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An Analysis of the Passive Autocatalytic Recombiner Performance under a Design Basis Accident for an Implementation into the KNGR

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Abstract

A new, simpler device called a catalytic recombiner or passive autocatalytic recombiner (PAR) has been developed for cost-effective control of combustible gases. PARs, which are stainless steel sheet metal boxes open at the top and bottom and contain many vertical flat catalytic cartridges or plates, recombine hydrogen and oxygen in the 1-cm-wide flow channels between them. For an implementation of PARs into the Korean Next Generation Reactor (KNGR), the number of PARs within the containment was derived out with a conservative approach to meet design requirements, based upon an evaluation of different PAR performance models under design basis accident. Whereas the Passive Hydrogen Recombination System (PHRS) for combustible gas control consists of two redundant PAR groups, it was evaluated that four PARs should be provided inside the containment above the operating deck and two PARs inside the IRWST steam space above normal water level. At detailed design stage of the KNGR, if PARs are practically implemented into KNGR design, the design of KNGR-specific PAR equipment depending upon allowable spaces and anticipated gas flow pattern within the containment will be required.

1. Introduction

During and following a design basis loss of coolant accident, relatively small amounts of hydrogen and oxygen can be released to the containment. To mitigate such release, the regulations of the Korean Regulatory Body require combustible gas control systems (CGC) to prevent volume average concentrations from reaching combustible levels. Almost all these systems in today’ s units include electrically powered thermal recombiners. The surveillance and maintenance of these devices, some of which are quite complex, can be significant operations and maintenance (O&M) cost burden.

During the past decade, a new, simpler device called a catalytic recombiner or passive autocatalytic recombiner (PAR) has been developed for cost-effective control of combustible gases[1-2]. In nature, PARs are relatively inexpensive to install and can greatly reduce the operating and maintenance cost associated with current active recombiners. From this advantageous viewpoint, some plants including AP600 had determined the use of PARs[3]. Furthermore, a comparative study had been performed to investigate the effectiveness of PARs for the mitigation of DBA and severe accident in the Korean Next Generation Reactor (KNGR) Design[4]. Based upon the study results, the KNGR is going to incorporate the PARs as one of many advanced design features.

This paper especially shows the evaluation results on the PAR performance under design basis accident. As a result, with a conservative approach to meet design requirements, the number of PARs within the containment was derived out for an implementation of PARs into the KNGR.

2. Overview of PAR Performance

A PAR consists of a stainless steel sheet metal boxes with openings at the top and bottom and many vertical flat catalytic cartridges or plates with open gas flow channels between them[1-2]. Figure 1 shows the full-scale NIS PAR unit from one of representative suppliers. During an accident, the platinum or palladium catalyst in the PAR recombines hydrogen and oxygen in the 1-cm-wide flow channels to steam, which rises and is expelled from the top of the units due to buoyancy, drawing gases from the containment atmosphere into the unit from below. A "chimney" can extend above the catalytic region to provide additional lift to enhance throughput and recombination capacity. Heated gases and water vapor exhaust at the top of the unit and mix with the containment atmosphere via natural and PAR-induced convection.

Under dry room-temperature conditions, the catalytic recombination process starts up almost immediately at concentrations far below flammability levels. If the PAR is wet from spray or condensed steam, startup can be delayed while the heat of recombination dries the water on the catalyst. Of course, initial wetness can be reduced by adding a hydrophobic coating on the catalyst elements. Recombination rate increases with increasing concentrations of combustible gases and is not retarded by steam. Although the catalyst material is not consumed as it functions and, as a non-corrosive metal, is not expected to be vulnerable to long-term aging degradation, periodic surveillance is needed to detect potential functional degradation due to buildup of contaminants during operation or other unknown aging mechanisms.

For PAR performance degradation issues such as PAR inhibitor and catalyst poisons, experimental investigations had been performed by the vendors (Siemens and NIS), utility applicants or institutes (Westinghouse, Consolidated Edison Co., Wyle Lab., Polestar, EPRI, EdF, etc.) and regulatory body and supporting institutes (SNL, ACRS, etc.)[1-3,5-9]. As discussed above, separate effects tests performed on the PARs have been generally positive. Tests include poisoning due to fire exposure, and a wide variety of aerosols and fission product gases. Although the tests for the separate effects of the PAR did not include synergistic effects which occur in practice, it can be expected from these tests that the combined impact of poisons, pyrolysis and blockage on PAR performance becomes a reduction of less than 25%.

