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PWR SPENT NUCLEAR FUEL RESEARCH STATUS FOR DRY STORAGE AND TRANSPORTATION IN KOREA

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ABSTRACT: *Current PWR Spent Nuclear Fuel(SNF) inventory in Korea is approaching to the limit of wet storage capacity in the nuclear power plant. Upcoming series of nuclear power plant decommission also push this problem to more urgent situation. According to a new national polish on high level radioactive waste management announced in 2016 by the government, dry storage inside the plant site will be the first implementation. R&D for the domestic SNF which will support the licensing process of this dry storage business is essential and very important. This article shows the major R&D activities in detail which consist of characterizing PWR SNF and evaluating SNF integrity at static & dynamic conditions.*

KEYWORDS: *spent nuclear fuel, dry storage, low burnup*

I. SNF Inventory

Table 1 shows the current status of operating NPPs and SNF inventory in ROK as of March 2016 [Ref 1]. There is two types of NPPs but the major type is the pressurized water reactor(PWR) while there is no more plan of newly constructing pressurized heavy water reactor (PHWR, called as CANDU) type. The number of CANDU SNF assembly amount is very larger than PWR because CANDU utilizes natural uranium instead of enrichment and then the fuel refilling period of it is extremely very shorter than PWR. This is one of the reasons why CANDU is not preferred any more in the SNF management point of view in ROK. The majority of spent fuel generated from NPPs is stored in the spent fuel pools in each unit. The storage capacity for spent fuel has been expanded as a consequence of the delayed construction schedule of the away-from-reactor interim storage.

For PWRs, high-density storage racks have been installed to expand storage capacity. When the storage capacity of the spent fuel pools has been reached beyond reracking activity, the spent fuel has been transferred to the storage pools at neighboring units in the same site.

For PHWRs at the Wolsong site, there is two types of dry storage systems; the old one is the concrete silo which stores 9 baskets in the vertical stack inside of it. Because each basket contains 60 CANDU SNF bundles, therefore each concrete silo stores 540 SNF bundles. It has been safely operated since 1990 and its number became up to 300 units. Despite of large number of silos, there was still more storage needs. The new one, MACSTOR/KN-400 (Modular Air-Cooled STORage 400) modified from Canadian technology was developed and installed in the same site. In this system each canisters store 10 baskets vertically and totally 40 canisters are contained in a module. 7 modules has been safely operated since 2010.

II. National Polish of SNF Management

Spent nuclear fuel accumulation is a hot issue to the continuous nuclear power plants operation in Korea. As Kori 1 Unit was decided to shutdown, be dismantled and decommissioned June 2017, 2022 is supposed to be the target date of D&D business kick-off. With this backgrounds, PWR SNF(spent nuclear fuel) dry storage system is necessary in urgent situation. The government, MOTIE(Ministry of Trade, Industry, and Energy), has announced July 2016 ‘Basic management plan for high level radioactive waste’ to solve this problem [Ref 2]. This plan mentioned that KHNP will install PWR SNF dry storage system inside KHNP NPP site temporarily until government find an appropriate away-from-reactor site. This means that KORAD needs to wait SNF business until SNF is moved out of NPP site, and so they have to focus on the centralized dry storage and disposal in the future (MOTIE plan says that centralized dry storage could be 2035 and disposal could be 2053) (Fig 1). According to MOTIE's plan, KHNP will be dry storage system licensee themselves by 2020. Therefore SNF R&D results which is very critical to safety analysis of SNF dry storage activities have to support the licensee before this timeline.

