Mechanical Design Evaluation of Fuel Assembly for PGSFR

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Abstract. The PGSFR (Prototype GEN-IV Sodium-cooled Fast Reactor) core is composed of uranium-10% zirconium (U-10Zr) metal alloy fuel with 112 assemblies: 52 inner core fuel assemblies, 60 outer core fuel assemblies, 6 primary control assemblies, 3 secondary control assemblies, 90 reflector assemblies, and 174 B_4C shield assemblies. The core was designed to produce 150 MWe with an average temperature rise of 155 ℃, which means that the inlet temperature is 390 ℃ and the bulk outlet temperature is 545 ℃. The core height is 900 mm and the gas plenum length is 1,250 mm. The fuel assembly is composed of several structural parts, which are a handling socket, upper/lower reflector, nose piece, hexagonal duct, and fuel rods. The face-to-face dimensions and length are 132.36 mm and 4,550 mm, respectively.

In this paper, there are two kinds of analyses for the mechanical design and evaluation of the PGSFR fuel assembly (FA). One is a dynamic behavior analysis of FA itself, and the other is a structural analysis of the FA components at the design level. All of these analysis results will be verified through an out-pile test of an actual sized test FA.

Key Words: Mechanical design, Fuel assembly, Integrity, Dynamic behavior.

1. Introduction

The PGSFR is under developing in combination with the pyro-electrochemical processing of spent PWR fuel [1]. U-Zr fuel is a driver for the initial core of the PGSFR, and U-TRU-Zr fuel will gradually replace U-Zr fuel through its qualification in the PGSFR. Based on the radiation shielding analysis to protect both lower and upper support structures in the core from radiation damage, the lengths of the upper and lower reflectors are 500 mm and 900 mm, respectively. Fuel assemblies adopt the hydraulic hold-down concept rather than a mechanical hold-down device.

The FA design work includes the core physics, thermal-hydraulics, and mechanical designs. The mechanical design and evaluation of the PGSFR FA is presented in this paper. The design verification is established through a structural analysis and assembly-wise out-pile test using an actual sized test FA.

2. Mechanical Design of Fuel Assembly

The fuel assembly for PGSFR is depicted in Fig. 1. It is composed of a handling socket, a nose piece, top/bottom reflectors, and a hexagonal duct, which contains the fuel rods [2]. The PGSFR core consists of uranium-10% zirconium (U-10Zr) metal alloy fuel with 112 assemblies: 52 inner core fuel assemblies, 60 outer core fuel assemblies, 6 primary control assemblies, 3 secondary control assemblies, 90 reflector assemblies, and 174 B_4C shield assemblies. This configuration is shown in Fig. 1. The core was designed to produce 150 MWe with an average temperature rise of 155 ℃, which means that the inlet temperature is 390 ℃ and the bulk outlet temperature is 545 ℃. The core height is 900 mm and the gas plenum length is 1,250 mm. The fuel gap between the fuel slug and cladding is filled with liquid sodium to enhance heat transfer.

2.1. Overall Fuel Assembly

Upper and lower reflectors are used for neutron shielding. The fuel alloy is U-10%Zr. All of these structural parts are made of HT9. This ferritic-martensitic steel was chosen for its low irradiation swelling characteristics. A schematic drawing of the FA is shown in Fig. 2.

2.2. Stress Limits for Fuel Assembly Component Design

Because the general design codes available for a high temperature reactor components [3,4] do not include the material of HT9, it is necessary to determine the stress limits particularly for the present work. Thus we investigated other references [5] and finally set up the limits at each service level of the PGSFR. This is summarized in Table 1. The primary membrane, bending and the secondary stresses (P_m, P_b and Q in order) are classified for the stresses to be evaluated. It is noted that the limit of Level D is set as 0.9 σ_u regardless of P_m, (P_m+P_b) and (P_m+P_b+Q). It was determined arbitrarily because they were not defined in the references [5]. Because the material cannot withstand the ultimate strength in any case, it was determined so with accommodating some allowance (i.e., 10%). For normal operation condition, the stress limits are 0.55 σ_u for P_m and (P_m+P_b); 0.6 σ_u for (P_m+P_b+Q) (shaded rows of Table 1) where σ_u is the ultimate strength at the temperature of a component.

TABLE 1: STRESS LIMITS OF EACH SERVICE LEVEL FOR PGSFR FA MECHANICAL DESIGN.

