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Feasibility Study of the Combustible Gas Control System Following a LOCA

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냉각재 상실사고시 가연성 가스제거 계통의 타당성 조사

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Abstract

The feasibility of not employing recombiners rather using the postaccident purge system alone to control hydrogen concentration in the containment following a LOCA, is analyzed in this paper. For this study, the hydrogen concentration in the containment, hydrogen removal through the purge system, and additional off-site dose due to hydrogen purge were calculated. The economic justification of a hydrogen recombiner system (2 recombiners) was also investigated by using the cost-benefit concept. As a result, the purge system is sufficient to maintain the hydrogen concentration at a safe level without hydrogen recombiners, and it meets the dose limit requirements set forth in 10 CFR part 100. A hydrogen recombiner system would be justified based on cost-benefit concept for common use in a site with 4 units or more.

요약

본 연구에서는 냉각수 상실사고(LOCA)시 격납용기내의 수소농도를 제어하기 위해 수소재결합기 없이 수소 퍼지계통만을 사용할 때의 타당성을 분석하였다. 이 타당성 연구를 위해 격납용기내의 수소농도, 수소퍼지 계통의 수소제거, 그리고 퍼지로 인한 추가소외 선량이 계산되었다. 또한 비용-편익 개념을 사용하여 수소 재결합기 계통(2대의 재결합기 설치)의 경제성을 분석하였다. 분석결과, 수소퍼지 계통은 수소 재결합기 없이도 수소농도를 제어하기에 충분하며, 10 CFR 100에 있는 선량 제한치를 만족시키고 있었다. 비용-편익 개념에 의하면 수소 재결합기 계통은 동일부지내에 있는 4~6기의 발전소에 공용될 때 경제성이 있는 것으로 입증되었다.

1. Introduction

Hydrogen gas may be generated inside the containment following a postulated loss-of-coolant-accident (LOCA) by reactions such as zirconium metal with water, corrosion of structural materials, and radiolysis of aqueous solution in the core and sump. If a sufficient amount of hydrogen is accumulated, it may react with oxygen present in the containment atmosphere. The reaction would take place at the rates rapid enough to lead to the failure of containment structural integrity, and the damage of the system and/or components essential to the safe control of post-LOCA conditions. Hence, the flammability limit of 4 volume percent(v/o) hydrogen should be kept in the containment atmosphere.

Following a LOCA, to ensure that the hydrogen concentration is maintained at a safe level, recombiners are provided along with the post-accident purge system. This work was performed to investigate the feasibility of not employing recombiners rather using the post-accident purge system alone to control hydrogen concentration in the containment following a LOCA. The cost-benefit concept was used for this feasibility study. Korea Nuclear Units 5 and 6 (KNU 5 & 6) were chosen as the sample plant for this study.

2. Method and Result

2.1. Hydrogen Generation

The potential sources of hydrogen accumulated in the containment following a LOCA are:

a. metal-water reaction involving the fuel cladding (zirconium) and the reactor coolant,

b. hydrogen contained in the primary coolant system,

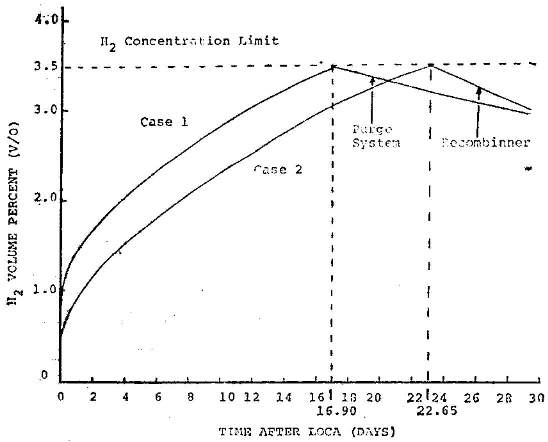
c. Corrosion of plant material (especially Al, Zn) by the solutions used for emergency cooling, and

d. radiolytic decomposition of the emergency core cooling solutions (core solution radiolysis and sump solution radiolysis).

