A STUDY TO EVALUATE THE HANDLING INTEGRITY OF SPENT NUCLEAR FUEL FOR DRY STORAGE IN KOREA

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ABSTRACT

In this study, we have developed a strategy to improve the handling integrity of the spent fuels for future transporting to the dry storage. At first, it has been investigated that the status of the spent fuels stored in spent fuel pools such as the type and its number of fuels, burnup, material of components, connecting methods between top nozzle and guide tube, and the handling load transferring mechanisms according to the connecting method. Based on the investigation, a representative spent nuclear fuel type was selected, which seemed to be critical in handling integrity point of view among the spent nuclear fuels, and the 3-dimensional finite element analysis model was developed using ABAQUS software for the representative fuel assembly. For the verification of the developed analysis model, a series of strength tests were performed with simulated specimens considering hydrogen embrittlement.

1. Introduction

In Korea, since the commencement of commercial operation of nuclear power plants in 1978, 25 nuclear power plants have been constructed and operated. They are 14x14, 16x16 and 17x17 Westinghouse type power plants, OPR1000 which is 16x16 Combustion Engineering Type and APR1400 power plants. Along with the long history of nuclear power generation, various types of spent nuclear fuel are stored in spent fuel pool of each power plant, and the storage pools are expected to be saturated in the near future. Therefore, various social discussions and researches are under way to construct a dry storage facility. In order to move and store those spent fuels to interim storage, the handling integrity of the fuels must be guaranteed. As reported at Nuclear Regulatory Commission (NRC) Information Notice 2002-09, however, the North Anna power plant and some power plants including a Korean plant experienced top nozzle separation of a certain type of Westinghouse type fuel [1]. The top nozzle separation had occurred at the bulge joints connecting the stainless steel grid sleeves to the Zircaloy-4 guide tubes. The root cause was known as IGSCC (Intergranular stress-corrosion cracking) accelerated by the presence of chlorides, fluorides, and sulfates [1]. Therefore, it is crucial to evaluate the handling integrity of the spent fuels prior to the transportation and storage. In previous study, it had been investigated that the status of the spent fuels stored in spent fuel pools such as the type and population of fuels, burnup, material of components, connecting methods between top nozzle and guide tube, and the handling load transferring mechanisms according to the connecting method [2]. Based on the investigation, a representative nuclear fuel type was selected, which seemed to be critical in handling integrity point of view among the spent fuels, and the 3-dimensional finite element analysis model for single bulge joint between guide tube and sleeve was developed using ABAQUS software for the representative fuel assembly. For the verification of the developed analysis model, a series of strength tests were performed using fresh materials with hydrogen embrittlement treatment and without. The analysis results were in quite good agreement with strength test results [3].

In this study, we extended the previous single guide tube model to full size top nozzle-to-guide tube connection model that simulates the spent nuclear fuel conditions in order to identify the bearing load distribution of each guide tube and improve the handling integrity of the spent nuclear fuels. And full size strength tests corresponding the analysis model are planned to verify the analysis model and the results. In addition, we have developed reinforcement devices to improve the handling integrity of the spent nuclear fuels classified as potentially damaging when transporting spent nuclear fuels to the dry storage. With aid of the analysis results, the optimal position of the reinforcing device for the SNF with separation concerns and the number of necessary reinforcing devices are determined, which improve the handling integrity of the separation susceptible spent nuclear fuel (SNF).

Therefore, it is expected that the safe handling of spent nuclear fuels will be ensured with aid of this research when the spent nuclear fuel stored in spent fuel pools in Korea are transported and stored in the dry storage. As a further study, we are going to enhance this model to simulate the IGSCC mechanism based on the results of the hot cell test for a spent fuel assembly with IGSCC concern.

