ACTIVITIES FOR HYDROGEN CONTROL DURING SEVERE ACCIDENTS IN KOREA

Jong-In Lee, Han-Chul Kim
Korea Institute of Nuclear Safety, Korea

Goon-Cherl Park
Seoul National University, Korea

ABSTRACT

Since the TMI and Chernobyl accidents, the issue of safety to prevent severe accidents has become a major regulatory issue in Korea as in other countries during the early 1990s. Thus, the provision for adequate measures to control hydrogen during severe accidents became a conditional requirement of the construction permit for the first Korean standard plants, UCN 3 and 4, in 1993. This paper is to introduce the status of measures and the accident management program to control hydrogen during severe accidents in Korean plants, especially UCN 3 and 4, and the position of the regulatory authority, KINS, for current and future plants. Also, experimental and analytical research activities related to this area in Korea are discussed technically. These particularly include the local measurement of hydrogen mixing, to be able to provide data to confirm the 3D code and studies for ignition characteristics of hydrogen/air/steam mixtures and to examine the performance of igniters

INTRODUCTION

Korea has proceeded with an active nuclear program since the first commercial operation of Kori Unit 1 in 1978. Besides having twelve operating nuclear power plants, six plants are under construction and two plants have applied for construction permit. Sixteen are the large dry containment-type PWRs (including sub-atmospheric containment) and four of them are PHWRs. It is planned that a few more plants of the conventional PWR type will be constructed until 2007 and subsequently the next generation of plants will be constructed.

However, since the TMI and Chernobyl accidents, the issue of safety to prevent severe accidents has become a major regulatory issue in Korea, as in other countries during the early 1990s. Studies including experience in the TMI accident have shown that a large amount of hydrogen can be generated and released to the containment during severe accidents in water-cooled reactors. Hydrogen combustion, resulting from high hydrogen concentrations, can threaten containment integrity due to overpressurization and contribute to equipment failure due to the thermal and pressure effects. Among many other problems during severe accidents, the control of hydrogen emerged as a current issue in Korean nuclear power plants under construction as well as those to be constructed.

Some control actions, such as installation of external hydrogen recombiners and post-LOCA hydrogen purge systems, have been implemented for hydrogen mitigation during the design basis accidents, such as LOCA in the Korean nuclear power plants. Because large dry PWR containment has large dilution volumes, and also high ultimate load capabilities, no measures were taken against severe accidents up to the early 1990s, when there came a licensing environment in Korea that the mitigation of hydrogen combustion should be treated as a licensing requirement.

In 1992 a construction permit was issued for a new CANDU-6 PHWR plant (Wolsong-2) which had a new design concept of hydrogen control with igniters following a large break in the primary circuit with a coincident loss of emergency core cooling injection system accident. In 1993, the first Korean standard plants, UCN 3 and 4, obtained construction permits with a conditional requirement of the provision of hydrogen control capability for severe accidents. The regulatory authority required the licensee to provide an analysis report of hydrogen distribution following a 100% fuel clad-metal water reaction and a plan for the provision of hydrogen control capability for the UCN 3 and 4 [1] and the next standard plants, YGN 5 and 6.

A preliminary analysis by MAAP [2] and CONTAIN 1.12 [3] codes with 20 nodes in the UCN 3 and 4 containment shows that hydrogen concentrations in some compartments are over the detonation limit. Thus, the licensee has suggested installation of hot-surface type hydrogen igniters in four rooms and provided a schematic plan for the installation. The adequacy of the number and location will be confirmed by detailed analysis using a three-dimensional code, which is enforced in the licensing process of YGN 5 and 6. This design specification will provide a basis for the design of future conventional plants prior to the Korean Next Generation Reactor(KNGR), which will be required to meet the more strict requirements being provided currently by the regulatory authority and nuclear industry. The regulatory organization, Korea Institute of Nuclear Safety (KINS), prepared review guidance (draft) for hydrogen control during severe accidents for new plants with the conventional design as well as the next generation plants.