Stress	Service Level	Suggested for PGSFR Fuel Assembly
P_m, P_m+P_b	A	0.55 σ_u
	B	0.6 σ_u
	C	0.75 σ_u
	D	0.9 σ_u
P_m+P_b+Q	A	0.6 σ_u
	B	0.6 σ_u
	C	0.8 σ_u
	D	0.9 σ_u

2.3. Basic Geometrical Data of Fuel Assembly

In table 2, the geometrical dimensions of the FA are summarized. The total mass of a fuel rod and FA are about 563 g and 296 kg, respectively.

TABLE 2: GEOMETRICAL DIMENSION DATA [6] FOR PGSFR.

Item	Value(mm)	Material	Item	Value(mm)	Material
fuel rod length	2,240	HT9/FC92	clad thickness	0.5	
fuel rod pitch	8.436		plenum length	1,250	
fuel slug length	900	U-10Zr	FA length	4,550	HT9
slug diameter	5.54		FA pitch	136.36	
clad diameter	7.4	FC92	duct inside distance	126.36	HT9

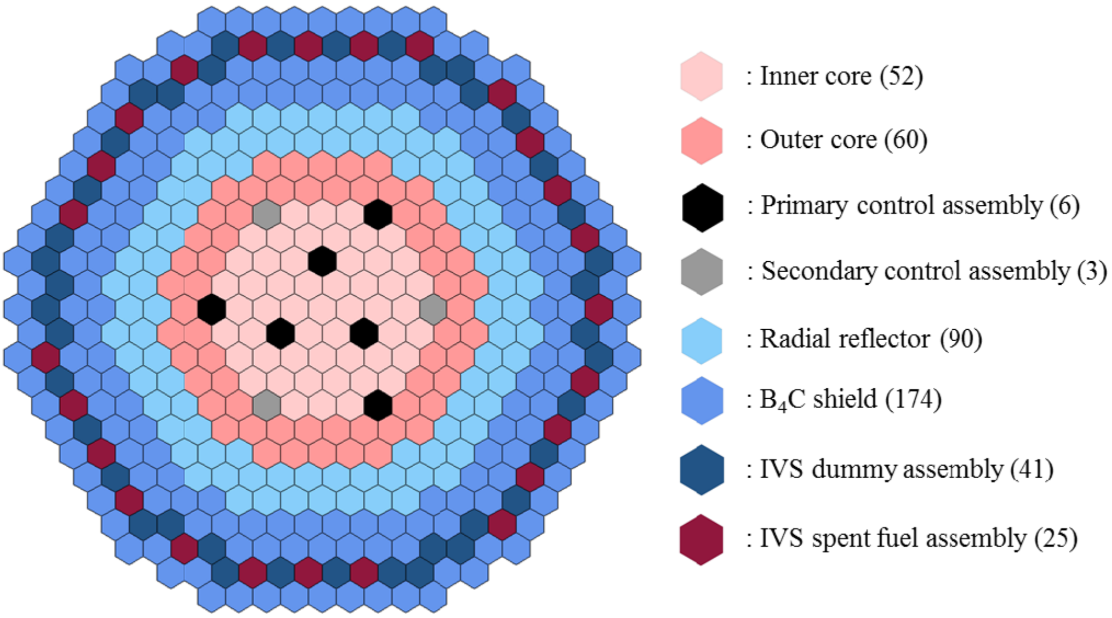


FIG.1. CORE RADIAL CONFIGURATION OF 150 MWE FOR PGSFR.

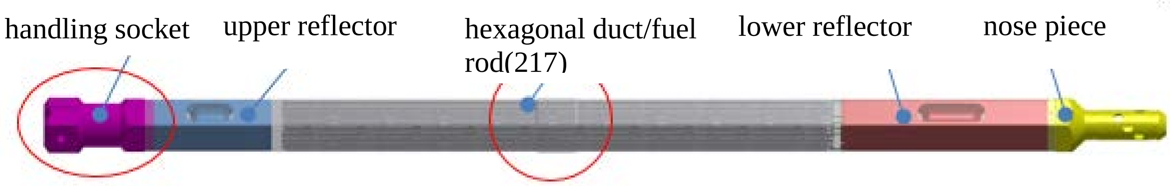


FIG. 2. SCHEMATIC DRAWING OF A FUEL ASSEMBLY FOR PGSFR.