2. Classification of Spent Fuels

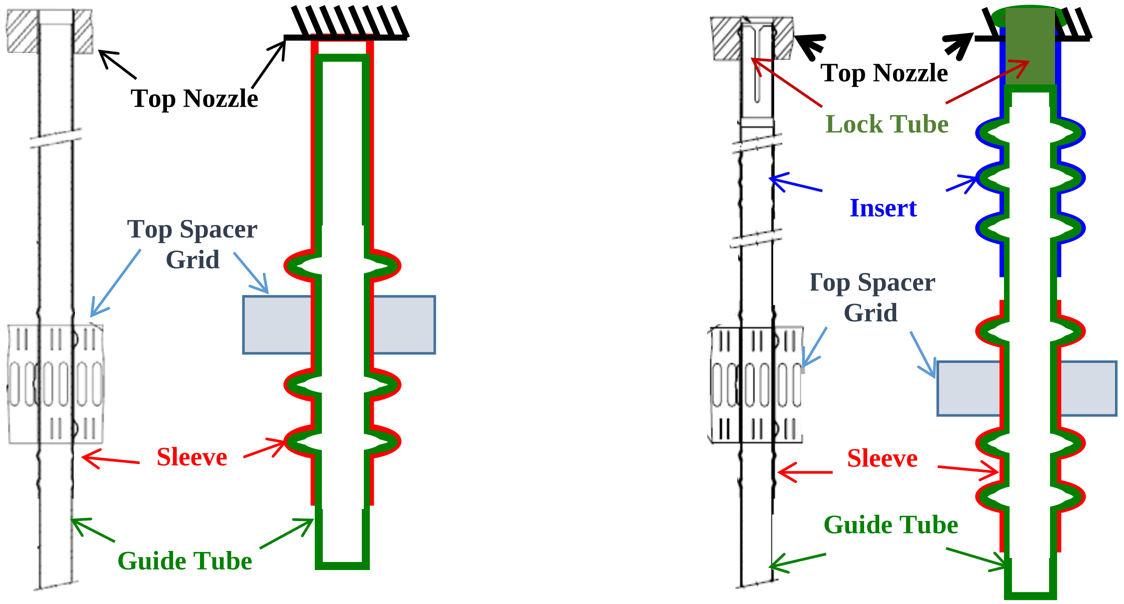
There are round 13,000 tons of spent fuel in the spent fuel pools of 25 nuclear power plants in Korea [2]. They can be classified as the Westinghouse 14x14, 16x16, 17x17 nuclear fuels and Korean standard nuclear fuels. The fuels with various design characteristics such as STD, OFA^{TM}, KSFA^{TM}, V5H^{TM}, RFA^{TM}, Guardian^{TM} and PLUS7^{TM} are stored in those nuclear power plants. Depending on the history of the nuclear power plant operation, cooling period of the some spent fuels are longer than 35 years in the spent fuel storage tank. The materials used for the fuel also are very diverse such as Zircaloy-4, Improved Zircaloy-4, OPTIN^{TM}, ZIRLO^{TM} and M5^{TM} for the fuel cladding and SS304, SS304L, SS321 for the guide tubes. In addition, the burnup range of the spent fuels varies from less than 20 GWD / MTU to more than 50 GWD / MTU. In this situation, since it is almost impossible to evaluate the handling integrity of all of the spent nuclear fuels for dry storage, therefore, we tried to select the high priority fuels to be evaluated first among the representative candidate spent nuclear fuels classified by the national spent nuclear fuel roadmap plan, as shown in Table 1 [4].