This paper is to introduce the status of measures and accident management programs to control hydrogen during severe accidents in Korean plants, and the position of the regulatory authority, KINS, for hydrogen control. Also, experimental and analytical research activities related to this area in Korea are discussed technically, including particularly hydrogen mixing and ignition kinetics. The local measurement of hydrogen mixing was performed in subcompartments to understand the local behavior of hydrogen mixing and provide data to confirm the existing 3D code or to be developed. The ignition characteristics of a hydrogen/ air/steam mixture are numerically investigated adopting the stagnation point flow as a model problem to simulate igniters used for severe accident mitigation. Detailed kinetics are used in this study along with experimental studies to substantiate numerical results.

PROVISION FOR HYDROGEN CONTROL

Actions for Hydrogen Control in the Korean Standard Plants

According to the conditional requirement of the UCN 3and 4 construction permit, the licensee prepared the analysis reports on hydrogen concentration distribution and a plan for provision of hydrogen control capability. During the licensing process some additional reports were provided to evaluate the hydrogen combustion phenomena with the hydrogen control system. Other actions following the issue of the construction permit include;

1) provision for embedments in a total of 162 locations for future installation of hydrogen igniters and electric power cables,
2) addition of an electric penetration in the in-core instrumentation cavity,
3) addition of auxiliary spray nozzles under the operating floor in the containment and vents for some confined areas such as the reactor drain tank room,
4) and expansion of the detection range of hydrogen analyzers from 10% to 15% of hydrogen concentration.

As a confirmatory review of the UCN 3and 4 design, the IAEA International Peer Review Service (IPERS) has been conducted on the PSA. The mission team recommended consideration of realistic hydrogen generation sources and also to consider the adverse effects of hydrogen igniters, if they were to be installed. These aspects were considered partly in the following PSAs and the analyses on hydrogen mixing and combustion.

Meanwhile, the regulatory organization, Korea Institute of Nuclear Safety (KINS), prepared review guidance (draft) for hydrogen control during severe accidents. As for the new plants with the conventional design, the application of the guidance has been focused on local hydrogen control to lessen the possibility of detonation in case of hydrogen generation from the equivalent of a 100% fuel clad metal-water reaction. It assumes that molten corium-concrete interaction (MCCI) could occur after a reactor vessel failure but be terminated after hydrogen is generated by the prescribed quantity. It admits the best-estimate approach to analyze the hydrogen mixing and combustion phenomena, however with additional requirements in regard to uncertainty analysis. The scope of the guidance will be expanded to global hydrogen control for the next generation plants.

Hydrogen Concentration Distribution Following Severe Accidents

The licensee conducted the best-estimate calculations on accidents important to hydrogen release such as large break LOCA (LBLOCA), medium break LOCA (MBLOCA), small break LOCA (SBLOCA), station blackout (SBO), and total loss of feedwater (TLOFW). Hydrogen generation was calculated by the MAAP 4.01 code and hydrogen concentration distribution and combustion phenomena by CONTAIN 1.12. The containment model was based on 20 nodes. The analyses were done according to the KINS review guidance (draft) and also referred to 10 CFR 50.34(f). However the time period considered was only about 24 hours after accidents. The equivalent hydrogen mass due to metal-water reaction with 100% fuel cladding surrounding the active fuel was estimated to be 820 kg. The assumption of hydrogen release partly from MCCI following a vessel failure resulted in relatively lower hydrogen concentration due to the inerting effect of steam during corium cooling in the reactor cavity immersed with water from the broken reactor coolant system, and the refueling water tank, etc. Therefore, some sensitivity analyses were required to take into account the quantity of water and its capability of cooling the corium and the heat transfer to the atmosphere.