TABLE I. SNF inventory in ROK as of March 2016

	Site	NPPs	Capacity (SNF assembly)	Accumulated (SNF assembly)	Percentage (%)	Anticipated Saturation (Year)
PWR	Hanbit	6	9,017	5,766	63.9	2024
	Kori	7	7,244	5,677	78.4	2024
	Hanul	6	7,066	4,855	68.7	2037
	Shin-Wolsong	2	1,046	129	12.3	2038
	Sum	**21**	**24,373**	**16,427**	**67.3**	
PHWR (CANDU)	Wolsong	4	499,632	413,124	82.7	2019

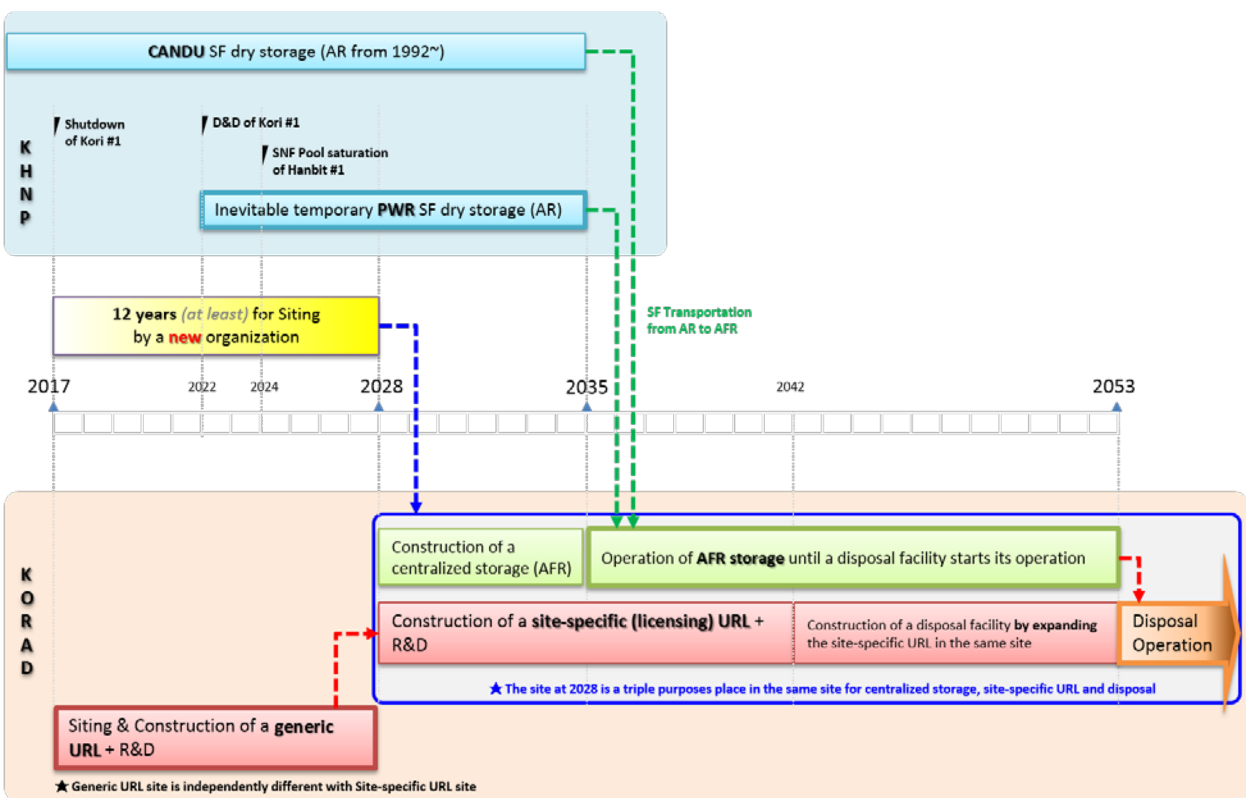

Fig. 1. National Roadmap for SNF Management in Korea.

III. SNF R&D Activities in Korea

SNF R&D planning consists of two steps: low burnup and high burnup. The reasons for low burnup research for the front phase are: the first, there is over 80% occupation (Fig 2) of low burnup fuel in Korea because there has been no activity to remove it from NPP pool for the last 35 years, the second, we have no experience for PWR SNF dry storage licensing, and therefore we had better follow the other nation's system for the first time, and the third, we need incubation time to build our capabilities for SNF testing, validation & verification of testing data, comprehensive methodologies of integrity evaluation and how to apply our results into the real business and licensing. The first 5 years R&D results(2015-2019) are supposed to contribute PWR SNF dry storage licensing and then it can move to high burnup area with low burnup experience, experimental testing devices, and experienced working forces.