2.4. Actual Boundary Conditions of the FA at the Core

The nose piece of the FA is inserted into the receptacle by four rings. The other end of the FA has a free-end condition. Therefore, it is a cantilever structure. There are two contact parts between the adjacent FAs. One is the above core load pad (ACLP), and the other is top load pad (TLP). These two contact parts constrain the lateral deflection of the FA during the fuel cycle life. The receptacles for the subassemblies are inserted between the upper and lower grid plates. The boundary conditions of the FA are depicted in Fig. 3.

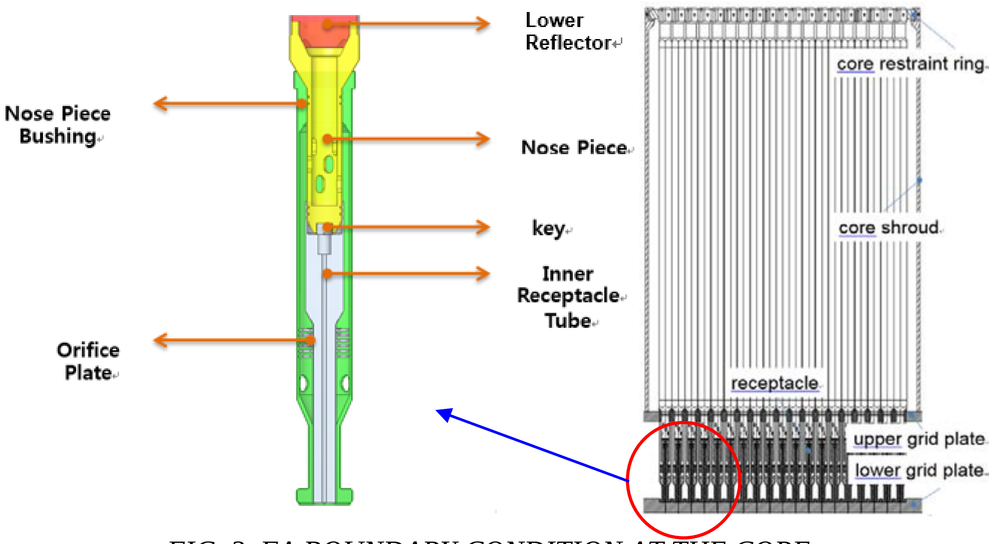


FIG. 3. FA BOUNDARY CONDITION AT THE CORE.

3. Design Evaluation of Fuel Assembly

3.1. Structural Analysis during Normal Operating Condition

○ Structural analysis

To evaluate the FA bowing under the operating conditions, its tilt stiffness need to be obtained. The external load applied was 445 N on the TLP under the FA seated conditions. The tilt stiffness analysis results are summarized in Table 3, and the comparison results between the analysis and test are shown in Fig. 4. The tilt stiffness values of the test were linearly fitted from the lateral bending test data that was conducted with using 5 mm increments.

TABLE 3: FA TILT STIFFNESS BY FE AND TEST METHOD.

	FE method	tilt stiffness test
maximum displacement	26.1 mm	23.5 & 23.7 mm
tilt stiffness	17.1 N/mm	18.8 & 18.9 N/mm

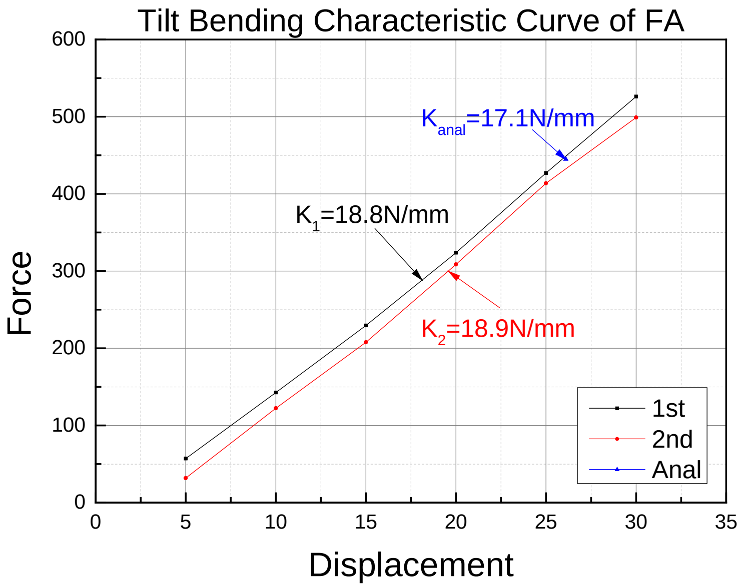


FIG. 4. COMPARISON RESULT OF TILT STIFFNESS BY FE AND TEST METHOD.