The calculation of hydrogen accumulation in the containment of KNU 5 & 6 was based on the USNRC model as discussed in Regulatory Guide (R.G.) 1.7 and Standard Review Plan (SRP) Section 6.2.5. FSAR values were used for the parameters and assumptions to calculate the hydrogen concentration except the metal-water reaction rate. The conservative value of 5 percent given in R.G. 1.7 was used instead of 1.5 percent used in the FSAR of KNU 5 & 6. The hydrogen concentration in the containment is shown in Figure 1 as a function of time following the LOCA, and is compared with the result in the FSAR. As shown in Figure 1, it takes 16.90 days to reach the hydrogen concentration of 3.5 volume percent (with 0.5 volume percent margin for conservatism) following the initiation of the LOCA,

2.2. Hydrogen Removal

The post-accident containment purge system must be actuated to remove the hydrogen within 16.90 days after the initiation of the LOCA.



Case 1: metal-water reaction rate: 5%
Case 2: metal-water reaction rate: 1.5%
(KNU 5 & 6 FSAR)

Fig. 1. Hydrogen Concentration in the Containment

The purge flows are set up to exhaust hydrogen-bearing gases from the containment to the environment atmosphere and to supply hydrogen-free air from environment atmosphere to the containment. The exhaust gases are filtered through HEPA and charcoal filters to limit discharge of radioactive particulates and iodines. The amount of hydrogen N in the containment may be expressed by

$$\frac{dN}{dt} = P - \Lambda N$$

where N is the total amount of hydrogen in the containment (m^3), P is hydrogen production rate (m^3/hr), and Λ is hydrogen removal rate (containment volume/hr).

Hence, the hydrogen concentration in the containment at a given time t following the initiation of hydrogen removal is given by

$$C(t) = \frac{N(t)}{V} \times 100$$
$$= \mathrm{Co}\ e^{-\Lambda t} + 100 \times e^{-\Lambda t} \int_0^t \frac{P(t')}{V} e^{\Lambda t'}\, dt'$$

where $C(t)$ is hydrogen concentration in the containment (v/o), V is containment free volume (m^3), and Co is hydrogen concentration in the containment at $t=0$ (initiation of the post-accident purge system), (v/o).

The purge flow rate was assumed constant as 85 m^3/hr (50 ft^3/min). in this calculation and the complete mixing was considered by the post-LOCA mixing fans. The effect of hydrogen purge system on the hydrogen concentration is shown in Figure 1.

2. 3. **Environmental Effects**

2. 3. 1. Source Term Calculation

The source term of the equilibrium reactor core was calculated at 104. 5% of the rated core power level. It was assumed that 100 percent of the noble gases and 25 percent of the iodine inventories in the core are immediately available for release from the containment. And 91 percent of this 25 percent was assumed to be in the form of elemental iodine, 5 percent in the form of particulate iodine, and 4 percent in the form of organic iodine.

The differential equations for estimating the release of iodine isotope are as follows:

$$\frac{dA1j}{dt} = (L_{21} + (1-f)L_p)\ A_{2j}(t)$$
$$+ (L_{31} + (1-f)L_p)\ A_{3j}(t)$$
$$\frac{dA2j}{dt} = -(\lambda dj + \lambda s + L_{21} + L_{23} + L_p) A_{2j}(t)$$
$$+ L_{32} A_{3j}(t)$$
$$\frac{dA3j}{dt} = -(\lambda dj + L_{31} + L_{32} + L_p) A_{3j}(t)$$
$$+ L_{23} A_{2j}(t)$$

where $Aij(t)$ is the activity of iodine isotope j in the node i (node 1: environment, node 2: sprayed region, node 3: unsprayed region) (Bq); Lik is the transfer rate from node i to node k (hr^{-1}); λdj and λs are decay constant for iodine isotope j (hr^{-1}) and the spray removal constant (hr^{-1}), respectively; and f and L_p are filter efficiency of the purge system and filtered rate exhausted through the purge system (hr^{-1}), respectively.

