Integrity Study of Spent PWR Fuel under Dry Storage Conditions – 14236

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ABSTRACT

Technical issues related to long-term spent fuel integrity are reviewed considering the spent fuel storage and handling conditions expected in Korea and some experimental cold and hot tests including creep and hydride reorientation were examined to build up our own spent fuel DB. A small scaled-dry storage simulation facility called 'DrySim6' was developed. All experimental test methods and equipments were specially designed to optimize the limited hot experiments with several interacting factors to produce critical data for updating the existing degradation models. The experimental data from the DrySim6 operation and sequential hot cell works will be compared with the reference fuel data to predict and evaluate the spent fuel integrity under dry storage conditions.

INTRODUCTION

Korea's nuclear power program currently has twenty three operating power plants consisting of four CANDU and nineteen pressurized-water reactors (PWR), and the government plans to have eleven more nuclear units until the mid-2020s [1]. Such an active nuclear energy program is causing a significant spent fuel accumulation problem, which may affect the construction plan of new nuclear plants in Korea. The cumulative amount of spent fuel is currently about 14,000 tons as of Dec. 2012, and is expected to increase up to 20,000 tons by around 2020. At present, this spent fuel is stored in temporary storage facilities at plant sites. In fact, the government has tried to construct an off-site interim storage facility since the late 1980s, but it has failed because of the difficulty of securing a site. Therefore, KHNP (Korea Hydro & Nuclear Power Co., Ltd.), which owns and operates all nuclear power plants in Korea, has been performing its own program to extend the on-site storage capacity since early 1990s by the replacement of the storage rack and spent fuel transshipments to neighboring reactors and the construction of a concrete dry storage facility. Most standard storage racks at the pool storage facilities of the PWRs have been replaced with high density storage racks (HDSR), which increases the storage capacity with neutron absorbers such as Boral or Borated Stainless Steel. In the CANDU plant, a concrete dry storage facility (silo) was constructed for the first time in 1990, and a total of 300 concrete-silos were installed. A new dry storage system called MACSTOR/KN-400 with a higher storage density than a concrete-silo was installed in 2010. Unfortunately all of these storage facilities are expected to reach their full capacity in the mid-2020s because there is no more available area to increase the on-site storage capacity.

Considering such expansion limit at the plant sites, the government made a decision to construct an interim spent fuel storage facility during this available period (~12 years from now) earlier this year. For the long-term safe management of spent fuels in the country, the government also very recently made an official team to organize a "Commission for Public Participation" to facilitate and encourage open social/public discussion and a democratic, transparent decision-making process concerning the establishment of the national long-term management plan of spent fuel. It is expected that the Korean government will decide on the national policy for spent fuel management through public participation in the near future. As we have already experienced, however, if all processes to make a long-term spent fuel management plan through public engagement go at a snail's pace or are unsuccessful because of some unexpected political or social issues, the storage period of spent fuels at the interim storage facility will naturally increase before a final solution such as disposal or recycling.

Korea initiated a national R&D program to develop key technologies of a dry storage system, as shown in Figure 1, which will be applicable commercially for a spent PWR fuel dry storage facility, to be installed around the mid-2020s.

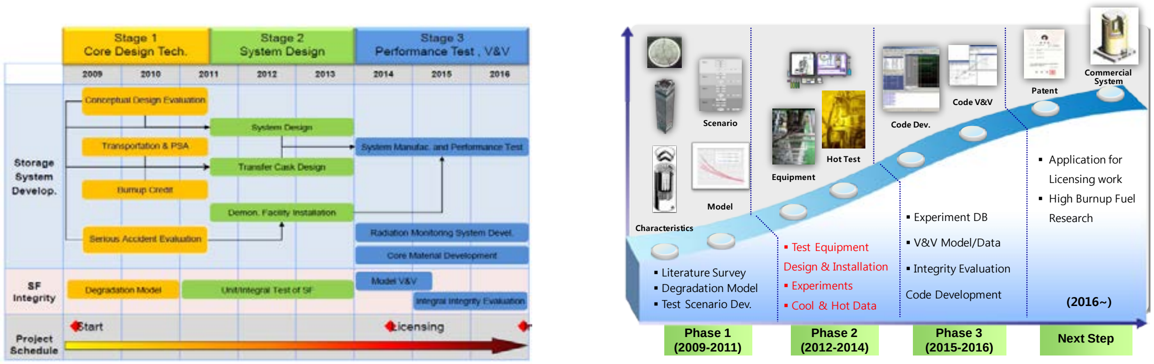

Fig.1. R&D plan to develop a Interim Dry storage Facility for PWR Spent Fuel in Korea (a) and Long-term Integrity Study Plan (b) .