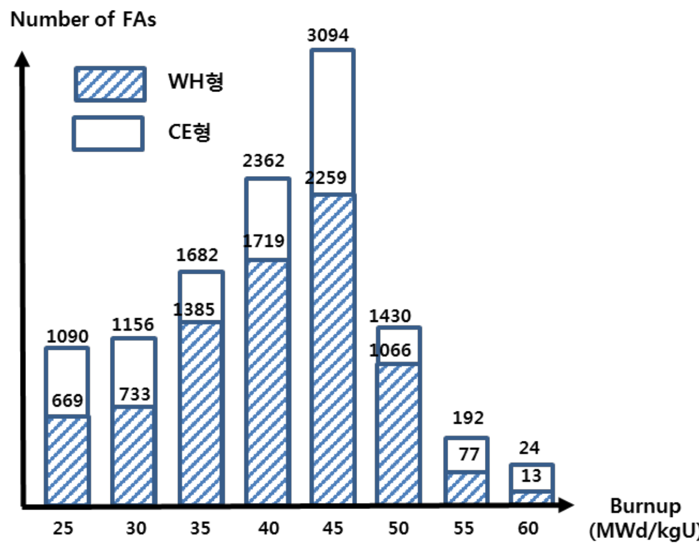

Fig. 2. SNF Burnup Distribution in Korea (Courtesy of KHNP)

SNF R&D project consists of three activities: the first is the characterization of domestic low-burnup SNF condition before dry storage, the second is the improvement of SNF degradation evaluation methodologies at static condition, and the third is the establishment of SNF mechanical integrity evaluation system at dynamic condition [Ref 3]. This project has been implemented by the fuel expert groups like KAERI, KHNP, and KEPCO NF together. Collaboration with foreign expert and organization is also very active to discuss and confirm the research direction.

III.A. Characterization of domestic low-burnup SNF condition before dry storage

III.A.1. SNF distribution analysis for all Nuclear Power Plants

It is known that 18 species of PWR Nuclear Fuel has been used in in Korean NPP. However most of them are similar each other because it has been upgraded version from the original design. Westinghouse(WH) was the major company who supplied nuclear fuel to Korea from 1978 to early 2000, and Combustion Engineering(CE) is another nuclear fuel supplier for their own design NPPs. Korea revised CE NPP as KS(Korea Standard) NPP. Korea does not have BWR and 15x15 fuel type of PWR. Kori #1 Unit only uses 14x14, and every 17x17 fuel was supplied by Westinghouse. Westinghouse SNF occupies the majority of low burnup SNF because WH NPP operation history is longer than KS NPP. Because KS NPP became the standardized PWR NPP in Korea, most of high burnup SNF is being now and will be in the future produced from KS NPPs. [Ref 4] Zircaloy-4 was world widely popular PWR nuclear fuel cladding material before 2000 and after that Zirlo was major cladding for PWR NPP. M5 is just one of extremely minor cladding in Korea and HANA cladding which was developed by domestic own technology will be the major cladding in near future.

III.A.2. Categorizing SNF specifics and selecting the representative testing SNF rod & assembly

There is huge limitation of irradiated SNF testing numbers because availability of hotcell facility is not enough and budget & schedule are usually very shorter than full experimental demand. This situation urges the project to select some representative SNF. This is about not only rod but also assembly to minimize testing numbers. One big question of representative fuel selection was how to evaluate conservatively weak fuel. Single effects of degradation like creep and hydride effect can be applied to only SNF rod and mechanical transformation like bowing and twisting is major topic of SNF assembly. This difference lead to a premise that a selected representative rod could be independent from a selected representative assembly. For example, though we evaluated zircaloy-4 cladding of 14x14 as a representative rod in the conservatively weak point of view, 17x17 Westinghouse Vantage 5H assembly could be selected as of conservatively weak representative assembly considering handling point of view. This un-coupled approach seems to be complicated, but we can give them a double conservatism simultaneously even though there is no actual SNF assembly which consists of 14x14 zircaloy-4 cladding and 17x17 Westinghouse Vantage 5H together.

