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Development of a Methodology for VHTR Accident Consequence Assessment

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1. Introduction

A Very High Temperature Reactor (VHTR) is one of the Generation-4 reactors for the production of process heat, electricity, and hydrogen. This reactor can provide high-temperature process heat (up to 950℃) that can be used as a substitute for the burning of fossil. That is, the substitution of the VHTR for burning fossil fuels conserves these hydrocarbon resources for other uses and eliminates the emissions of greenhouse. In Korea, for these reasons, constructing the VHTR plan for hydrogen production is in progress[1]. In this study, the consequence analysis for the off-site releases of radioactive materials during severe accidents has been performed using the level 3 PRA technology.

2. Methods and Results

2.1 Very High Temperature Reactor

The VHTR represents the evolution of traditional gas-cooled reactors. The design of the VHTR is therefore similar to current gas-cooled reactors, which fall into two general categories: prismatic block reactors, and pebble bed reactors. In Korea, the prismatic block reactor design has been adopted. Prismatic block reactors involve a fuel core surrounded by a hexagonal graphite reflector. The fuel in each of the blocks will consist of graphite coated fuel particles and these particles act as their own mini pressure vessels, isolating fission products both during and after operation, therefore minimizing radioactive release[2]. The fuel column will be built inside of a ceramic core. The ceramic structure will be able to withstand higher temperatures than the casing around the control rod sheaths, supposedly providing inherent safety in an accident scenario[2].

The coolant will be helium, which is attractive due to its negligible neutron absorption cross-section[3]. The helium will directly power a power generation applications and will use an intermediate heat exchanger (IHX) for hydrogen production applications. The IHX simplifies the hydrogen production plant, since it will not have to be built to nuclear-standards, and provides a thermal buffer between the direct helium coolant line and the sensitive chemical processes in the hydrogen production process

Also the VHTR has passive safe nuclear reactor systems with an easily understood safety basis that improved siting flexibility compared to current light water reactors (LWRs). Other features considered in the design are shown in the table I.

Table I: The Design Features of the Korean VHTR

Core Thermal Power	600 MW(t)
Helium Pressure	70 Bar
Helium Flow Rate	250 kg/s
He In/Ex Temp.	490/950
Core Bypass Flow Fraction	10 %
Heat Removal by RCCS	Modeling
Reactor Cavity Relief Valve Opening Set-Point	1.7 bar

2.2. Approach

The probabilistic risk assessment(PSA) provides a systematic analysis to identify and quantify all risks that the plant imposes to the operators, general public and the environment and thus demonstrates compliance to regulatory risk criteria. The PSA is consists of three steps of analysis: estimating core damage frequency(Level-1), assessing large early release frequency(Level-2) and evaluating effect of released radioactive materials to environment(Level-3).

In this study, to focus on the accident consequences such as effects to public and environment after the accidents, the quantification of frequency was not performed but selection of accident scenarios. The release fraction neither cannot be obtained because the VHTR design has not completed so far. Therefore release fraction and initial inventory values are taken from reference plant for the accident consequence assessment.

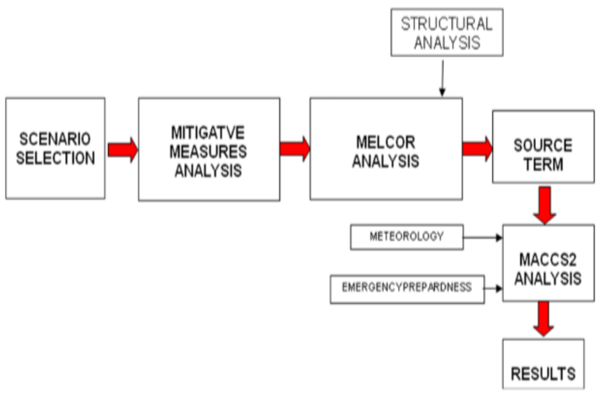

Fig. 1. Reactor Consequence Analyses process[4]

2.3 Accident Scenario Selection

To cover the scenarios comprehensively, the VHTR system was divided into four parts. And the accidents were assumed to be occurred in the primary coolant system, the secondary coolant system, both of the two systems and the transient. Finally, four scenarios were selected for the accident consequence assessment: He pressure boundary break(HPBB), loss of secondary cooling(LOSC), Transient and water ingress(WTIG).

2.4 Radiation Sources

Current studies on VHTR in Korea are at the design phase. Therefore, the initial inventory of U.S. NGNP plant as a reference VHTR, having the same design capacity and fuel structure with the Korean VHTR, was used to calculate the accident consequence[5].