3. Analytical Evaluation of PAR Performance

It has been, until now, found that there are three models used to analyze PAR performance. Fischer[8] developed an empirical model at Battelle to evaluate the performance of the NIS PAR. He reported that the hydrogen removal rate (in kg/hr) for the full-scale prototypic PAR is:

$$R = 0.85\, Q\, \rho_{H_2} \left(1 - e^{-t/\tau}\right) \tag{1}$$

where

0.85 = efficiency factor,

Q = volumetric flow rate of containment gas through the PAR (m^3/s),

ρ_{H_2} = mass density of hydrogen in the PAR (kg/m^3),

t = time (sec) and

τ = thermal accommodation time constant (1800 sec).

Fischer found that the experiment results obtained at Battelle were best fit by assuming the Q is an exponential function of the volume fraction of hydrogen:

$$Q = 0.67\, C_{H_2}^{0.307} \tag{2}$$

where

C_{H_2} = hydrogen volume fraction in the containment.

The factor in the parentheses of Eq. (1) represents a transient response lasting roughly 0.5 hour while the PAR reaches thermal equilibrium.

Sher, et al.[9] at Polestar Applied Technology developed analytical models of steady-state and transient, using first principles mass and energy conservation equations. The analytical model calculates a removal rate per cartridge, R_c (so that any scale PAR can be analyzed). Also, the analytical model calculates the temperature rise of the gas (ΔT_g) and the gas velocity (v) through the PAR. This Polestar model was well agreed with the experimental results of Battelle MC-series and KALI tests. A detail of model descriptions and characteristics is included in Reference 9. The third model is the depletion rate equations of NIS PAR based on the test data summarized in the EPRI report for the AP600 Design Certification application [6]. This model explains instrument error and PAR start-up behavior.

To compare the predictions of the PAR performance models, simple test configuration was established using an identical set of initial conditions: (1) 2.5 bar vessel pressure, (2) 383 K gas temperature, (3) 650 m^3 volume, and (4) gas concentrations of 50% air, 40% steam, and 10% hydrogen. A full-scale NIS PAR was assumed to start after the vessel initial conditions were set. Figure 2 compares the hydrogen depletion rates as a function of the hydrogen concentration. Not considering PAR transients due to start-up, the prediction of EPRI model is more conservative than those of the other models. The EPRI model eliminated any uncertainties for making empirical correlation, and therefore, adopted the lower bound estimation. For PAR start-up delay from experimental observations, it has a little impact on the prediction of hydrogen concentration as shown in Figure 3.

4. Hydrogen Control Analysis for the KNGR Containment

The design basis LOCA hydrogen generation and accumulation analysis was performed using the NRC

Regulatory Guide (R.G.) 1.7 model to derive the number of PAR to be installed within the KNGR containment. The hydrogen generation mechanisms are radiolysis of water, corrosion of metals such as zinc and aluminum by the containment spray, reaction of the zirconium cladding with steam and the hydrogen dissolved in the solution of the reactor coolant system and pressurizer steam space. The parameters which determine hydrogen generation during the design basis LOCA in KNGR containment are listed in Table 1. The hydrogen generation from various mechanisms is shown in Figure 4. Herein, the hydrogen generation rates of corrodible metals were calculated from thermodynamic conditions resulting from double-ended discharge leg slot break (DEDLSB) accident. The DEDLSB showed the highest containment temperature history among referenced accidents for the containment DBA P/T analyses. Of course, these conditions were used to calculate the hydrogen concentration.

The computer program, STARGAP[9] was used to evaluate the possible hydrogen accumulation after a LOCA with and without the hydrogen control system. The STARGAP is a Polestar-proprietary enhanced version of the COGAP code that incorporates models for calculating the performance of PARs in containment volumes following a DBA. For STARGAP analysis, the containment was divided into two compartments: containment atmosphere and IRWST free space. These two compartments are physically separated with concrete structures. Although four flow vent paths exist between two compartments, it is conservatively assumed that there are no gas flows. This is since the flow rates through these vent paths could not be verified and credited. Among various mechanisms presented in Figure 4, only the radiolytic decomposition of the water occupied in IRWST becomes hydrogen source term for IRWST free space. On the other hand, based on an evaluation of PAR performance in Section 3, the EPRI model for AP600 evaluation was used as the basic model of KNGR hydrogen control analysis.