The analysis results are summarized in Table 1. It was shown that in some compartments the hydrogen concentrations following various kinds of accidents exceeded the detonation limit which was assumed conservatively to be 10% and those in most of the other rooms were also higher than the flammability limit of the CONTAIN code. The uniform distributed hydrogen concentration in the dry containment was estimated to be 11.8%. Therefore it was confirmed that a hydrogen control system was required to prevent loss of containment integrity or loss of appropriate mitigating features due to unintended combustion or detonation.

The licensee analyzed the hydrogen concentration distribution with hydrogen igniters. They assumed that hydrogen igniters were available at four compartments; two steam generator compartments, the reactor drain tank (RDT) room, and the reactor cavity where the hydrogen is released or accumulated. Five accident scenarios were analyzed up to 2.9 to 4.6 days following the initiation of accidents, depending on the scenario. The results show that at least 43.7% of hydrogen was consumed except following a LBLOCA. However, the combustion did not usually occur when the early peak hydrogen concentrations were obtained in the containment because steam concentrations also peak coincidently with them and thus have an inerting effect in most cases. After early peaks, hydrogen concentrations were maintained under the flammability level between 6 and 6.9% and approached to the almost uniform values in the long-term. Steam condensation proceeded slowly to reach about 15 to 20% at the end of computation. Therefore, the analyses of hydrogen control confirmed the following:

1) In spite of occurrence of hydrogen concentration peaks higher than 10% in the short term for some sequences, the possibility of detonation is sufficiently low due to steam inerting, and

2) Hydrogen concentrations were maintained under the flammability limit due to the sustaining effect of steam inerting and the removal effect of hydrogen igniters.

Provision for Hydrogen Control Capability

Based on the above analyses results, the licensee provided a plan for installation of hot-surface type hydrogen igniters in four rooms for UCN 3 and 4 plants. Although it was not a perfect measure for every kind of accident in which hydrogen burn was involved, the concept was based on a reasonable and practical rationale. It includes installation of igniters in the main recirculation flow, especially in the steam generator compartments, in order to remove hydrogen gradually with making most of the large free volume of the containment and also the effects of steam inerting and mixing of the atmosphere. It is planned to install a total of 18 hydrogen igniters; three igniters will be installed in the reactor cavity and its exit, three for RDT room, six for each steam generator room. The adequacy of the number and the location will be confirmed by detailed analysis using a three-dimensional computer code that has the hydrogen mixing and combustion model.

The hydrogen igniter system has been designed to be incorporated of non-safety grade, nevertheless proper quality standards, seismic classification, environment qualification and separation requirements will be applied to the design. Considering the importance of reliable electric power supply, the igniters will be powered from several Class 1E power sources that may be emergency diesel generators or alternate AC power sources. The two-division concept will be applied to the power supply of igniters. For the purpose of equipment survivability transmitters and power supplies will be placed outside the containment. Separation between the igniters and safety-related equipment is essential for obtaining critical safety functions during and after severe environment including hydrogen burn. However, the equipment survivability against multiple burns should be studied more in the future.

The system will be actuated by manual operation when operators find core uncovery or detect high hydrogen concentration. Experience obtained from installation and operation of igniters at Wolsong Units 2-4, will be useful to provide operation and test procedures related to the system.. The possible adverse effects of hydrogen igniters under some accident conditions such as rapid condensation of steam in the containment atmosphere, should be considered in depth when developing the accident management program.

Pressure increases due to complete burning of hydrogen generated during an accident that releases hydrogen which is generated from 100% fuel clad metal-water reaction was calculated according to the Adiabatic Isochoric Complete Combustion model. The estimated pressure is between 0.66 and 7.2 Mpa (99.4 and 108.5 psia) depending on the assumptions, and is below the established limit of 7.6 Mpa (114.5 psia) based on the elasticity of the containment.

These design specifications will provide a basis for the design of the hydrogen control system in the Korean standard plants prior to KNGR which will be required to meet more strict requirements currently being provided by the regulatory authority and the nuclear industry.

