Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

An Assessment of the VHTR Safety Distance Using the Reliability Physics Model

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1. Introduction

Hydrogen is an environmentally harmless and renewable fuel. It is recognized as the only alternative to solve the exhaustion of fossil energy resources and global environmental pollution problem at the same time. However, hydrogen is secondary energy which has to be processed with primary energy such as fossil energy, solar energy and nuclear energy[1].

In Korea, therefore, planning the production of hydrogen using high temperature from nuclear power is in progress[2]. To produce hydrogen from nuclear plants, supplying temperature above 800℃ is required. Therefore, Very High Temperature Reactor (VHTR) which is able to provide about 950℃ is suitable[3].

In situation of high temperature and corrosion where hydrogen might be released easily, hydrogen production facility using VHTR has a danger of explosion. Moreover explosion not only has a bad influence upon facility itself but also on VHTR. Those explosions result in unsafe situation that cause serious damage. However, In terms of thermal-hydraulics view, long distance makes low efficiency

Thus, in this study, a methodology for the safety assessment of safety distance between the hydrogen production facilities and the VHTR is developed with reliability physics model.

2. Methods

2.1 Reliability physics model

For the safety assessment of hydrogen explosion, it has to be determined how much the overpressure caused by a hydrogen explosion debases the safety of the VHTR. Through using the reliability physics model, the failure probability is obtained from the overpressure.

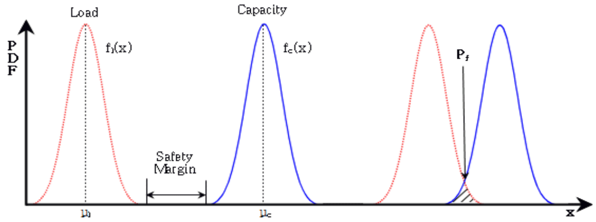

Fig. 1. Reliability physics model

The overlapped area between load and capacity is the probability of failure of the system[4]. The probability of failure of the system (Pr_f) is expressed as shown in Eqn(1) below.

$$Pr_f = Pr(S>R) \tag{1}$$

S and R each represent a system load and a system capacity. The relationship between the probability of failure and the probability of success is $Pr_R = 1\text{-}Pr_f$.

The probability of system failure can be obtained from the following Eqn (2).

$$Pr_R = Pr(S>R) = \int_{-\infty}^{\infty} f(s) \int_{-\infty}^{S} g(r) ds = \int_{-\infty}^{\infty} f(s) G(s) ds \tag{2}$$

The f represents the probability density function of the load, while the g denotes the probability density function of the capacity. The function G is the cumulative distribution function of the capacity.

2.2 Load Variable

In order to apply a reliability physics model, the definition of the load and the capacity is required. Since the current VHTR and hydrogen production facility has not been designed completely, the data of conventional nuclear power plants and other available data were applied.

First, the overpressure data corresponding to each distance and detonation volume had been obtained by the Idaho National Engineering Laboratory at 1994, and those data were used for the load data[5-6].

Table I: The overpressure data (psi)

Distance (ft)	Detonation Volume(ft^3)			Distance (ft)	Detonation Volume(ft^3)
	3000	3700	4500		15000
120	4.64	5.3	6.01	350	1.93
140	3.52	3.98	4.48	380	1.72
160	2.81	3.15	3.53	440	1.41
180	2.33	2.6	2.89	500	1.2
200	1.99	2.21	2.44	560	1.04
230	1.64	1.8	1.98	620	0.92
260	1.39	1.52	1.67	680	0.83
290	1.21	1.32	1.44	740	0.75
320	1.07	1.17	1.27	800	0.69

When an overpressure has less value, a distance becomes shorter. The results of the failure probability for overpressure below 50psi were too small to derive the accurate values. Therefore, to obtain the failure probability values between 0 and 1, an exponential growth fitting was performed with Origin Pro ver.8. The exponential growth fitting is simple and accurate tool for predicting the precise distance.

The exponential growth fitting finds formulas as the Eqn (3) below. Through this method, the graphs of overpressure for each volume were found.

$$y = y_0 + A_1 e^{x/t_1} + A_2 e^{x/t_2} + A_3 e^{x/t_3} \qquad (3)$$

Table II. Results of exponential growth fitting

Detonation Volume(ft^3)	3000	3700	4500	15000
y0	0.430	0.311	0.341	0.138
A1	407.893	18.284	2.876	3.415
t1	-15.489	-59.439	-252.959	-230.050
A2	37.144	165.089	15.828	1.048
t2	-40.845	-22.830	-64.980	-931.162
A3	4.228	2.735	124.826	18.660
t3	-167.668	-252.924	-26.647	-86.470

Using the derived formula, overpressure values depending on the distance of each detonation volume (V_D) were obtained.