There had been several R&D projects which dealt with domestic SNF rods for last 30 years in hotcell. Even though almost those data range do not comply exactly with SNF dry storage condition, some of them could be referred to current R&D data set. Under a kind of monopoly situation of hotcell operation, KAERI owns every SNF data in Korea which were produced from KEPCO NF (nuclear fuel supplier company) new fuel development program, KHNP (NPP operation company) operation experience like damaged fuel evaluation project, and KAERI itself like DUPIC(Direct Use of PWR spent nuclear fuel Into CANDU) and Pyroprocess. This huge data set could backup some of vacancy of test matrix which are very difficult to test with available experimental situation.

KEPCO NF serves design(including dimensions) and manufacturing(including material composition) information of fuel, and KHNP serves operation history(NDR(Nuclear Design Report) for neutronics calculation and operation planning for every period, overhaul, and shutdown. All information has been input into a database which consists of fuel ID, fuel supplier, fuel type(like Westinghouse V5H), fuel cladding, fuel arrangement(like 17x17), nuclear reactor unit, the first loaded date in reactor, initial enrichment, initial uranium weight, the final discharged date from reactor, burnup values after each operation period, the discharged burnup, nuclear reactor spent fuel pool name which is now storing this fuel , cooling time, fuel design blueprint , damaged fuel, possibility of rod pulling out from assembly , cladding inner & outer diameter, guide tube material, guide tube inner & outer diameter, sleeve material, insert tube material, flange material, outer guide post material, inner extension material. The last material information will be used for structural analysis and impact stress analysis to grid, guide tube, and cladding. Perfection on this database is not easy, but every project members has agreed officially to contribute all information for this.

History for abnormal situation like sudden reactor trip because of damaged fuel is very important to evaluate fuel performance and its final material condition. Radioactivity checking record in spent fuel pool is a basic information to follow fuel history. If a fuel which has been reported a 'concerned fuel', the other fuels which has been operated with the concerned fuel could be separately grouped and be eliminated from the representative fuel selection.

Kori Unit 1 is the first NPP in Korea which started its operation 1978 and it is now planned to be decommissioned 2022 after it is shutdowned June 2017. In other hand, Hanbit Unit 1 is supposed to be saturated with its spent fuel pool 2024. Kori site has another possibility to expand NPP area, but Hanbit doesn't. These two boundary conditions compete each other for what fuel type is more urgent in spent fuel data generation.

III.A.3. Characterization of the representative testing SNF rod and assembly part

The results of representative SNF rod selection based on the above grouping work are Westinghouse 14x14 Standard and Westinghouse 17x17 Vantage 5H. The main factors which has influenced the results are low burnup, Zircaloy-4, Reactor type, majority, and national urgent need. Several technical expert meetings from KAERI, KHNP, and KEPCO NF led to these results. Another key factor was whether KAERI hotcell owns these SNF itself. Korea has only one SNF transportation cask(KSC-1) from NPP site to KAERI hotcell. But, this cask has got in a trouble for its every 5 years licensing renewal because its safety analysis results is no more enough to cautious regulation. This situation caused a worry about SNF transportation from NPP site to KAERI. Original planning in project is to carry SNF from NPP, but above situation urge us to prepare a redundant options. KAERI owns hundreds of Westinghouse 14x14 Standard and Westinghouse 17x17 Vantage 5H

SNF rod in KAERI PIEF spent fuel pool. If original plan does not work, KAERI owned SNF rod could be the representative fuel rod.

Westinghouse 14x14 OFA was selected for the representative SNF assembly. A 25 years ago EPRI report has reported that Westinghouse 17x17 Vantage 5H has little bit more conservatism than Westinghouse 14x14, but our own computational analysis work by KEPCO NF showed the reverse result. They analyzed vertical impact and horizontal impact mode. In vertical mode, two fuel competed with very few values difference, but horizontal mode, Westinghouse 14 showed a doubled weakness value. Even though most fuel handling in reactor is fulfilled by vertical mode, the comprehensive conservatism stand point decided Westinghouse 17 fuel as a representative.

Even though the representative SNF rod is not exactly same with the representative SNF assembly, this mismatch could lead to more conservative result because safety analysis methodologies for rod and assembly are independently separated.