In this program, KAERI (Korea Atomic Energy Research Institute) has been responsible for an integrity study of spent PWR fuels under the dry storage condition since 2009. This study consists of the following three phases: a degradation mechanism review (2009-2010), demonstration test design (2011-2013), and evaluation code development (2014-2015). KAERI performed the characterization of spent PWR fuel stored at plant sites and developed a reference degradation model to estimate the spent fuel integrity with respect to the storage temperatures, atmosphere, burnup, and so on during the past years. These days, KAERI has been developing a dry storage simulation facility called ‘DrySim6’ (Figure 4)[3], the purpose of which is to validate the reference degradation model using 6 spent fuel rods and provide information to predict the spent fuel integrity under the given dry storage condition and carry out some basic hot cell operations to characterize the reference spent fuel rods to be tested, the purpose of which is to compare with the data from the DrySim6 experiments. All the spent fuel tests and DrySim6 experiments will be done in the hot cell from 2014 to 2015. It is expected that a useful methodology as well as information to demonstrate the integrity of long-term spent fuel storage can be developed through this R&D program in Korea. This paper presents the current status of a spent fuel integrity study being performed in Korea, and some key results such as the spent fuel characteristics, reference degradation model, and conceptual design features of DrySim6. The future plans are also discussed.

REFERENCE SPENT FUEL MATERIAL AND INTEGRITY TEST PLAN

The reference fuel material to be tested in this study was sampled from PWR spent fuel irradiated at Ulchin unit 2 with 55 GWd/tHM, which has been cooled for 10 years under water. It is expected to be a representative of 78% of the spent PWR fuel generated in Korea.
In this study, a total of 12 spent fuel rods selected from the reference fuel assemble as described in Table I, will be tested and examined through a set of non-destructive tests, and 6 of the fuel rods were then examined through destructive tests, and the other 6 rods experienced dry storage conditions at a dry storage simulation facility for about three years. Figure 2 shows a summary of integrity test plan for this study.

TABLE I. Description of Spent PWR Fuel tested in this study

Fuel	K23 Assembly irradiated at Ulchin Unit 2 (17x17)
Cladding	Zircaloy-4
Enrichment	4.2 wt%
Burnup	52,327 MWd/tHM
Discharge	May 15, 2001
Cooling Period	Approximately 11 years

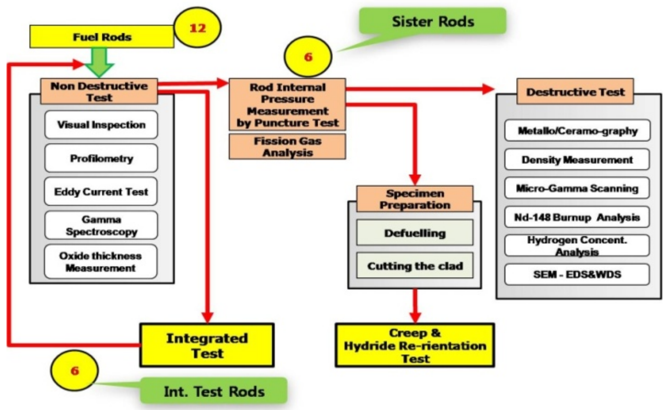

Fig. 2. Integrity Test Plan using Spent PWR Fuel.

CONSIDERATION OF DEGRADATION MECHANISMS OF SPENT FUEL

In Korea, a lot of spent fuel placed in wet storage of plant sites might have been exposed several times to thermal cycling during reactor operation and replacement of the storage rack or transfer to a neighboring storage facility to increase some on-site storage capacity. If a dry storage system for interim storage is introduced, spent fuel stored in pool storage at 30-40°C would be moved to a dry storage facility. Such a significant change in storage condition may cause fuel degradation against the long-term storage safety of the spent fuel.