Table 1 Summary of hydrogen concentration distribution without hydrogen control [4]

	LBLOCA		MBLOCA	SBLOCA	SBO		TLOFW
In-vessel H_2 generation (%)	26		34	69	48		54
Higher hydrogen concentration	Wet cavity	Dry cavity			Wet cavity	Dry cavity & less heat transfer	
Location	Rx. Cavity	Rx. Cavity	Rx. Cavity	RDT room	RDT room	Rx. Cavity	Rx. Cavity
Peak value	19.5%	32.9%	17.5%	11.3%	8.8%	20.9%	11.4%
Time after initiation of the Accident	15,000s	15,000~ 25,000s	24,000s	52,000s	28,000s	18,000s	55,500s
	S/G comp.: 10.1% Rx. Cavity Entrance: 13.3% ICI cavity: 15.2% ~23,000s			Lower Annulus: 10.0% 64,000s	RDT room: 16.5% 9,000s ICI cavity: 20.4% 18,000s		RDT room: 12.5% 20,800s

HYDROGEN RESEARCH ACTIVITIES IN KOREA

In Korea, research has not been active in the field of hydrogen control. However, fundamental studies have been continuously performed mainly at SNU (Seoul National University) with the collaboration of national institutes and utilities.

Status of Hydrogen Research in KAERI

At KAERI (Korea Atomic Energy Research Institute), research of nuclear reactor safety during hypothetical severe accidents has been carried out for years, and research on the hydrogen combustion characteristics is one of them. The analytical study of hydrogen control, which has been carried out for the past few years in collaboration with Seoul National University, is composed of:

- local hydrogen concentration analysis using integral code, CONTAIN, for UCN 3 and 4,
- code development for hydrogen burn analysis,
- model improvement for flame velocity in the CONTAIN code.

Recently in the design of KNGR, where the installation of proper hydrogen control systems is required, the limiting deflagration-to-detonation transition (DDT) criteria to evaluate the possibility of DDT is establishing with the integration of detonation experimental data. For the close investigation of the hydrogen combustion phenomena, KAERI is planning a joint research program with BNL (Brookhaven National Laboratory) to obtain profitable experimental data for hydrogen mixtures which are prototypic to severe accident scenarios. The critical tube and hot jet initiation experiments will be carried out in this program. In the critical tube experiment, the critical hydrogen-air-steam mixture which represents the transition from detonation failure to transmission will be measured. From the hot jet experiment, critical mixture composition for initiation of a detonation due to hot turbulent jet will be measured.

Fundamental Study on Hydrogen Control in SNU

In SNU, fundamental research on hydrogen control focuses on hydrogen mixing in subcompartments of the containment [5] and characteristics of hydrogen combustion including igniters [6]. Most of the previous works for hydrogen management were concerned the hydrogen concentration distribution for the global flow of hydrogen in the containment building. However, such lumped analysis has been limited to meet the requirements of 10CFR50.44(f) which states the local hydrogen limit of 10%, to ensure the equipment survivability and to determine the exact positions of control measures such as igniters or passive autocatalytic recombiners (PAR). Specially, if obstacles exist in the way of hydrogen behavior, those would be expected to cause remarkable concentration gradients of hydrogen within the compartment. Thus, local concentrations peaking as a result of such non-uniform distribution would lead to hydrogen deflagrations and moreover bring about a flame flow path, even though the result obtained from the lumped analysis meets the limit.