Table Ⅱ: Initial Inventory of Reference VHTR[5]

Fission Product Class	Fission Product	Initial inventory	
		Curies	Bq
Noble Gases	Xe-133	3.63×10^{7}	1.34×10^{18}
	Kr-85	1.90×10^{5}	7.03×10^{15}
	Kr-88	1.85×10^{7}	6.85×10^{17}
I, Br, Te, Se	I-131	2.00×10^{7}	7.40×10^{17}
	I-133	3.60×10^{7}	1.33×10^{18}
	Te-132	2.71×10^{7}	1.00×10^{18}
Cs,Rb	Cs-137	1.69×10^{6}	6.25×10^{16}
	Cs-134	1.90×10^{6}	7.03×10^{16}
Sr,Ba,Eu	Sr-90	1.69×10^{6}	6.25×10^{16}
Ag,Pd	Ag-110m	2.81×10^{4}	1.04×10^{15}
	Ag-111	2.96×10^{6}	1.10×10^{17}
Sb	Sb-125	2.35×10^{5}	8.70×10^{15}
Mo,Ru,Rh,Tc	Ru-103	3.61×10^{7}	1.34×10^{18}
La,Cegroups	Ce-144	2.33×10^{7}	8.62×10^{17}
	La-140	3.27×10^{7}	1.21×10^{18}
Pu,actinides	Pu-239	4.66×10^{3}	1.72×10^{14}

The release fractions of each scenario were taken from the release fraction of scenarios of the reference plant which have the same sequences. The source term release fraction of each scenario were shown in the table Ⅲ.

Table Ⅲ: Source Term Release Fraction of Scenarios

Fission Product Class	Accident Scenarios			
	HPBB	LOSC	Transient	WTIG
Noble Gases	2.87×10^{-6}	2.87×10^{-7}	1.10×10^{-6}	1.10×10^{-7}
I, Br, Te, Se	1.98×10^{-8}	1.98×10^{-9}	9.39×10^{-8}	9.39×10^{-9}
Cs,Rb	3.85×10^{-6}	3.85×10^{-7}	1.31×10^{-6}	1.31×10^{-7}
Sr,Ba,Eu	2.42×10^{-6}	2.42×10^{-7}	3.12×10^{-8}	3.12×10^{-9}
Ag,Pd	4.38×10^{-7}	4.38×10^{-8}	1.07×10^{-7}	1.07×10^{-8}
Sb	3.93×10^{-10}	3.93×10^{-11}	9.22×10^{-9}	9.22×10^{-10}
Mo,Ru,Rh,Tc	3.35×10^{-9}	3.35×10^{-10}	6.39×10^{-9}	6.39×10^{-10}
La,Cegroups	2.79×10^{-10}	2.79×10^{-11}	1.34×10^{-9}	1.34×10^{-10}
Pu,actinides	2.87×10^{-6}	2.87×10^{-7}	1.10×10^{-6}	1.10×10^{-7}

2.5 Accident Consequence Analysis and Results

The MACCS2 code was used to calculate the accident consequence. The site was assumed to be located at Gyeong-ju where the second Korea Atomic Energy Research Institute will be built. The area set has 30km radius distance from the VHTR site. This area includes Gyeong-ju, Ulsan and Pohang where about 8 hundred thousand people live. With this area set, the land fraction and population data were obtained. The emergency response activities were assumed to 95% evacuation and 5% sheltering.

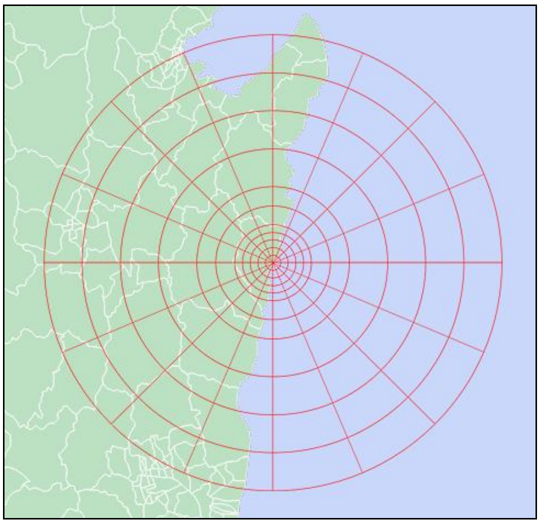

Fig.2. Area set for land fraction and demographic input data

The accident consequence evaluation was conducted and the results of dose and fatality as the effect of the accident were obtained. First, the whole body doses results at each distance are shown in the Table.