Assuming no hydrogen removal, the hydrogen concentrations increase with time as shown in Figure 5. The time when the hydrogen concentration inside IRWST reaches the flammable limit of 4 vol% is at most 2.4 hours, which is very shorter than that for the containment atmosphere (192 hours). Therefore, a hydrogen control system, especially in IRWST free space, is required to prevent the hydrogen accumulation from reaching the flammable limit and start prior to reaching this limit.

As a result of a simple hand-calculation based on the PAR performance capacity, the KNGR Passive Hydrogen Recombination System (PHRS) which consists of two redundant PAR groups, was preliminarily determined so that four PARs would be provided inside the containment above the operating deck and two PARs inside the IRWST free space above normal water level. Figure 5 shows also the effect of single-group PAR operation on the containment hydrogen concentration. The hydrogen concentration never exceeds 2 vol% for all compartments, which indicates ample margin in the PAR capacity. Although the possibility of hydrogen control within IRWST space depends upon the PAR size to be installed, it is expected that IRWST free space can accommodate the NIS full-size PAR so that it may work efficiently as designed.

A further demonstration of the PAR's available capacity margin is provided by calculation of containment concentrations with reduced depletion rates. This also explains PAR performance degradation during the plant operation. Figures 6 and 7 provide the impacts of reduced PAR capacity of 50, 20 and 1 %, respectively. The curves provide indication of the abundant hydrogen control margin. Also, provided in Figures 6 and 7 are the results of a calculation when assuming no recombination until the hydrogen concentration reaches 3.5 vol% threshold. Whereas this situation is considered as excessively conservative, the results emphasize the abundant margin.

Figures 8 and 9 show the sensitivity calculation using various hydrogen depletion models, which confirms KNGR conservative approach for the estimation of hydrogen depletion rate.

5. Conclusion

Based upon the analyses results described above, it is demonstrated that the KNGR PHRS was conservatively designed to maintain the hydrogen concentration within the containment atmosphere below its lower flammability limit of 4% in accordance with R.G. 1.7. As a result, the KNGR Passive Hydrogen Recombination System (PHRS) was designed so that four PARs were provided inside the containment above the operating deck and two PARs inside the IRWST free space above normal water level.

At detailed design stage of the KNGR, the plant-specific PAR equipments depending upon allowable spaces and anticipated gas flow pattern within the KNGR containment, will be required for the practical implementation in the detailed design. And PAR design criteria and placement criteria for this design work should be established.

6. References

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Table 1 Hydrogen Generation Parameters of the KNGR

Parameter	Value	Parameter	Value
Reactor Power, MWt	4,000	Reactor Operating Time, Hours	24,000
Containment Net Free Volume (Minimum), ft^3	3.12 x 10^6	IRWST Freeboard Volume (Design Basis LOCA), ft^3	75,931
Initial Temperature, EF	120	Initial Pressure, psia	15.7
Initial Relative Humidity, %	100	Cladding Zirconium Mass (Surrounding Active Fuel), lbm	55,656
Dissolved Hydrogen in Reactor Coolant (Maximum), cc(STP) per kg of water	100	Radiolysis Water Distribution (Containment/IRWST) Fraction	36.3 / 63.7
Aluminum Inventory, lbm	1,803	Zinc Inventory, lbm	71,220
Dissolved Hydrogen in Pressurizer Steam Space (Maximum), by Weight	2/10 of 1%		