○ Modal analysis

To evaluate the modal characteristics of the FA, a finite element (FE) model was created using ANSYS ver. 14.5. In this FE model, SOLID186 and BEAM189 element types were used. The contact and target elements (CONTA174 and TARGE170 element types) were used for the contact surfaces of the nose piece/hexagonal duct and hexagonal duct/fuel rods. The numbers of nodes and elements in the FE model are summarized in Table 4. The FE model is shown in Fig. 5.

TABLE 4: FE MODEL DATA FOR MODAL ANALYSIS.

Element Type	Number of Node	Number of Element
SOLID186	838,788	259,529
BEAM189	124,045	62,017
CONTA173	2,523	2,005
TARGE170	4,641	2,223
subtotal	960,742	325,905

The analysis results are only for the extracted beam mode only. The fundamental frequency was 3.95 Hz and five modes are summarized in Fig. 6.

3.2. Structural Analysis during Accident Condition

○ Lift-off analysis of FA under SSE event

To evaluate the lift-off behavior of the FA owing to a safety shutdown earthquake (SSE), a dynamic analysis was executed using the DYNA-3D explicit code. The SSE conditions were considered such as the maximum vertical accelerations of 0.3g and 1.0g. Of these values, 0.3g was for the peak ground acceleration, and 1.0g was for an actual earthquake accident, which are shown in Fig. 7.

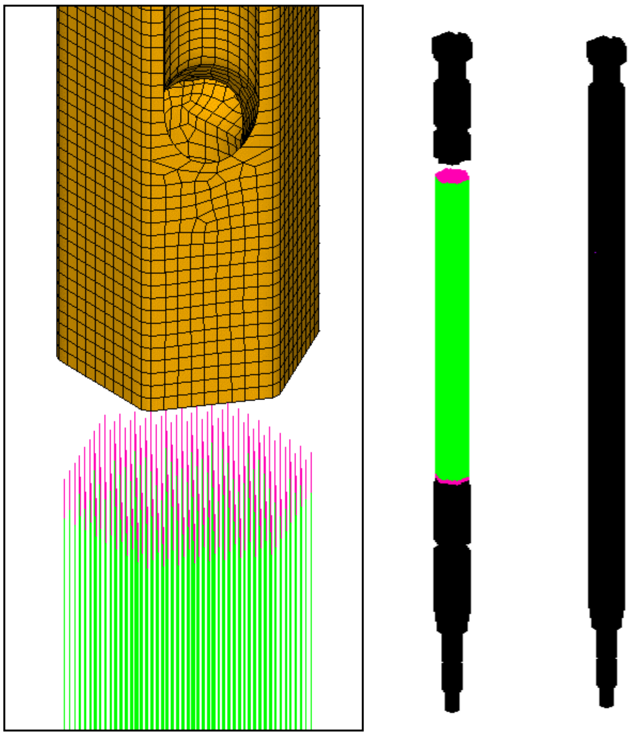
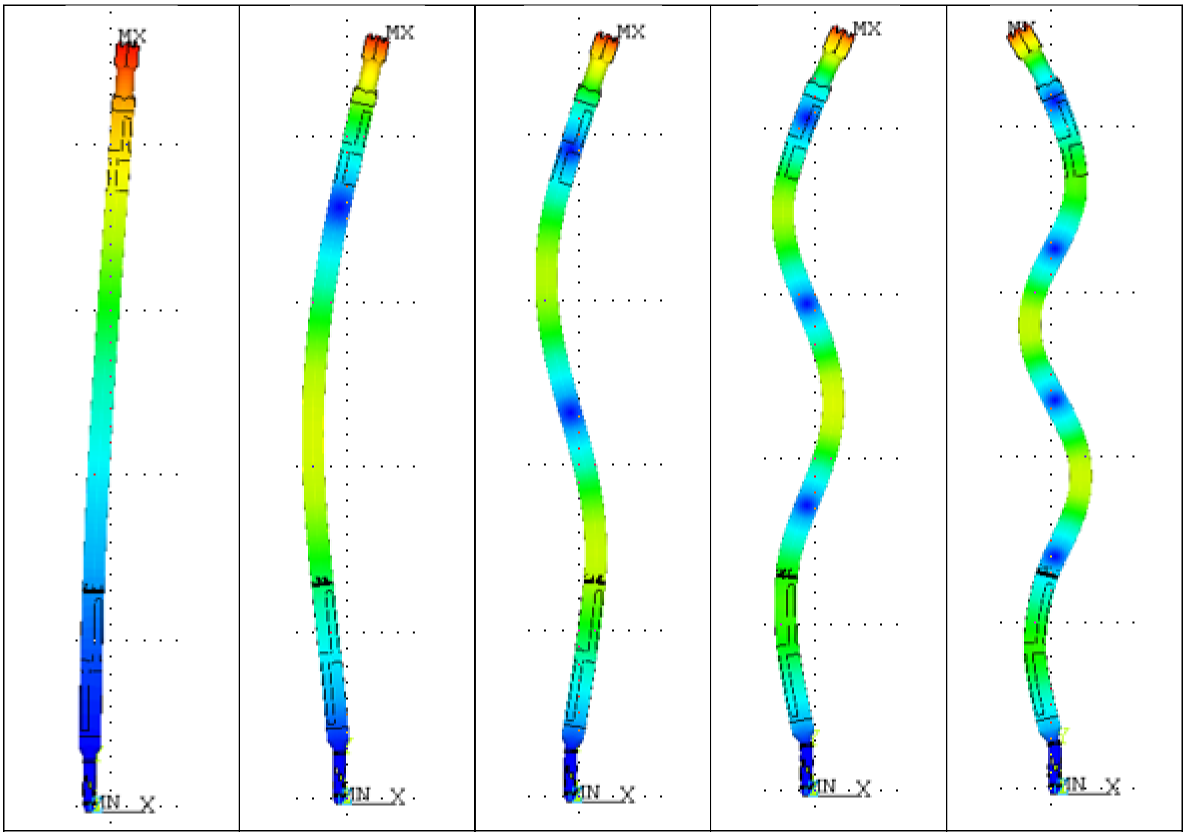