Fuel degradation can occur as a result of mechanisms that may affect the cladding integrity of spent PWR fuels during dry storage, and subsequent handling and transportation operations are air oxidation, thermal creep, stress corrosion cracking (SCC), delayed hydride cracking (DHC), hydride re-orientation, and hydrogen migration and re-distribution [4,5]. Consequently, many countries are conducting an R&D program related to a spent fuel performance evaluation for long term storage. The degradation mechanisms are also related to the safety issues for the fuel transfer to the disposal facility to be introduced eventually as a final management step.

Current issues in the degradation mechanism are mostly focused on the effects of hydride reorientation on the mechanical properties of spent fuel cladding rather than on other mechanisms like creep or stress. During dry storage, the US Nuclear Regulatory Commission (NRC) supports the conclusions that under normal conditions, storage creep will not cause a gross rupture of the cladding, and that the geometric configuration of the spent fuel will be preserved, provided that the maximum cladding temperature does not exceed 400°C. In Germany, an operating license is granted for 40 year-storage of spent fuel burnt up to 65 GWd/tHM (UO2) and 55 GWd/tHM (MOX) when the initial maximum cladding temperature will not exceed 400°C, the tangential hoop stress will not exceed 120 MPa, the circumferential plastic strain will not exceed 1%, and fuel cladding is considered as additional confinement. Short-term creep and rupture tests performed on Zircaloy-4 cladding from fuel burnt up to 64 GWd/tHM did not show any adverse effects of the integrity under dry cask storage conditions [6]. R&D work is now in progress on commercial BWR and PWR cladding materials with burnups between 55 and 80 GWd/tHM. Long-term thermal creep tests have been performed at a temperature of about 400°C and circumferential stresses of 130 to 150 MPa over 2 to 3 years and are especially intended to provide information on cladding integrity and the hydrogen effects under thermal cycling conditions. Preliminary results indicate that, even at very high burn-ups under thermal cycling conditions, the German engineering limits of 120 MPa circumferential stress and 1% strain are not challenged [4]. As the reactor core management technology and the nuclear fuel design are greatly improved, at present, the average discharge burnup of the spent fuel increases over 65 GWd/tHM. It is no longer a technical issue to dispose of high-level waste even in advanced countries like the United States, Germany, and Japan. Most countries are considering the prospect of extended long-term storage (i.e., >60 to 100 years) and have been conducting R&D activities on the long-term dry storage of high-burnup spent fuel. Most works include the development of models to predict the cladding integrity (zirconium hydrides precipitation and reorientation) and define the failure criteria for claddings under the handling or transportation accident conditions, and characterizing the dynamic loading on fuel rods as a result of an accidental drop of a spent fuel cask.

CREEP TEST

Creep had been regarded as the major mechanism of spent fuel degradation at the early dry storage, however, it is no longer considered to be a critical issue for long-term dry storage. Because some research results have shown that long-term thermal creep tests on high burnup (~64 GWd/tHM) Zircaloy-4 cladding did not show any adverse effects on the integrity under dry cask storage conditions and even at very high burn-ups under thermal cycling conditions [6, 7]. However, the creep property of an irradiated cladding would be still one of the key factors to evaluate the spent fuel integrity during reactor operation and/or dry storage at least for a spent fuel DB-poor country like Korea.

To obtain the basic data for ensuring the integrity of spent fuel cladding under dry storage conditions, the internal pressure creep test techniques and the creep test equipment were developed in this study. The creep test equipment, as shown in Figure 3, consists of three independent parts: an argon gas supply system to simulate a certain cladding hoop stress, a heating furnace and a laser extensometer. Of course, the radiation shielding structures were also installed in this equipment. The desired hoop stress in the 25-cm cladding tube specimen is applied by an inner pressure of argon gas in the argon gas supply system. The specimen is heated up over 400°C in the furnace, and creep deformation under the given temperature and hoop stress conditions is then measured using a laser extensometer. The performance of this equipment was successfully tested using unirradiated cladding tube specimens of PLUS7 and 17×17 ACE7 fuel and irradiated PLUS7 cladding tube.

Preliminary performance test results showed that the given hoop stress simulated by Ar gas in the cladding remained steady, and the heating furnace also maintained comparatively a satisfactory temperature profile along the cladding specimen, as shown in Figure 4.