The above first-order simultaneous ordinary differential equations are solved numerically to obtain the total activity in each region as a function of time by the use of the advanced matrix method.[1,2]

The total released iodine isotope j from the containment is obtained by integrating the release rate over the time interval.

$$Q_j = \int_t ((L_{21} + (1-f)L_p) A_{2j}$$
$$+ (L_{31} + (1-f)L_p) A_{3j})\, dt$$

As noble gases are not affected by spray, each noble gas release is simply calculated by one-region containment model. The time dependent activity of noble gas j is calculated by following equations.

$$\frac{dA1j}{dt} = (L_{21} + L_p) A_{2j}(t)$$
$$\frac{dA2j}{dt} = -(\lambda dj + L_{21} + L_p) A_{2j}(t)$$

where $A1j(t)$, $A2j(t)$ are the activity in the environment (node 1) and in the containment (node 2), respectively.

The activity released to the environment over the time period t_{m-1} to t_m is as follows:

$$Qj=\int_{t_{m-1}}^{t_m}(L_{21}+L_p)A_{2j}(t)dt$$
$$=\frac{(L_{21}+L_p)A_j(0)}{\lambda dj+L_{21}+L_p}(\exp(-(\lambda dj+L_{21}+L_p)t_{m-1})-\exp(-(\lambda dj+L_{21}+L_p)t_m))$$

where $A_j(0)$ is activity in the containment at time $t=0$ (Bq).

The values of the variables used in source term calculation are given in the FSAR.

2. 3. 2. Dose Calculations

The atmospheric dilution factors following the accident were calculated to predict the radioactivity concentrations in the air and subsequent doses to the surrounding populations. The calculations are divided into two cases: dose calculation to an individual and collective dose calculation to the surrounding population. The meteorologial conditions used for these two cases have been reduced from the onsite data ('79. 3 ~'82. 2). Five percentile X/Q values are used for maximum individual dose calculations at the Exclusion Area Boundary (EAB) and the Low Population Zone (LPZ) outer boundary. 22.5° sector averaged X/Q values were calculated at 10 distance (1, 2, 3, 4, 5, 10, 20, 30, 40, 50 mile) for four different time periods by multiplying the directional wind frequencies of the corresponding sector.

The 0~2 hour doses at the EAB were calculated to be 1.36 Sv for thyroid and 2.61×10^{-2} Sv for whole body regardless of the operation of the hydrogen purge system. However, for 0~30 day doses at the LPZ outer boundary the additional doses due to hydrogen purge should be considered. The radiological consequences at the LPZ outer boundary are shown in Table 1. The resultant doses at the EAB and the LPZ outer boundary are in compliance with the limits set forth in 10 CFR part 100.

Table 1. Maximum Individual Dose at the LPZ Outer Boundary Following the LOCA (0~30 days)

	Thyroid (Sv)	Whole-Body (Sv)
10 CFR 100 Limit	3.00	2.50×10^{-1}
Without Purge (Only Leakage)	3.19×10^{-1}	4.10×10^{-3}
Additional Dose due to Purge	1.00×10^{-2}	2.20×10^{-4}
With Purge (Leakage+Purge)	3.29×10^{-1}	4.32×10^{-3}

* Purge System Operation: 16.90 days after a LOCA

2.4. Cost-Benefit Analysis

The cost-benefit study is proposed in Appendix I to 10 CFR part 50 to demonstrate that the design of reasonably demonstrated technology for reducing the collective dose equivalent in a population due to release of radioactive materials from the reactor during normal plant operation and anticipated operational occurrences to level as low as reasonably achievable(ALARA). The same cost-benefit technique is employed in the assessment of safety features (especially engineered safety features-ESF's)[3] using risk concepts to comply with ALARA principles.

In the previous section, it was shown that the post-accident purge system was sufficient to control the hydrogen concentration in the containment without recombiners, and at the same time it met the dose limit requirements set forth in 10 CFR part 100. However, in making this decision, it is meaningful to execute the cost-benefit study for hydrogen recombiners and to show that further reduction in dose would not justify the incremental cost required to accomplish it.