Table 1. Classification of the spent nuclear fuels classified by the national SNF roadmap plan

Items	Condition
Initial UO_2 Enrichment	Lower than 4.5 wt%
Burnup	Lower than 45,000 MWD/MTU
Cooling Period	Longer than 10 Year
Cladding Material	Zircaloy-4

3. Selection of Representative Spent Fuels

Even if the nuclear fuel to be evaluated is limited according to the classification conditions described above, there are still more than 10 different kinds of nuclear fuel corresponding to these conditions. Therefore, it would be effective to select representative spent fuel to cover the candidate fuels and/or most conservative one in terms of fuel handling integrity for dry storage. First, we investigated and classified all of the spent fuels stored in spent fuel pools and most of the nuclear fuel corresponding to the above classification criteria were found to be Westinghouse type fuel. And then the design characteristics of the top nozzle connection structure of the Westinghouse type fuels has been investigated, since the top nozzle connection feature is critical in terms of the fuel handling integrity. The Westinghouse type nuclear fuels are subdivided by 14x14, 16x16 and 17x17 type fuels, but their top nozzle to guide tube connection design is either the standard method or Reconstitutable Top Nozzle (RTN) method regardless of the 14x14, 16x16 or 17x17 types. As shown in Figure 1, the standard method is a method in which the sleeve is welded to the top nozzle and the fixed sleeve and guide tube are jointed with 3 bulges; one is above top spacer grid, two are below. In the RTN method, the guide tube and the top nozzle insert are jointed using 3 bulges, and the lock tube is inserted inside the insert to fasten the top nozzle and the guide tube.



[Standard Type] **[RTN Type]**

Figure 1. Configurations of top nozzle to guide tube joint of Westinghouse type fuels

The materials used for the Westinghouse type nuclear fuels are mostly SS304 or SS304L for the sleeve and RTN insert, and Zircaloy-4, Improved Zircaloy-4 or ZIRLO^{TM} for the guide tube, respectively. And in addition, plant lifetime, number of fuel assembly according to the fuel type, and even manufacturability of the test assembly for verification tests were considered to select representative spent fuel to be evaluated. As a result, the Westinghouse 17X17 type fuel with RTN connection method was selected as the representative fuel for the handling integrity evaluation.

4. Finite Element Modeling

In previous study, a finite element model was developed considering the connection part of the representative fuel using the ABAQUS which is the multi-purpose commercial finite element analysis software [5]. Figure 2 shows a representative finite element (FE) analysis model of the bulge connection. The model consists of small section of the top nozzle plate, insert, guide tube and lock tube, as shown in Fig.2 [3].

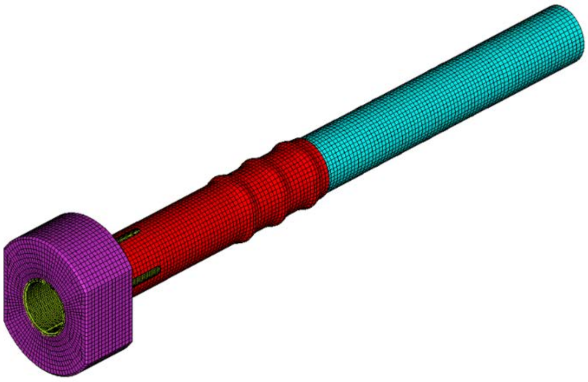
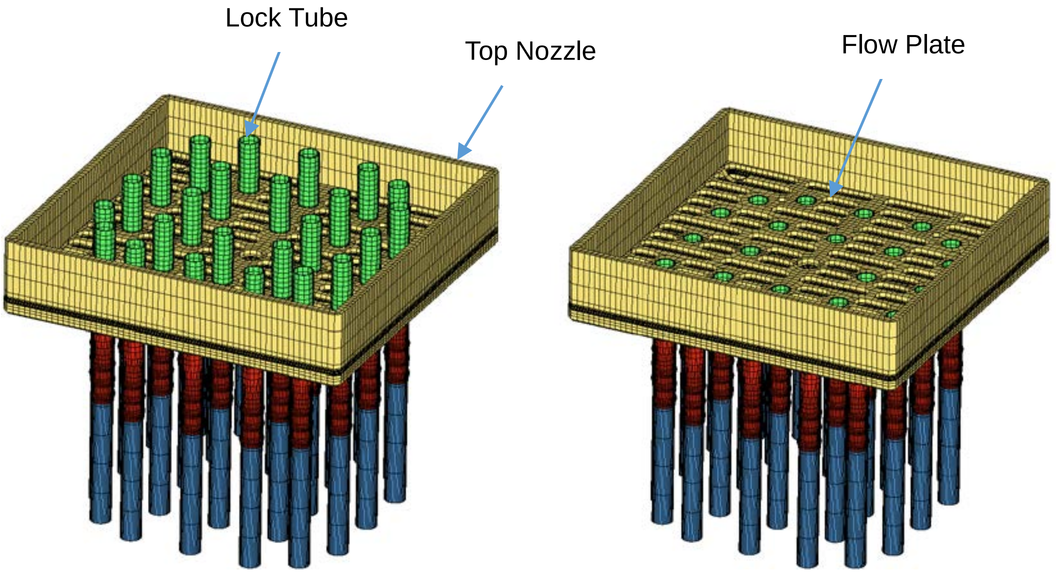


