Fatigue Evaluation of the Mid Grid with ATF Cladding Tube

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1. Introduction

The necessity for Accident Tolerant Fuel (ATF) arose following the 2011 Fukushima Daiichi nuclear power plant accident in Japan. KEPCO Nuclear Fuel (KNF) is currently developing technologies for short-term challenges in ATF. Among these, KNF is focusing on the application of chromium-coated zirconium cladding tube and (La)-Al-Si-doped (LAS) UO_2 pellets [1]. Especially, the chromium-coated cladding tube aims to delay oxidation and nuclear fuel melting caused by high-temperature steam. Currently, comprehensive evaluations are being conducted to verify the performance of the chromium-coated cladding tube (or ATF cladding tube) for nuclear fuel application. This study specifically focuses on the design evaluation regarding fatigue effects when ATF cladding tube is inserted into the mid grid (MG) of a fuel assembly as shown in Fig. 1.

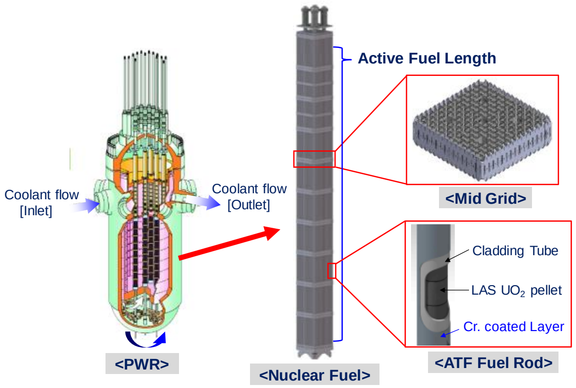

Fig. 1. Nuclear fuel with mid grid and ATF fuel rod

As burn-up of the fuel increases in-core operation, the spring/dimple's initial force of the mid grid can be reduced due to the neutron irradiation and thermal relaxation even worse in case of zirconium material. This degradation makes the results that the supporting force of the spring/dimple to the fuel rod becomes weak, and a gap may occur between the fuel rod and spring/dimple. After all, fuel rod vibration caused by high-speed flow with above degradation effect in a reactor may cause a failure of the fuel integrity.

When ATF is applied, the fuel rod diameter increases slightly and the some of the material properties are changed, so an evaluation of the fatigue effect on the mid grid must be carried out. Lastly, in this study, two cases of evaluations that are conventional and ATF cladding tube applied to the mid grid were compared and discussed.

2. Fatigue Evaluation

2.1 Methodology

For the fatigue evaluation of the mid grid, a model is created to be similar to the actual operating condition. After that, the stress formed in the mid grid by the fuel rod loading is produced using finite element analysis (FEA). The acquired stress is made into alternating stress (or stress range) by adjusting level of the stress through comparation with one-cell unit fatigue test [2] and previous fuel assembly test data. Finally, this stress is used in-core operating cycle to be utilized as a fatigue stress, and the fatigue life is calculated for determining fatigue failure risk.

The overall flow of fatigue evaluation of the mid grid is summarized as follows.

- Creation of the MG model → Stress analysis → Alternating stress($\Delta\sigma$) → S-N fatigue model → Evaluation for whole operation → Cumulative usage factor

2.2 S-N Curves of HANA-6 Alloy

KNF has achieved obtaining the fatigue S-N curves through its own test for the indigenous material of HANA-6 which is a zirconium alloy. The fatigue test specimens were in the form of plate-shaped dog bone and hydrogen was contained to simulate embrittlement for in-core property condition. The test conditions were conducted at high temperature of 650 °F, in ambient air. Fig. 2 shows the S-N curves for hydrided and non-hydrided HANA-6 models, respectively.