III.B. Improvement of SNF degradation evaluation methodologies at static condition

III.B.1. Analysis of the previously known methodologies of SNF degradation

Creep, hydride effect (hydride reorientation and delayed hydride cracking) are famous SNF rod degradation. Though creep seems to be a self-limiting mechanism, it is basic for rod degradation analysis.

III.B.2. Database update for single effect test results from other organizations

Most test data for these mechanism are produced in USA, Germany, and Japan. Korea has to collect them and build our own database structure based on those early available data. A big portion of test data set is for unirradiated cladding material. Therefore our first target of database update is to test unirradiated cladding (fresh and hydride treated) in more narrow test conditions because most test data has sparsely wide range to cover targeting test condition with limited experimental situation.

III.B.3. Development of QA(Quality Assurance) process dedicated for irradiated material test in hotcell

Some very old irradiated material test results are suspicious for QA control. Those are produced in 1970~1980 when QA is not hot issue yet. But, nowadays every business documents ask QA process to ensure the overall quality control. One of biggest problem to irradiated material in the QA point of view, the tested irradiated material specimen is unique one in the world, and so it is impossible to have another exactly same specimen, that is no reproducibility. Second problem is that we never know the specimen's real material condition exactly until we destroy it and perform a optical analysis. The last one is that it is very difficult to handle the test specimen with remote control in hotcell. There are lots of challenges to QA work on irradiated material test. But, we need to keep improving our testing data quality by applying bounding approach in a reasonable range.

III.B.4. Single effect tests in-depth for each SNF rod degradation mechanism (fresh, hydride treated and irradiated material cases)

A same testing matrix will be applied to fresh, hydride treated(circumferential hydride and re-oriented hydride), and irradiated material cases. Temperature range is 200 ~450 Celsius and Hoop stress range on cladding wall is 60~ 120 MPa.

III.B.5. Development of compatible relationship between 3 cases testing results (fresh, hydride treated and irradiated material cases)

Above quadruple approach can show quite obvious differences and trend among the materials simultaneously. It is widely believed that the different material is the different world. But, high difficulty for irradiated material testing causes this kind of relationship analysis. This relationship could help to suggest some sort of guideline before a new testing cases though every factors are not perfectly same.

III.B.6. Analysis of DrySim6 (a small scale dry storage demonstration with 6 SNF rods) test results

The primary target data which we can get from DrySim6 is creep data. About 3 years operation in dry storage condition is very short compared to a real dry storage operation lifetime, but 3 years are the maximum testing range within a given project plan. Temperature will be kept in a constant condition like 400 Celsius because 3 years are very short to mimic the real natural cooling environment and DrySim6 will be located under the water and so it is not easy to simulate the real natural cooling. Instead of it, a constant temperature condition could lead to sort of acceleration by keeping a same hoop stress on the cladding wall. Recent USA research shows that the real temperature inside of canister is pretty lower than the conservative design value. But, DrySim6 with only 6 SNF rods (not assembly !!) needs more powerful heating source inside it to mimic the real dry storage condition.

6 Sister rods which are paired with DrySim6 rods has been done for non-destructive testing and destructive testing for the time=0. And also 6 DrySim6 rods has been done for non-destructive testing. They are ready to be install inside DrySim6. But, it needs to be analyzed for its holding structure safety analysis under the PIEF pool water. After this holding structure safety analysis is done, DrySim6 performance test under water will be performed before November 2016, and its official operation will start early 2017.

After 3 years operation, time=3 years rod testing data will be produced in the next step R&D project (which is targeted for high burnup). For the dry storage licensing, basically single effect test data will be used, and DrySim6 test data will be supplemented while licensing process.

III.B.7. Modification of already known SNF rod degradation model and code by reflecting single effect test results and DrySim6 test results

Every engineering work's final goal is to create a good model and code which are supported by validated and verified(V&V) testing data. Historical legacy of other countries and our own testing data set will be merged, validated, verified, and simulated in models and eventually integrated into a degradation anticipation in-house code.