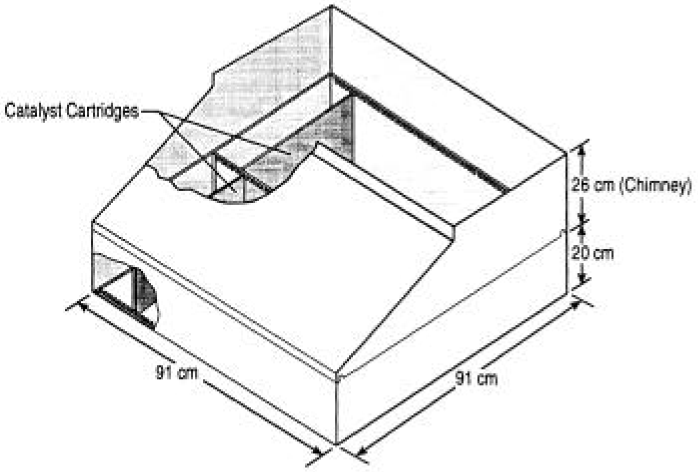

Figure 1 Schematic of the NIS Full-Size PAR

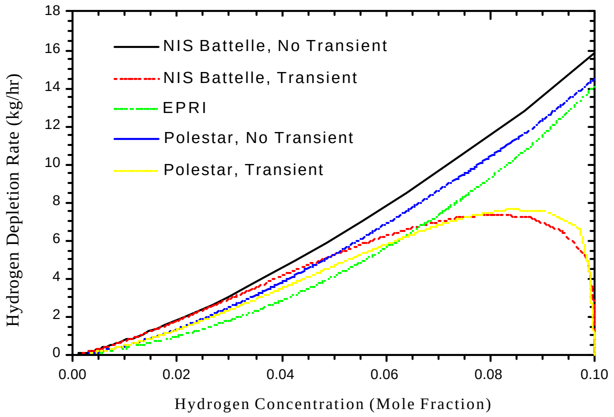

Figure 2 The Hydrogen Depletion Rates for PAR Performance Models

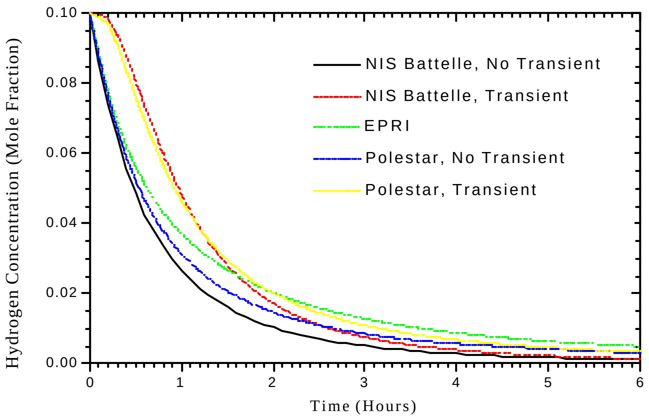

Figure 3 The Hydrogen Concentrations for PAR Performance Models

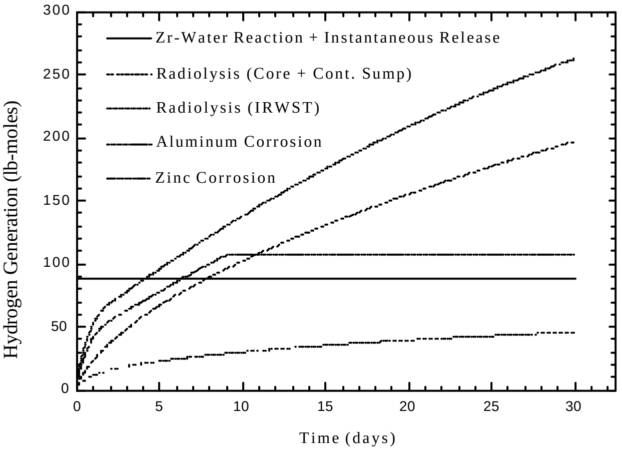

Figure 4 The KNGR Hydrogen Generation

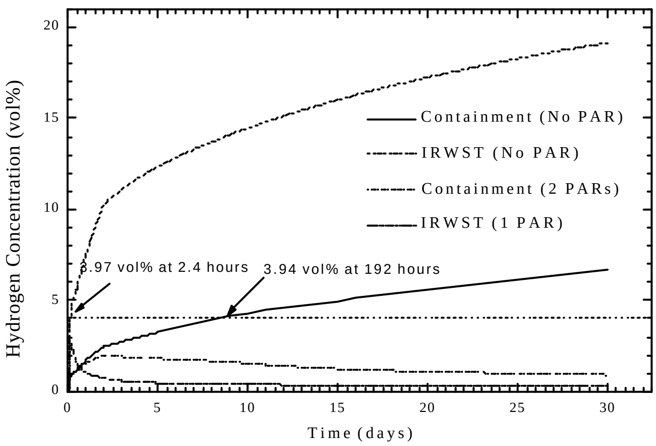

Figure 5 The KNGR DBA Hydrogen Control

