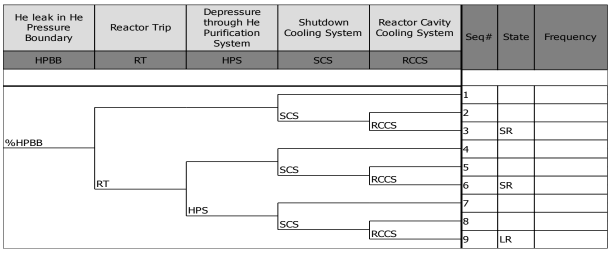

Fig.3. Event tree for loss of helium pressure boundary

2.3.2 Loss of Secondary Heat Transport System (LSHTS)

Loss of secondary heat transport system can result from failure of power conversion unit, secondary loop, service water. Although the primary coolant pressure boundary maintains in sound condition, pressure transient of the primary system can occur due to the secondary cooling system failure. Fig.4 shows the event tree for this event.

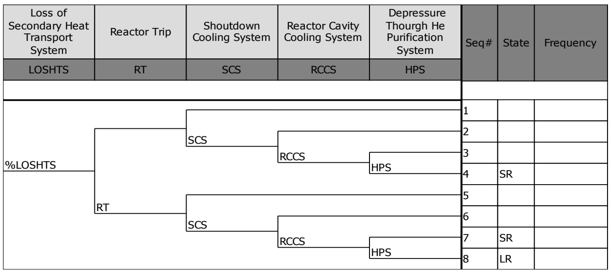

Fig.4. Event tree for loss of secondary heat transport system

2.3.3 Water Ingress (WTIG)

Steam generator tube break and intermediate heat exchanger leak at the same time can lead to water ingress. This brings about a challenge to the function of controlling chemical attack. Furthermore, it can be of interest due to its reactivity effect on the core. Fig.5 shows the event tree for this event.

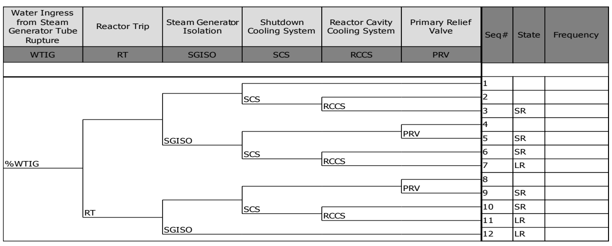

Fig.5. Event tree for water ingress

2.3.4 Transient (TRN)

Transient consists of initiating events that have similar accident sequence after the initiating events happen. It includes loss of offsite power and general transients such as planned shutdown and scram due to small disturbances. Fig.6 shows the event tree for this event.

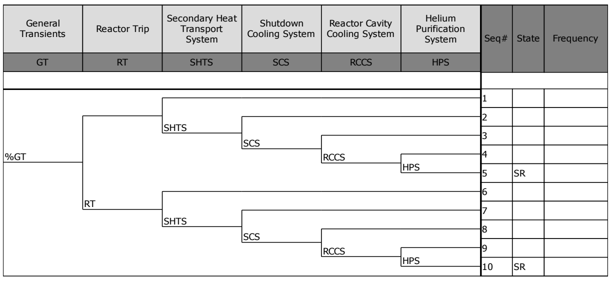

Fig.6. Event tree for transient

2.4 Results

The results of the quantitative accident sequence analysis are shown in Table III. The 5^{th} percentile, 95^{th} percentile, and error factor are also presented as a result of uncertainty analysis. Fig.7 shows the contributions of each initiating events to SR and LR.

Table Ⅲ: Results of the accident sequence analysis

	SR (/RY)	LR (/RY)
LHPB	4.01E-10 (EF=3.18) [9.84E-11, 9.95E-10]	2.11E-17 (EF=7.11) [1.39E-18, 9.44E-17]
LSHTS	1.34E-10 (EF=15.31) [2.26E-12, 5.17E-10]	6.83E-16 (EF=21.88) [4.07E-18, 2.52E-15]
WTIG	2.01E-11 (EF=4.06) [3.93E-12, 5.63E-11]	8.76E-17 (EF=4.69) [1.32E-17, 2.63E-16]
TRN	1.97E-10 (EF=7.80) [1.15E-11, 7.03E-10]	
Sum	7.52E-10 (EF=2.97) [2.26E-10, 1.75E-09]	7.91E-16 (EF=11.05) [5.36E-17, 2.69E-15]

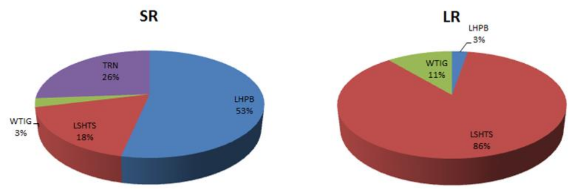

Fig.7. Contributions of initiating events to SR and LR

The point estimate for the SR frequency is 7.52E-10/RY, and that of the LR is 7.91E-16/RY. For the SR, helium pressure boundary break is the largest contributor accounting for 53%. The second largest contributor is transient which contributes 26% to the SR. The third largest contributor is loss of secondary heat transport system which contributes 18% to the SR. The remaining type of initiating event is water ingress accounting for 3% to the SR. For the LR, loss of secondary heat transport system constitutes 86% to the LR. Water ingress accounts for 11%, and loss of helium pressure boundary contributes 3% to the LR.

3. Conclusions

In this study, initiating events which may occur in VHTRs were selected through MLD method. The initiating events were then grouped into four categories for the accident sequence analysis. Initiating events frequency and safety systems failure rate were calculated by using reliability data obtained from the available sources and fault tree analysis. After quantification, uncertainty analysis was conducted. The SR and LR frequency are calculated respectively 7.52E-10/RY and 7.91E-16/RY, which are relatively less than the core damage frequency of LWRs. However, it does not guarantee that VHTR is safer than LWR because consequence analysis is needed for estimating risk. The results shown in this study might contribute to designing the VHTR to be constructed in future.

Acknowledgement

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