2. 4. 1. Cost Analysis of Hydrogen Recombiners

The annual cost of having hydrogen recombiners was obtained using the method presented in R.G. 1.110. The total annual cost is the sum of the annual fixed cost (AFC), the annual operating cost (AOC) and the annual maintenance cost (AMC).

The annual fixed cost is defined as follows:

AFC=TDC×ICF×CRF

where TDC is total direct cost, ICF is indirect cost factor, and CRF is capital recovery factor.

The total direct cost includes the costs of structures, electrical services, equipment, and instrumentation and controls, site labor, and site materials. Spare parts and contingency allowance are also included in the direct cost. The process equipment and material cost and the appropriate labor cost of hydrogen recombiners are obtained by adding the 10% contingency to the cost given in NUREG-0241[4] (in terms of 1977 dollars). The total direct cost of two hydrogen recombiners is 978,000 US dollars.

The indirect cost includes 1) construction facilities, equipment, and services 2) engineering and construction management services 3) other owner's cost 4) interest during construction.

The indirect cost factor of 1.75 was used in this calculation. The capital recovery factor is a levelized annual charge which takes into account the cost of borrowed money and the depreciation of assets. The capital recovery factor of 0.1241 was used based on a service life of 30 years and 12% per year cost of money. The annual operating and maintenance cost was neglected. Therefore, the total annual cost of two hydrogen recombiners, equal to the annual fixed cost, 2.124×10^5 $ per year.

2.4.2. Annual Risk Calculation

The risk following an accident is defined as the probability of occurrence and environmental consequences per occurrence. As the consequences in this calculation are caused by the release of radioactive material resulting from the operation of the hydrogen purge system, those are measured by the collective dose equivalent in a population. The annual risk following an accident is defined by

$$R=p\int_{\theta}\int_{r} d\theta dr\ 2\pi r\ D(r,\theta)\ P(r,\theta)$$

Where p is probability of occurrence of the accident per year (yr^{-1}), $D(r,\theta)$ is dose equivalent in thyroid and whole body of an individual at the location (r,θ) (Sv), and $P(r,\theta)$ is the exposed population density distribution at the location (r,θ) (persons/m^2).

For the calculational purpose, the region is extended up to 50 miles from the site and divided into 160 subregions formed by 16 directional sectors and 10 distances. The annual risk becomes

$$R=p\sum_{i=1}^{10}\sum_{j=1}^{16} Dij\times Pij$$

where Dij is sector averaged dose equivalent to an individual in the given subregion and Pij is population numbers in the given subregion.

And subscript i and j denote 10 distances (1, 2, 3, 4, 5, 10, 20, 30, 40, 50) and 16 compass points, respectively. Pij values of the year 2020 around Kori site in the FSAR were used.

The calculated annual risks are summarized in Table 2.

According to the Reactor Safecty Study[5] (RSS), the probability of a large LOCA occurrence is estimated to be about 1×10^{-4}/reactor year.

2.4.3. Summary of Cost-Benefit Study

Table 3 summarizes the cost-benefit study for the hydrogen recombiners of KNU 5 & 6. Based upon the study, the costs per man-thyroid-sievert and per whole body man-sievert reduction for hydrogen recombiners are much higher than the values of $100,000 per-thyroid-sievert and $100,000 per whole body mansievert proposed in Appendix I to 10 CFRpart 50.