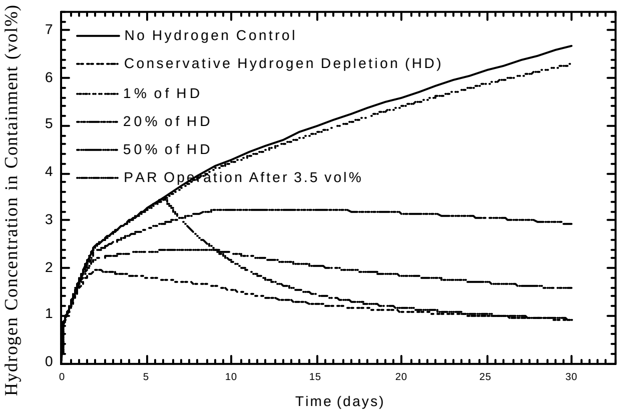

Figure 6 PAR Performance Sensitivity Calculation For the Containment Atmosphere

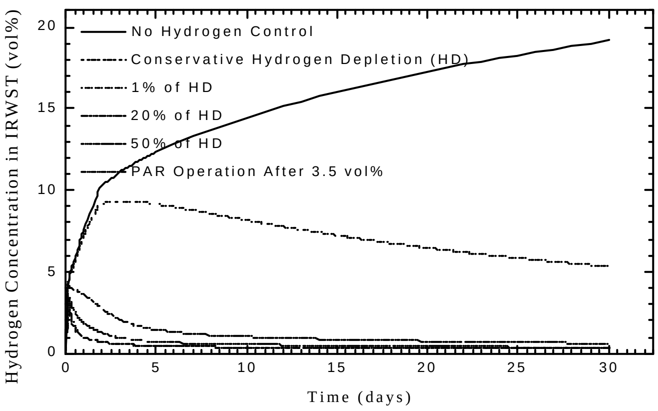

Figure 7 PAR Performance Sensitivity Calculation For the IRWST Free Space

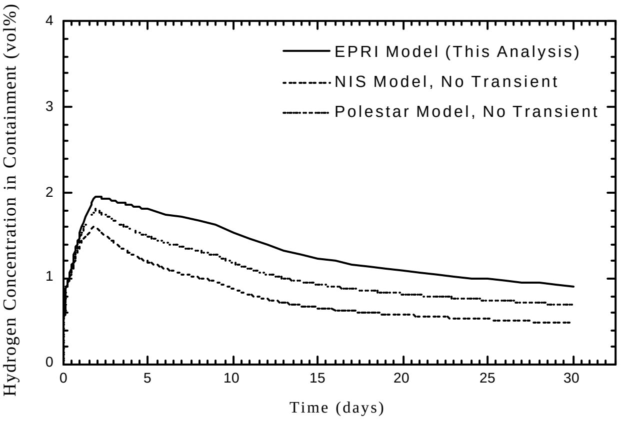

Figure 8 PAR Analytical Model Sensitivity Calculation For the Containment Atmosphere

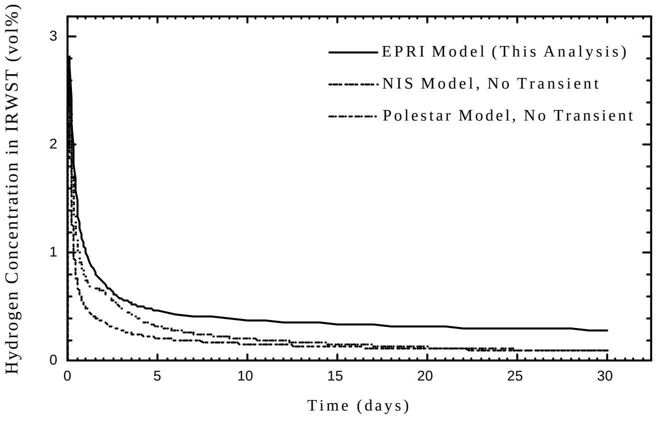

Figure 9 PAR Analytical Model Sensitivity Calculation For the IRWST Free Space