HYDRIDE REORIENTATION TEST

Hydride reorientation can occur during the reactor operation and the dry storage of spent fuel and associated handling processes. During reactor operation, part of the elemental hydrogen created by the oxidation of the cladding by water is absorbed by zirconium-based alloy, and once the solubility limit of hydrogen in the cladding material matrix is reached, hydrogen precipitates in the form of hydride platelets predominantly aligned in the circumferential and axial directions. Additional circumferential-axial hydrides precipitate during reactor shutdown owing to the decrease of the hydrogen solubility limit with temperature. When spent fuel is moved to dry storage from a wet storage facility, dry storage and/or transport operations may

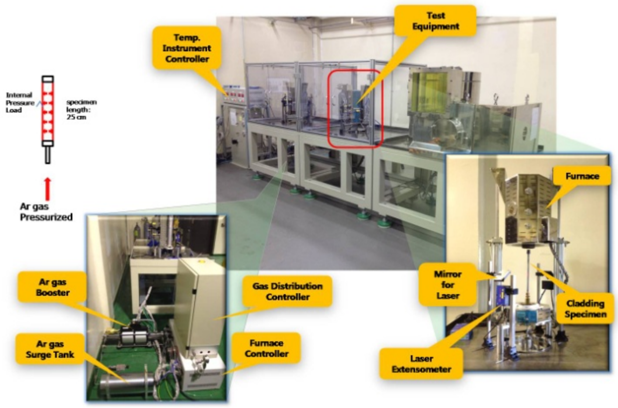

Fig. 3 Creep Test Equipment

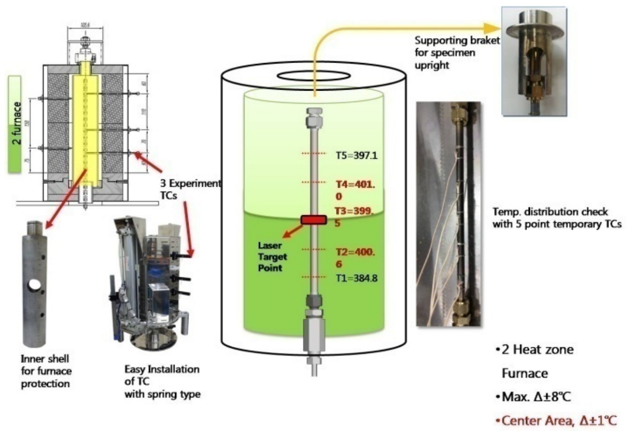

Fig.4 Performance Test of the Furnace of the Creep Test Equipment : Temperature Profile along 25cm-cladding tube specimen heated up to 400°C in the furnace

cause significant increases in cladding temperature: peak cladding temperatures of up to 400°C (dry storage) or up to 420°C (transport) are generally considered. The sudden increase of fuel temperature from pool storage conditions to dry conditions results in hydride dissolution and in a corresponding increase of the hydrogen in solid solution in the zirconium based cladding material. The temperature increase also leads to an increase of the rod’s internal pressure. Subsequent cooling during dry storage or re-wetting after transportation causes hydrogen in a solid solution in the cladding materials to re-precipitate, but possibly aligned in the radial directions owing to the influence of the tensile hoop stress in the cladding, caused by the internal rod pressure that is no longer compensated by external means such as the coolant pressure in the reactor. It is well known that hydride orientation has a significant influence on the integrity of fuel cladding [7]. The creation of radially reoriented hydrides can significantly weaken the cladding’s mechanical integrity. Therefore, ensuring cladding integrity in spent fuel is central to establishing regulatory acceptance criteria for licensing a dry storage and/or handling system. Past works on zirconium alloy cladding have shown that many experimental parameters affect hydride reorientation. The most important parameters include: the (1) material type, (2) hydrogen content and distribution, (3) fluence, (4) temperature, (5) applied stress, (6) cooling rate, and (7) extent of temperature variations when thermal cycling is involved. These parameters are very closely related with the design parameters of the storage and transfer system, and thus it is meaningful to quantify these parameters with respect to safe storage conditions even at the laboratory scale.