2.5. Sensitivity Study

In general, the accident at TMI-2 raises the question of whether the short-term design basis for post-accident combustible gas control system (metal-water reaction) might be underestimated and the long-term design basis

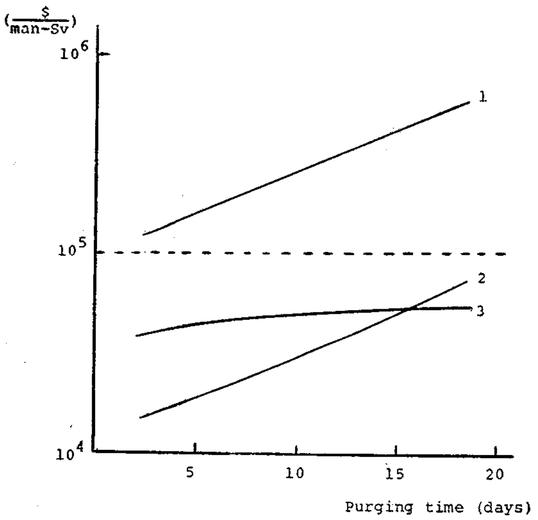
Table 2. Annual Risk to Population

Without Purge (man-Sv/yr)		With Purge (man-Sv/yr)		Addition Collective Dose (man-Sv/yr)	
Thyroid	Whole-Body	Thyroid	Whole-Body	Thyroid	Whole-Body
1.63×10^4	1.20×10^2	2.03×10^4	2.06×10^2	4.00×10^3	8.57×10^1

Table 3. Summary of Cost-Benefit Study

Annual Cost ($ /year)	Additional Collective Dose Equivalent (man-Sv/yr)		Incremental Cost for Dose Reduction ($ /man-Sv)	
	Thyroid	Whole-Body	Thyroid	Whole-Body
2.124×10^5	4.00×10^3	8.57×10^1	5.31×10^5	2.48×10^7

(radiolysis and corrosion) be overestimated.[6] If it is true, the purge-starting time, at which the hydrogen concentration becomes 3.5 v/o, would appear earlier. And it is the dominant factor in assessing the radiological consequences. Assuming the purge should start 1 day after the initiation of the accident, 0~30 day individual doses at the LPZ outer boundary are 3.94×10^{-1} Sv for thyroid and 7.54×10^{-3} Sv for whole body. The values also satisfy the limits of 10 CFR part 100. The sensitivity study was performed with some uncertain factors as a function of the purge starting time.



1) Filter Efficiency: 95, 95, 99
2) Filter Efficiency: 90, 30, 95
3) X/Q Model : R.G. 1.4

Fig. Incremental Cost per man-theyroid-sievert Reduction for two Hydrogen Recombiners

The factors are as follows:

a. Charcoal filter efficiency of the hydrogen purge system according to USNRC R.G. 1.52; The charcoal filter efficiency is dependent on the relative humidity. If the relative humidity exceeds 70%, the efficiencies are 90%, 30%, and 95% for elemental, organic, and particulate, respectively.

b. Atmospheric dilution factor (X/Q) according to USNRC R.G. 1.4: For conservatism, the accident X/Q values calculated by using the meteorological conditions in R.G. 1.4.

The effects of these factors on dollars per man-thyroid-sievert reduction are shown in Figure 2.

3. Conclusions

Based upon the results of study, the following observations and conclusions apply:

a. The hydrogen concentration reaches 3.5 volume percent in the containment following the LOCA at 16.9 days after the initiation of the accident.

b. To maintain the concentration at a safe level, the post-accident purge system is sufficient without hydrogen recombiners.

c. The incremental 0~30 day doses to the individual at the LPZ outer boundary due to purge are very minimal:

1×10^{-2} Sv for thyroid and 2×10^{-4} Sv for whole body.

This satisfies the guideline limits set forth in 10 CFR part 100.

d. The cost-benefit study shows that the reduction in dose (collective dose equivalent) would not justify the incremental cost of having recombiners to accomplish it. The cost of recombiners per mansievert reduction (thyroid dose is controlling) is calculated to be 5.3×10^5 US dollars per man-sievert reduction while the proposed guideline recommendation is 1.0×10^5 US dollars.

e. In the multi-unit site (e.g. 4 or 6 units in a site), a hydrogen recombiner system would be justified on cost-benefit concept for common use. As an example, if a hydrogen recombiner system is proposed for the Kori site (4 unit site), the cost of recombiners per man-sivert reduction roughly becomes 1.3×10^5 US dollars.

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