Table Ⅲ. Overpressures depending on the distance

V_D / Distance (ft)	3700 (ft^3)	V_D / Distance (ft)	4500 (ft^3)	V_D / Distance (ft)	15000 (ft^3)
126	4.829900	135	4.796940	186	4.688585
127	4.758354	136	4.731023	187	4.656120
128	4.688659	137	4.666660	188	4.623952
129	4.620755	138	4.603812	189	4.592107
130	4.554582	139	4.542427	190	4.560570
131	4.490080	140	4.482463	191	4.529343
132	4.427196	141	4.423878	192	4.498420
133	4.365875	142	4.366633	193	4.467791
134	4.30607	143	4.310687	194	4.437461
135	4.247722	144	4.256003	195	4.407425

3. Results

For the capacity value, the ultimate pressure capacity of the containment building on Kori 3&4 was used[7]. Failures are classified into two main types by damage size, rupture and leak.

TableⅣ. The pressure capacity

	Rupture	Leak
Median (psi)	138	178
Logarithmic standard deviation	0.29	0.17

The probability of rupture and leak of the containment building at pressure p is evaluated with the following formula:

$$P_{RUPTURE}(p) = \int_0^p f_r(p')\,dp' \qquad (4)$$

$$P_{\leq AK}(p) = [\int_0^p f_l(p')\,dp'][1 - \int_0^p f_l(p')\,dp'] \qquad (5)$$

The total probability of failure is the sum of probability of rupture and leak as equation (6).

$$P_{CF} = P_{RUPTURE}(p) + P_{LEAK}(p) \qquad (6)$$

Using the Eqn (6), the probability values of failure depending on the distance for each volume (3000, 3700, 4500 and 15000ft^3) were derived. These two tables below show the results for volume 4500 and 15000ft^3.

TableⅤ. Probability of failure for 4500 ft^3

Distance (ft)	Distance (meter)	Load	P_{Leak}	$P_{Rupture}$	Probability of Failure
213	64.92	2.219072	1.83E-06	6.21E-18	1.83E-06
214	65.23	2.203517	1.62E-06	4.33E-18	1.62E-06
215	65.53	2.188178	1.44E-06	3.03E-18	1.44E-06
216	65.84	2.173055	1.28E-06	2.12E-18	1.28E-06
217	66.14	2.158129	1.14E-06	1.48E-18	1.14E-06
218	66.45	2.143411	1.02E-06	1.04E-18	1.02E-06
219	66.75	2.128892	9.06E-07	7.28E-19	9.06E-07
220	67.06	2.114569	8.07E-07	5.11E-19	8.07E-07
221	67.36	2.100437	7.19E-07	3.59E-19	7.19E-07
222	67.67	2.086492	6.40E-07	2.52E-19	6.40E-07

TableⅥ. Probability of failure for 15000 ft^3

Distance (ft)	Distance (meter)	Load	P_{Leak}	$P_{Rupture}$	Probability of Failure
319	97.23	2.202168	1.61E-06	4.20E-18	1.61E-06
320	97.54	2.192307	1.49E-06	3.34E-18	1.49E-06
321	97.84	2.182525	1.38E-06	2.65E-18	1.38E-06
322	98.15	2.172821	1.28E-06	2.11E-18	1.28E-06
323	98.45	2.163193	1.19E-06	1.67E-18	1.19E-06
324	98.76	2.153642	1.10E-06	1.33E-18	1.10E-06
325	99.06	2.144166	1.02E-06	1.06E-18	1.02E-06
326	99.36	2.134765	9.50E-07	8.41E-19	9.50E-07
327	99.67	2.125438	8.81E-07	6.68E-19	8.81E-07
328	99.97	2.116185	8.17E-07	5.32E-19	8.17E-07

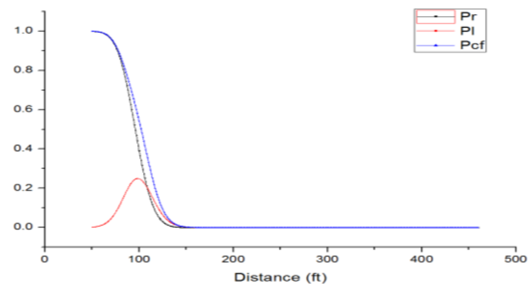

Fig. 2. Probability of failure for 4500 ft^3

Using US NRC's the safety criteria for 1×10^{-6}, the maximum distances not exceeding the safety criteria can be obtained as safety distances[8]. The results of the VHTR safety distance are shown in Table Ⅵ.

TableⅥ. Safety Distance

Detonation Volume (ft^3)	Distance (m)
3700	62.48
4500	66.75
15000	99.36

4. Conclusions

Based on the standard safety criteria which is a value of 1×10^{-6}, the safety distance between the hydrogen production facilities and the VHTR using reliability physics model are calculated to be a value of 60m ~ 100m.

In the future, assessment for characteristic of VHTR, the capacity to resist pressure from outside hydrogen explosion and the overpressure for the large amount of detonation volume in detail is expected to identify more precise safety distance using this reliability physics model.

This methodology shown in this study might contribute to enhancing the level of the VHTR design technology by reducing the uncertainty on the safety distance.

Acknowledgement

This work was supported by a National Research Foundation of Korea (NRF) grant funded by Ministry of Science, ICT & Future Planning and partly supported by a grant from the Nuclear Safety Research Program of the Korea Radiation Safety Foundation under NSSC.

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