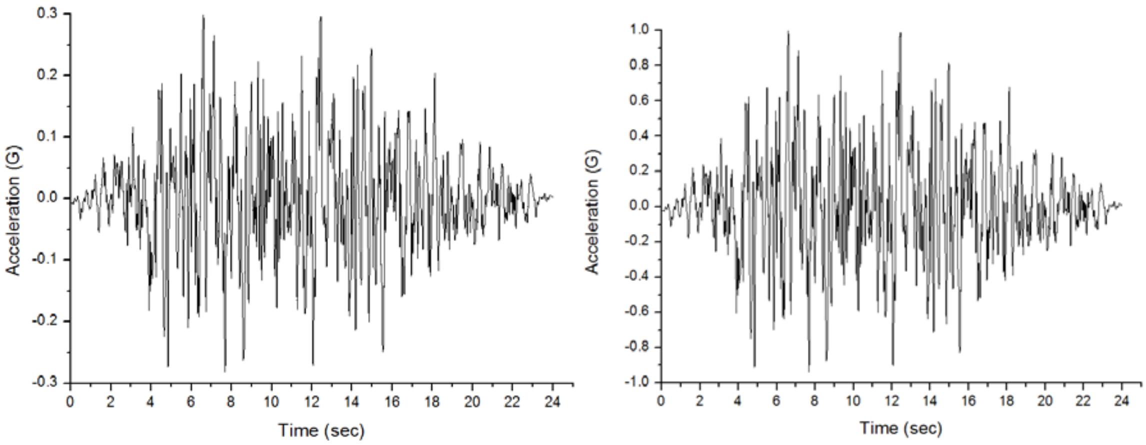
FIG. 5. FE MODEL OF FUEL ASSEMBLY FOR MODAL ANALYSIS.



3.95 Hz	20.40 Hz	57.07 Hz	119.19 Hz	201.82 Hz

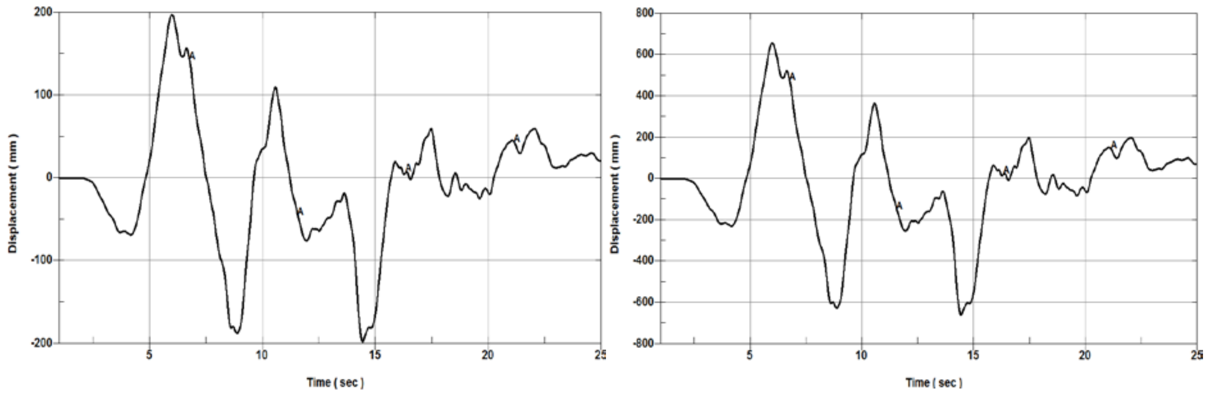
FIG. 6. FREQUENCIES AND MODE SHAPE FROM MODAL ANALYSIS.