Table Ⅲ: Whole Body Dose at Area sets

Distance (km)	L-EDEWBODY TOT LIF (μSv)			
	HPBB	LOSC	Transient	WTIG
1.0-2.0	4270	25200	0.90	1350
2.0-3.0	2170	13100	0.48	686
3.0-4.0	1360	8350	0.30	430
4.0-5.0	946	5860	0.21	298
5.0-7.5	563	3570	0.13	178
7.5-10.0	319	2050	0.08	101
10.0-15.0	163	1070	0.04	52
15.0-20.0	78	516	0.02	25
20.0-25.0	41	275	0.01	13
25.0-30.0	23	155	0.01	7

The Early Fatality results came out as 0 value at all area set considered for all scenarios. It means that nobody dies when the VHTR has any accident. The cancer fatality results are shown in the table Ⅴ and these are much lower than the safety standard.

Table Ⅳ: Mean Cancer Fatality at Area sets

Distance (km)	MEAN CANCER FATALITY			
	HPBB	LOSC	Transient	WTIG
7.5-10.0	8.36×10^{-07}	3.44×10^{-06}	1.26×10^{-10}	2.77×10^{-07}
10.0-15.0	4.28×10^{-07}	1.75×10^{-06}	6.42×10^{-11}	1.42×10^{-07}
15.0-20.0	2.04×10^{-07}	8.35×10^{-07}	3.07×10^{-11}	6.76×10^{-08}
20.0-25.0	1.08×10^{-07}	4.39×10^{-07}	1.63×10^{-11}	3.56×10^{-08}
25.0-30.0	6.02×10^{-08}	2.45×10^{-07}	9.20×10^{-12}	1.99×10^{-08}

2.6 Results Comparison between LWR and VHTR

For PRA applications, the radiological consequences are presented in the form of a complementary cumulative distribution function (CCDF). It shows the frequency that a consequence will exceed a given magnitude. The cancer fatalities shown in Figures 3 are those that would be predicted to occur after the selected reactor accident. As the frequency of the accidents has not taken into account, this figure shows CCDF results when assuming that an accident must occur.

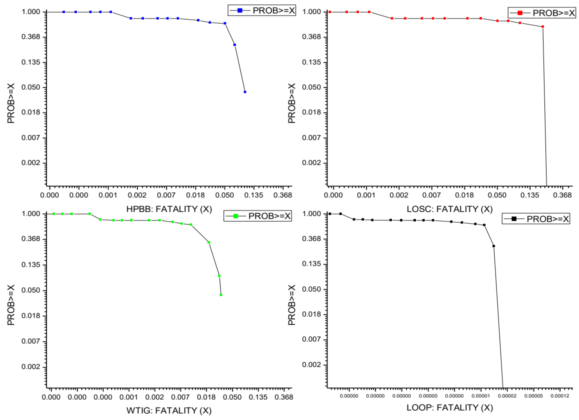

Fig.3. CCDF results of the VHTR accident scenarios

To compare the results of VHTR accident consequence with the advanced LWR, the accident consequence assessment of APR1400 has been conducted. HPBB and SBLOCA accident scenarios were selected for VHTR and LWR because these two accidents have similar sequences.

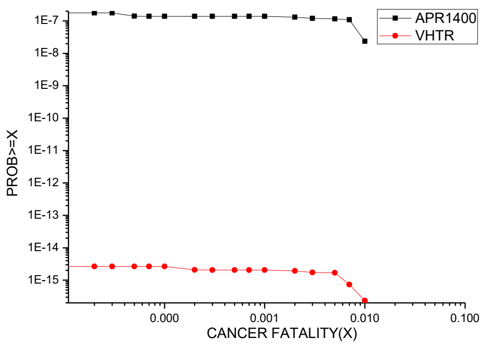

Fig.4. CCDF results of the VHTR and APR1400

The figure 4 shows the CCDF results including accident frequency. According to the result, the probability of that one person dies in 1000 people after VHTR accident is million times lower than that of APR1400.

3. Conclusions

The offsite consequence analysis for a VHTR using the MACCS code has been performed. Since the passive system such as the RCCS(Reactor Cavity Cooling System) are equipped, the frequency of occurrence of accidents has been evaluated to be very low[6].

For further study, the assessment for characteristic of VHTR safety system and precise quantification of its accident scenarios is expected to conduct more certain consequence analysis. This methodology shown in this study might contribute to enhancing the safety of VHTR design by utilizing the results having far lower effect on the environment than the LWRs.

Acknowledgement

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