Thus, local H2 concentrations have been measured at the SNU hydrogen mixing facility, shown in Figure 1, to understand the local behavior of hydrogen mixing and, in the future, to provide the data for confirming the three-dimensional code such as GOTHIC, or either to be developed if needed. The mixing chamber used in the experiment is a 1/11 linear scaled model of the safety injection (SI) tank subcompartment in YGN Units 3 and 4. Its height and diameter are about 100cm and 180cm, respectively. The chamber is divided by two-layers which simulate the compartment layers at 154ft and 169ft in elevation of the plant, and it also has a ring-type gap between each layer and SI tank. Hydrogen was simulated by helium in experiments due to safety and thus the working fluid is the mixture of He and steam. In this experiment, local He concentrations at 19 points as the maximum were measured in various operating conditions. The subjected conditions for the effect test were injection position and direction, mixing ratio, and injection velocity. The effect of condensation through the wall was also investigated. Results showed remarkably different local concentrations of He in several conditions, as shown in Figures 2 and 3, and thus the local analysis for hydrogen concentration, as well as the lumped compartment analysis, would be important to ensure the equipment survivability or to determine the positions of igniters.

The studies for characteristics of hydrogen combustion have touched on the following subjects [6];

a) Laminar burning velocity of the hydrogen/oxygen/water vapor mixture is studied numerically accounting detailed chemical mechanisms. Results are correlated in terms of pressure, temperature and mole fractions of hydrogen, oxygen and water vapor.

b) Ignition characteristics are numerically investigated determining minimum ignition energy simulation spark ignition.

c) Transition from deflagration to detonation has been studied numerically by applying excessive ignition energies, and the transition phenomena are investigated numerically.

Thermal ignitors are also modeled as a hot surface with impinging jet of hydrogen/air/water vapor, forming a stagnation-point flow. Ignition characteristics are determined numerically and the results are experimentally supported. Extinction conditions are determined for counterflow and stagnation point flow geometries to furnish basic flamelet library data in modeling turbulent hydrogen combustion.

CONCLUSION

As required by the condition of the construction permit for the recent Korean standard plants, best-estimate analyses were done on hydrogen concentration distribution with and without a hydrogen control system according to the regulatory organization's review guidance (draft) and 10 CFR 50.34(f). The results showed that the possibility of detonation is low due to steam inerting and hydrogen concentrations were maintained under the flammability limit due to steam inerting and removal by igniters. Based on results, a plan for installation of a total of 18 hot-surface type igniters was provided for UCN 3 and 4. In future, the adequacy of this design including the number and the location of ignitors will be confirmed by detailed analysis. Possible adverse effects of hydrogen igniters should be considered in developing the accident management program.

Also, experimental and analytical research activities related to this area in Korea were introduced. Mixing experiments showed that the local analysis for hydrogen concentration, as well as the lumped compartment analysis, are important in ensuring the equipment survivability or to determine the positions of igniters.

REFERENCES

1. Korea Electric Power Corporation 1996. Ulchin Nuclear Power Plant Units 3&4 Final Safety Analysis Report.
2. Henry, R.E., et al. “MAAP4 – Modular Accident Analysis Program for LWR Power Plants.” Fauske & Associates. 1994.
3. Murata, K.K., et al. “User’s Manual for CONTAIN 1.1 : A Computer Code for Severe Nuclear Reactor Accident Containment Analysis.” NUREG/CR-5026. 1989.
4. Korea Power Engineering Company, Inc. April 4,1997. 9-035-N462-005, Rev.2.
5. Park, G.C., et al. "Development and Application of Two- Dimensional Hydrogen Mixing Model in Containment Subcompartment Under Severe Accidents." Journal of Korean Nuclear Society. **29**, *p*.110, 1997.
6. Chung, S.H., et al. “Numerical Study on Initiation and Propagation of Deflagration and Detonation Wave in H_2/air/steam Mixture.” International Conference on PSA Methodology and Applications(PSA '95), Seoul. 1995.