Considering the symmetry, a quarter model was created in the FE analysis. The displacement time history was applied in the lift-off analysis as shown in Fig. 8. These displacement curve data are applied to the "Receptacle" using the boundary prescribed motion option. In addition, gravitational acceleration was applied to the nose piece.



(a) 0.3g (b) 1.0g

FIG. 7. VERTICAL ACCELERATION TIME HISTORY CURVE.



(a) 0.3g (b) 1.0g

FIG. 8. VERTICAL DISPLACEMENT TIME HISTORY CURVE.

- Result of 0.3g acceleration case result

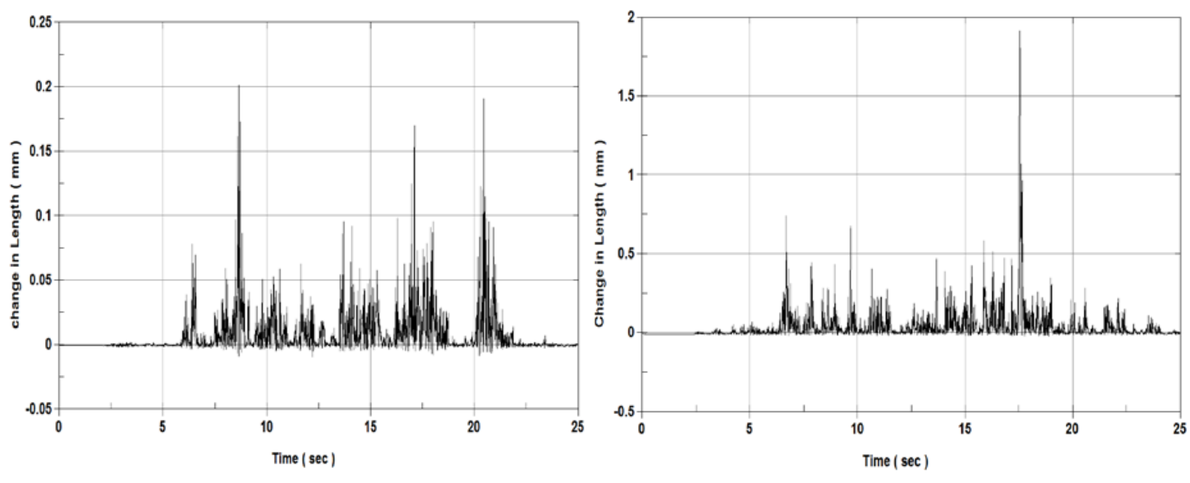
A node at the contact position between the bottom node of the nose piece and the top node of the key is shown in Fig. 9(a). The maximum vertical displacement is about 0.2 mm at 8.5 seconds. Therefore, there was no severe impact owing to the 0.3g acceleration event case.

- Result of 1.0g acceleration case result

For the same node as the 0.3g acceleration case, the maximum vertical displacement was about 1.9 mm at 17.5 seconds as shown in Fig. 9(b). Although this maximum displacement was much larger than the 0.3g case, it also showed no significant impact in terms of the integrity of the fuel assembly.

4. Conclusion

A fuel assembly was developed for the PGSFR. For the developed FA, analyses and tests were executed to evaluate the structural integrity. Lateral bending, lift-off and the SSE were considered here, and the structural integrity was found to be maintained. Of course, those are part of the mechanical design works of the PGSFR fuel assembly. The remaining design evaluation and experimental tests will be carried out.



(a) 0.3g case (b) 1.0g case

FIG. 9. MAXIMUM VERTICAL DISPLACEMENT AT 0.3G ACCELERATION.

References

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