III.B.8. Anticipation of SNF rod integrity for very long-term storage condition

This degradation anticipation code will be connected with fuel characteristic code (like ORIGEN), fuel performance code in reactor(like FRAPCON) and thermal analysis code (like COBRA-SFS) together. KAERI has already developed the own in-house codes which are very compatible and competitive to these famous codes. Integrated code fleet will help to anticipate SNF integrity after long storage operation.

III.C. Establishment of SNF mechanical integrity evaluation system at dynamic condition

III.C.1. Development of testing methods for fuel assembly parts

KAERI has experience for irradiated fuel assembly parts like spacer grid, guide tube, cell spring, and top & bottom end piece by KEPCO NF project. This experience was focused on a new fuel development purpose, but some testing methods need to be improved for the spent fuel research.

III.C.2. Testing of fuel assembly parts for fresh, hydride treated and irradiated material cases

There is almost no open literature which deals with fuel assembly part testing results. Most concerns on spent fuel have been focused on fuel rod than assembly. With this barren background, we need to produce fresh, hydride treated and irradiated material testing data. Full size assembly is too difficult to handle, and so some small span size & one grid set test will be performed.

III.C.3. Development of SNF assembly degradation evaluation methodologies

Previous section focused on mechanical testing, but material degradation of assembly part(grid, spring, guide tube, and end piece) also have to be concerned. KAERI has also experience of those part material testing. But, those experiences were based on several independent R&D projects, and so it is necessary to collect them, make a combined database, and suggest testing matrix which are vacant on that database.

III.C.4. Manufacturing a 'simulated fresh fuel assembly (SimAssem)'

KEPCO NF will manufacture a simulated fresh fuel assembly (SimAssem) for full size fuel assembly testing because irradiated full size assembly testing is not possible in Korea. SimAssem will help to understand full size assembly handling motion with regarding to spent fuel. KAERI has experience to test full size fuel assembly for thermal hydronic and mechanical purpose.

III.C.5. Development of testing and characterizing techniques for SimAssem

Previous mechanical tests on FAMeCT (Fuel Assembly Mechanical Characterization Tester) have been focused on reactor operation condition like vibration behavior, bending stiffness and impact performance at seismic case. SimAssem will be tested on this FAMeCT bed, but how to develop testing and characterizing techniques for SimAssem still remains challenges.

III.C.6. Analysis of SimAssem integrity at dynamic conditions

Our original plan was to use a shaker table like Sandia Laboratory's experiment with SimAssem. However, there is some argue with shaker testing device newly installation in KAERI because multi-axis motion shaker table is very expensive to only several tests. Outside order to another huge commercial mechanical laboratory could be one of the real solution and this is still remaining a problem to solve soon. Remodeling of FAMeCT could be another solution. Anyway SimAssem analysis at dynamic conditions will be performed with appropriate solution.

III.C.7. Development of SNF assembly integrity evaluation model and code by reflecting irradiated fuel assembly parts test results and SimAssem test results

SimAssem test result contribute the full size motion and irradiated fuel assembly part test results contribute the real material property information together. Integrating these information will be fulfilled in model and code development.

III.C.8. Recommendation for safety guideline on SNF assembly handling and transportation

Most concerns of SNF for transportation are fuel rod configuration and criticality. Fuel assembly parts are very important for fuel rod to keep its original shape at dynamic condition. After very long term dry storage, normal SNF handling from storage/transportation canister to disposal cask could be an hot issue unless disposal regulation accept canister-based disposal. Fuel assembly parts are very important at this time, too. Though information for fuel assembly and its part R&D for SNF are very rare, its importance keep us to develop a safety guideline with above R&D actions.

IV. CONCLUSIONS

Even though there were some testing data on PWR SNF in dry storage condition in other countries, it is very important to produce Korean SNF data because fuel operation history of KHNP is unique itself and the final status of SNF is different with them. R&D work to generate Korean own SNF data is actively undergoing in the two step approach by dividing burnup range as low and high. Current low burnup R&D work could contribute to building up domestic R&D infrastructure including skilled human forces, testing equipment and licensing experience. Based on these asset, Korea could expand its R&D capability up to high burnup SNF area and finally succeed to get trust from the public on the safe high level radioactive waste management.

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