STRUCTURAL SEISMIC CHARACTERISTICS ASSESSMENT OF LMFR FUEL ASSEMBLY HEXAGONAL WRAPPER OVER OPERATIONAL TEMPERATURE RANGE

by

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In this study, the structural integrity of liquid metal fast reactor fuel assembly has been established for different parameters considering the optimum fuel design. Analytical calculation of added mass effect due to lead bismuth eutectic and verification through previously presented theories, has been established. The integrity of the hexagonal wrapper of fuel assembly has been guaranteed over the entire operating temperature range. Effect of temperature on the density of lead bismuth eutectic, the subsequent change in added mass of lead bismuth eutectic, the effect on natural frequencies and effect on stresses on wrapper, has been studied in detail. A simple empirical relationship is presented for estimation of added mass effect for lead bismuth eutectic type fast reactors for any desired temperature. An approach for assessment of fast reactor fuel assembly performance has been outlined and calculated results are presented. Nuclear seismic rules require that systems and components which are important to safety, shall be capable of bearing earthquake effects and their integrity and functionality should be guaranteed. Mode shapes, natural frequencies, stresses on wrapper and seismic aspect has also been considered using ANSYS. Modal analysis has been compared in vacuum and lead bismuth eutectic using the calculated added mass.

Key words: liquid metal fast reactor, fuel assembly, seismic analysis, added mass, temperature

INTRODUCTION

The seismic qualification has been a major concern in the design and qualification of liquid metal fast breeder reactor (LMFBR) throughout the world. Earthquakes can effectively damage nuclear power plants especially in core region, which contains enriched uranium fuel assemblies that, should be particularly resistant. Therefore, it is mandatory to guarantee that the core will resist the worst possible earthquake. According to statistics, the global energy demand by 2030 will be increased by 50 %. In order to cope with the increasing energy demand in the country, chinese academy of sciences (CAS) has launched an engineering program for nuclear transmutation by developing an accelerator driven system (ADS). The design, proposed by institute of nuclear energy safety technology (INEST), was selected as the reference reactor [1-4]. Initially the design of a 10 MWth lead-bismuth cooled research reactor is under consideration [3-6]. The ADS is an advanced stage nuclear energy system for transmutation of long-lived radioactive wastes and fission fuel breeding [4-8].

In 2000, the generation IV international forum (GIF) was established for Research and Development of the next-generation advanced nuclear systems [9]. GIF is composed of six systems; advanced thermal reactors include, super critical water-cooled reactor (SCWR), very high temperature reactor (VHTR) and molten salt reactor (MSR). Fast neutron spectrum reactor includes sodium-cooled fast reactor (SFR), lead-cooled fast reactor (LFR) and gas-cooled fast reactor (GFR). The lead cooled system has been adopted by several countries: china lead-based reactor (CLEAR) by China, Super Safe, Small and Simple (4S) and LBE-cooled long-life safe single small portable proliferation-resistant reactor (LSPR) of Japan and proliferation-resistant, environmental-friendly, accident-tolerant, continuable, and economical reactor (PEACER) by Korea. Russia also has several plans that include, bystriy reaktor estestrennoy bezopasnosti (BREST) and svintsovo vismutovyi bystriy reaktor (SVBR). USA has small secure transportable autonomous reactor (SSTAR). Design selected by Europe was european lead-cooled system (ELSY) [10].

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Previously, 2-D models of fuel assemblies and whole core were used to design the LMFBR against seismic loadings, including models of a single row of fuel assemblies as well as horizontal plane of the whole core [10]. Preumont [11], in his research work, considered the fluid coupling due to thin fluid layers between fuel assemblies. Martelli [12] used a different approach by replacing the coupling effect by an added mass on individual fuel assemblies. Martelli research has been used for designing Phenix and Superphenix reactors in France. Recently Moussallam [13] demonstrated that computer capacities are sufficient enough to perform calculations on full-scale 3D models of LMFBR core considering a simplified fluid added mass effect [13]. Fuel assemblies have often been modeled as a single beam for simplifying calculations via fluid added mass effect [14, 15]. Cantilever behavior of the fuel assembly results in high displacements at the head level and high moments on the foot because flexural inertia is lowest at the foot level. The accomplishment of high burn-ups in fast reactor needs a comprehensive approach for determining the operational reliability of the system: especially, fuel assembly and core. This requires the qualification of performance of both, single fuel assembly and the core. The performance qualification of a single fuel assembly means to abstain substantial changes in geometrical dimensions and preservation of the integrity of fuel rods along with the hexagonal wrapper during its residence time in core. These problems need to be addressed through design and development efforts, a combination of complex calculations and experimental studies [13]. All these studies more or less ignored the dependence of temperature on different properties of LBE for the determination of added mass effect, added mass due to LBE varies with temperature over the entire operational temperature range of a fast reactor. The cumulative effect of change in added mass, along with a seismic event, could lead to the deformation of thin hexagonal wrapper bearing all mechanical loads and could cause reduction of the pitch between the fuel assemblies of an LMFR.