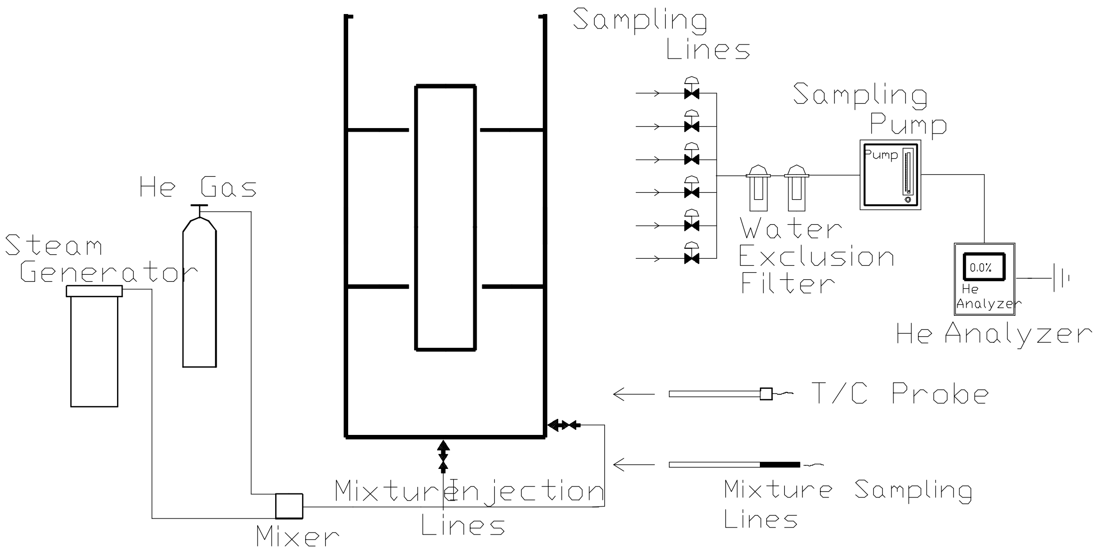

Figure 1 Configuration of SNU Hydrogen Mixing Facility

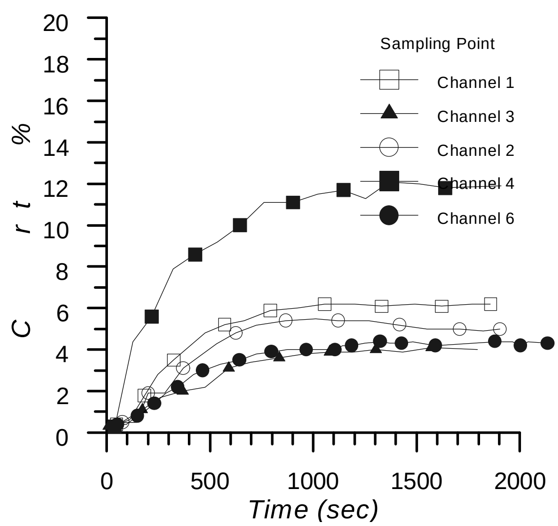

Figure 2 He concentration of center injection (Mixture Injection : 17 lit/min)

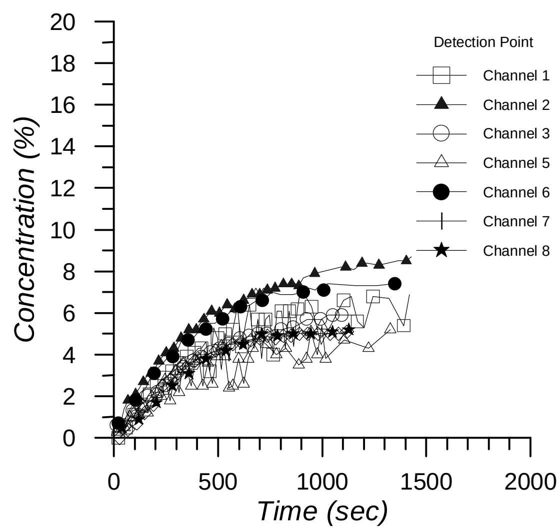

Figure 3 He concentration of side injection (Mixture Injection : 17 lit/min)