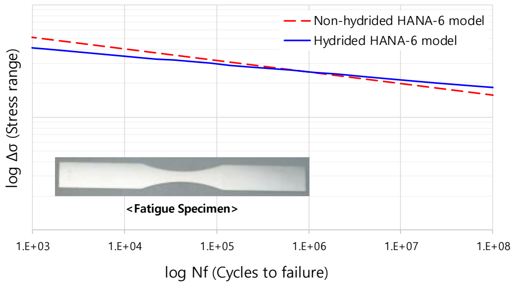

Fig. 2. S-N curves of HANA-6 (value removed)

2.3 Parameters and Stress Analysis

The purpose of the analysis is to obtain the stress intensity on the spring and dimples using FEA. Analysis was considered for typical one cell, and material properties and parameters were applied to the models. Table I shows the major parameters, and Fig. 2. explains boundary conditions for the model and shows where the maximum stress is concentrated. Basically, it was assumed that the other conditions except shown in Table I were the same. Table II shows a comparison of the stress intensities for two cases that are the conventional and ATF cladding tube, respectively. The values were normalized.

Table I: Comparison of the major parameters

Items		Conventional Cladding Tube	ATF Cladding Tube
Outer Diameter [mm]		9.50	9.53
Rod Vibration Freq. [Hz]		80	80
Mechanical Properties at 70°F (normalized)	E	1.0	0.92
	YS	1.0	0.86
	UTS	1.0	0.86
Coefficient of tube/MG		0.5	0.2

E: young's modulus, YT: yield strength, UT: Ultimate Tensile Strength

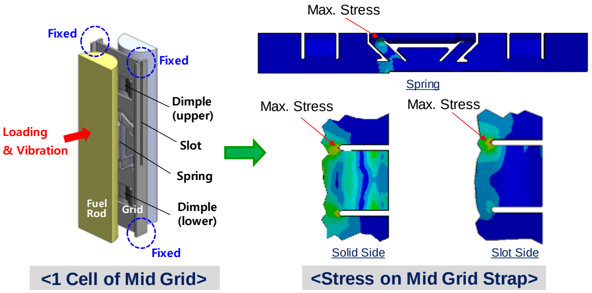

Fig. 3. Nuclear fuel with mid grid and ATF fuel tube

Table II: Comparison of the stress intensities (normalized)

Region on Mid Grid	Conventional Cladding Tube	ATF Cladding Tube
Spring	1.000	0.998
Dimple on Solid Side	0.070	0.053
Dimple on Slot Side	0.139	0.112

2.4 Evaluation

In order to conservative evaluate, the fatigue life is calculated according to the Palmgren-Miner law [3] by multiplying the stress term by 2 or the fatigue life by 20. The fuel rod vibration load is assumed to be normal distribution and operating cycles are reflected longer than actual period. The ratio of the calculated fatigue cycles and operating cycles that is cumulative fatigue usage factor is considered as the fatigue damage during the entire operation. The value is evaluated whether the sum dose not exceed 1.0. If the value is less than 1.0, the fuel integrity can be considered to be stable from fatigue failure. The basic form of calculating usage factor is shown in equation (1).

$$\sum_{i}^{n} \frac{N_c}{N_f} < 1.0 \qquad (1)$$

where, $i=1$: first month of the operation cycle
$n=72$: end month of the operation cycle
N_c : number of cycles at a stress level
N_f : number of cycles to failure

Table III shows cumulative fatigue usage factors. And the worse result is selected for evaluation. The results indicate that the mid grid with ATF cladding tube is better performance in terms of fatigue life than that of conventional.

Table III: Cumulative fatigue usage factor

Results	MG with Conv. Cladding Tube	MG with ATF Cladding Tube
2 x Stresses	0.0364	0.0050
20 x Cycles	0.0012	0.0002

3. Conclusions

The spring and dimples of the mid grid must not be failed by fatigue caused by the fuel rod vibration during in-core operation. KNF conducted fatigue evaluations because of changes in a diameter and mechanical properties of the cladding tube for the purpose of the ATF application to the fuel. Thus, it can affect stress distributions at the end of the spring and dimple slots of the mid grid.

From the evaluations, the fatigue life of the ATF cladding tube shows better performance than that of conventional cladding tube. The main reason is that increase of the cladding tube diameter by chromium coating, the mid grid cells provide more robust support to the fuel rods. Additionally, changes in the friction coefficient and other parameters may have an impact on reduced stresses on the mid grid. Therefore, it has brought a more mitigating effect from the fatigue failure risk.

ACKNOWLEDGEMENTS

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