Figure 2. FE model of top nozzle to guide tube joint

In this study, however, we extended the previous single guide tube model to full size top nozzle-to-guide tube connection model that simulates the SNF conditions in order to identify the bearing load distribution of each guide tube and improve the handling integrity of the spent nuclear fuels as shown in Fig.3. In this model, since the top nozzle components except flow plate do not affect the analysis, so it is modeled as a simple shape for convenience.



(a) Lock tube insertion model (b) Full size SNF top nozzle joint model

Figure 3. Full Size FE model of top nozzle to guide tube joint

The full size model was developed in two steps to simulate SNF conditions. In the first step, an analysis was performed to assemble the top nozzle and the lock tube (Fig.3a). The deformations that occur during assembling process were obtained with the analysis. And then, the SNF analysis model with deformed geometry obtained from the results of the analysis as the initial conditions of the SNF was generated (Fig.3-b).

5. Reinforcement Device

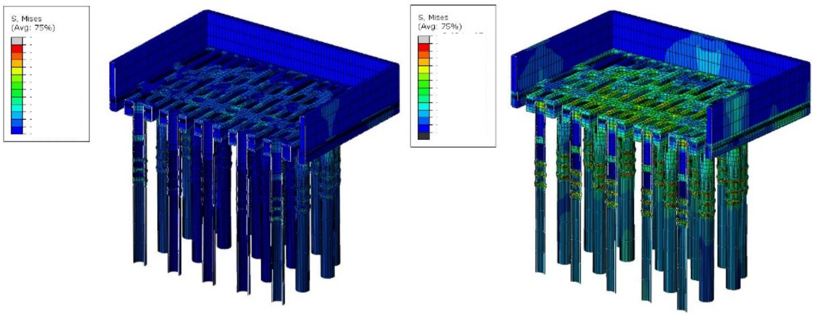
An anchor type reinforcement device as shown in Fig.4 has been developed, in order to improve the handling integrity of the SNF with top nozzle separation concerns. The fastening mechanism of the device uses a friction force between the guide tube and the anchor pin of the device. To evaluate the fastening force of the device, fastening strength test has been performed as shown in Fig.5.

Fig.4 Schematic configuration of reinforcement device

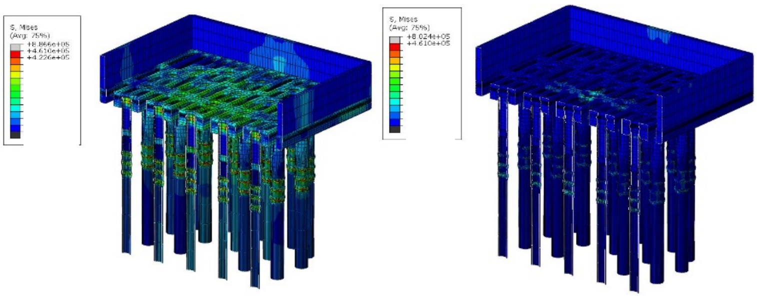
Fig. 5. Set up of the strength test of the reinforcement device