A set of preliminary tube tests has been conducted for hydride reorientation with a ring test. For the tube testing, the top end of the 25-cm tube is sealed with a high pressure fitting, and the bottom side is connected to an argon gas supply system to simulate the hoop stress during dry storage (see Fig.5). Because hydride reorientation testing requires the temperature to decrease slowly with time, it is necessary to control the gas pressure according to the ideal gas law in order to keep the hoop stress of the tube constant. The stress is expressed by a thin-walled formula. This method has some advantages. There is no azimuthal variation of the stress, and thus tube testing is much closer to the real conditions and it is easier to analyze the test results, even if the tube test method is more or less complicated and difficult compared to the ring test method. Moreover, it is possible to evaluate the changes in mechanical properties by performing tensile and compression tests using multiple samples from the same tube length after hydride reorientation. The preliminary test results show that the developed test techniques and equipment can be applicable to a study on the characteristic evaluation of hydride reorientation of zirconium based cladding materials.

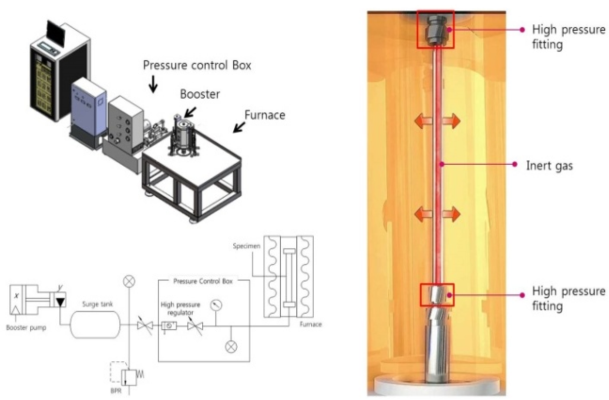

Fig. 5. Tube test for hydride reorientation

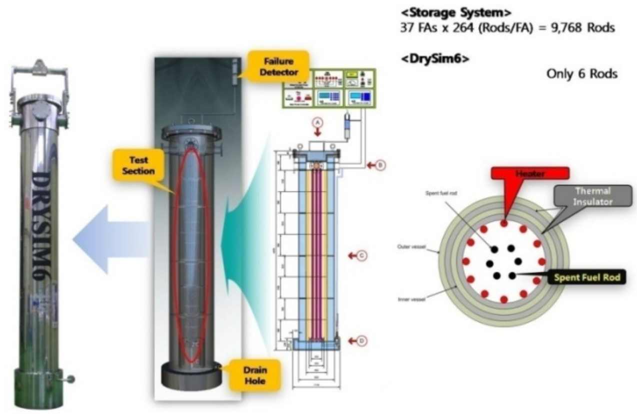

Fig.6 Dry Storage Simulation Facility with 6 spent fuel rods

INTEGRATED INTEGRITY TEST FACILITY

The small scaled-dry storage simulation facility called 'DrySim6(DRY storage SIMulation with 6 spent fuel rods)' (see Fig.6)[3] has been developed, the primary purpose of which is to validate the reference degradation model developed by comparison with experimental data from DrySim6 operation and sequential hot cell works and provide key information to predict and evaluate the spent fuel integrity under dry storage conditions. This facility was designed to store 6 spent fuel elements from Ulchin Unit2 and be heated up to 500°C to simulate 50-year dry storage conditions. One or two fuel rods will be examined every year to analyze its (or their) degradation behaviors during dry storage through a comparison with the basic characteristics of the reference spent fuel rods which have never been exposed to any dry storage conditions.

These days, a set of performance tests of DrySim6 have been carried out at a specially designed work shop. All the designed spent fuel tests and DrySim6 experiments will be done in the hot cell from the year 2014 to 2015. It is expected that a useful methodology as well as information to demonstrate the spent fuel integrity under the long-term dry storage can be developed through this study in Korea.

SUMMARY

Spent fuel degradation mechanisms were reviewed considering the spent fuel storage and handling conditions expected in Korea and some experimental cold and hot tests including creep and hydride reorientation were examined to build up our own spent fuel DB. A set of preliminary performance tests results of the developed test equipments appeared to be reasonable. A small scaled-dry storage simulation facility called 'DrySim6' was developed. All experimental test methods and equipment were specially designed to optimize the limited hot experiments with several interacting factors to produce critical data for updating the existing degradation models. The experimental data from the DrySim6 operation and sequential hot cell works will be compared with the reference fuel data to predict and evaluate the spent fuel integrity under the dry storage conditions.

Based on these experimental data and model developments, a spent fuel integrity evaluation code will be developed using the degradation models in 2016.

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