6. Results and Discussion

Using the FE analysis model developed in this study, the analysis has been performed by increasing the displacement until the top nozzle and guide tube bulge joints are separated. In this analysis, the bottom of guide tubes was constrained for 6 degree of freedom. As the first step of study, the analysis has been performed using unirradiated material properties specified in material specification of test specimens. Fig.6 shows the changes of stress distribution of the connection area while the top nozzle is disengaged from the beginning of displacement.



(a) Initial Displacement (b) Before Peak Loading



(c) Peak Loading (d) Top Nozzle Disengaging

Fig. 6. Stress distributions of the top nozzle to guide tube connection area

As shown in Fig.6, the stress distribution gradually increases with increase of displacement, and the stress rapidly extinguished as the top nozzle is separated. It is shown that when a large load of a certain size is applied, the groove part of the insert first undergoes plastic deformation and finally is separated from the top nozzle. Fig. 7 shows the result of analysis of the load versus deflection behavior of each guide tube according to the position of guide tube when the top nozzle is subjected to a load which causes top nozzle separation during fuel handling. As shown in this figure, the peak load acting on the guide tubes appears from the guide tubes located at the outer corner to guide tubes located at the center. Even though the peak load and its locations are not symmetrical because the top nozzle is not exactly symmetrical due to the positions of the guide pins and flow holes of the flow plate of the top nozzle, the asymmetry is insignificant. Therefore, it is considered that it is advantageous to position the reinforcement devices used to prevent the top nozzle separation accident at the corner locations symmetrically.

In addition, IGSCC accelerated by the presence of chlorides, fluorides, and sulfates, which are known to cause top nozzle separation accidents during handling of spent nuclear fuel, is known to significantly reduce the strength of joints [6]. Therefore, at this stage, the number of the reinforcement devices required to prevent the top nozzle separation accident will be conservatively determined by evaluating the fastening force of the reinforcement device by testing and analytical methods based on the assumption of that all the bulge joints connecting the top nozzle and the guide tube were already separated due to IGSCC. And the factors such as corrosion and oxidation are also expected to have an influence on the strength of the joint. Therefore, as the next step of this study, a hot cell test using the spent fuel is planned to investigate the material properties of the irradiated joint part. And finally, the results obtained from hot cell test will be applied to this study.

Fig. 7. Non-dimensional load-displacement curves by position of guide tube

7. Conclusion

In this study, we extended the previous single guide tube model to full size top nozzle-to-guide tube connection model that simulates the SNF conditions in order to identify the bearing load distribution of each guide tube and improve the handling integrity of the spent nuclear fuels.

In the analysis using the full size FE model, the peak load acting on the guide tubes appears from the guide tubes located at the outer corner to guide tubes located at the center. Therefore, it is considered that it is advantageous to position the reinforcement devices used to prevent the top nozzle separation accident at the outer corner locations symmetrically.

In order to accurately evaluate the handling integrity of the spent nuclear fuel, it is necessary to evaluate changed characteristics due to irradiation such as IGSCC which is serious phenomenon that damages the handling integrity, oxidation, corrosion and hydrogen embrittlement. Therefore, the number of the reinforcement devices required to prevent the top nozzle separation accident will be conservatively determined by evaluating the fastening force of the reinforcement device by testing and analytical methods based on the assumption of that all the bulge joints connecting the top nozzle and the guide tube were already separated due to IGSCC.

Finally, as the next step of this study, a hot cell test using the spent fuel is planned to investigate the material properties of the irradiated joint part. And finally, the results obtained from hot cell test will be applied to verify the representative spent fuel model, and the model is to be applied to the handling integrity analysis of the other spent fuel types.

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ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 2014171020166C)