To author's knowledge, no study has yet been made, which specifically encompasses the temperature-dependent added mass effect of LBE and the subsequent effect on stresses on hexagonal wrapper over the entire operational temperature range, along with the seismic aspect of fuel assembly of LMFR. Temperature plays a key role in nuclear power plant dynamics; drastic temperature changes produce thermal shock on nuclear power plant components, specifically in core where the temperature changes are severe from startup to upset or faulted conditions, in case of a seismic event. Fast reactors usually operate at very high temperatures as compared to other types of nuclear power plants. Any change of temperature in the core leads to the change of many factors including, nevertheless, the density of coolant, dynamic behavior of core components, *etc*. This study highlights the effect of temperature on natural frequencies, effect on density of LBE and subsequent change in added mass, effect of stresses on wrapper and presents the qualification of fuel assembly in detail, considering different loads like dead weight (DW), design and operating pressure (DP, OP), earthquake (as response spectra), different plant conditions and combination of aforesaid loads according to code requirements using ANSYS Mechanical APDL (ANSYS parametric design language). Nuclear fuel is the most critical and important component which bears safety Class-III, ASME Class-I, and seismic Class-I. To accomplish the requirements laid down in code, seismic qualification of the fuel rod is thus mandatory against operational basis earthquake (OBE) and safe shutdown earthquake (SSE). The present work deals with the seismic and stress analysis of Class-I component, which should be confirmed *by analysis* instead of *by rules*.

STRUCTURAL DESIGN AND PARAMETERS

From the structural analysis point, most of the LMFR cores share some common characteristics, the core is composed of several types of assemblies. Fuel assemblies are located at the central region of core, bounded by a large number of additional assemblies containing numerous materials such as reflector, breeding, and neutron shielding materials, experimental devices, *etc*. The assembly of the exterior shell is made up of a metallic hexagonal tube, commonly known as wrapper, typically a few meters in height, few tens of centimeters in diameter and a few millimeters in thickness. The wrapper provides bulk of flexural stiffness, whereas the fuel rods provide the bulk of mass to the fuel assembly. In respect of reducing technical risk and Research and Development cost of fuel assembly, UO_2 (19.75 %) was chosen as the reactor fuel due to its adequate chemical compatibility with the coolant lead-alloy [6]. Based on CLEAR-I design, each FA includes 61 fuel pins [2, 3], considering service conditions and design load cases, the preliminary structure design parameters of fuel assembly are listed in tab. 1.

Table 1. Technical parameters of fuel assembly

Component	Dimensions [mm]
Total length	2274.8
Spike length	500
Cone length	54.8
Wrapper length	1704.8
Wrapper and spike thickness	3.5
Lower fuel plate thickness	15
Upper fuel plate thickness	10
Lifting head length	45
Diameter of spike	90
Distance between 2 wrappers	3.5
Distance between 2 spikes	30.7

Fuel assemblies are vertically placed on the lower core plate or diagrid by directly inserting the spike of the assembly into diagrid seats of the lattice. The spikes of fuel assemblies are sealed in the lower diagrid in order to reduce the leakage of LBE from the diagrid plenum. Vertical displacement of fuel assembly is barred without any mechanical method due to the weight of the assembly exceeding the buoyant force. The fuel assembly is completely immersed in LBE pool except for the spike, which is inserted into the diagrid. The fluid pool fills the gaps between adjacent assemblies and forms thin fluid film between solid surfaces. These fluid film layers are usually few meters high, few centimeters wide and few millimeters thick. LBE coolant flows upward into the fuel assemblies through the holes in the assembly spike, extracts heat from the fissile region of fuel rods, exits the fuel assembly at the head level and is collected in the hot collector. Figure 1 shows the schematics of CLEAR-I fuel assembly.

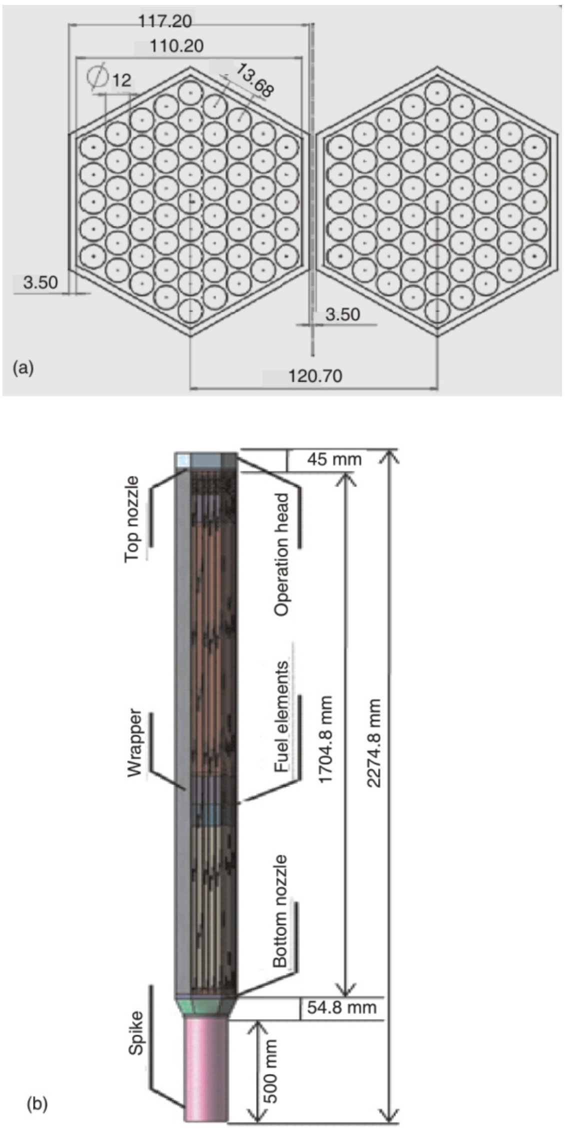

Figure 1. Schematic views of CLEAR-I fuel assembly (a) plane view, (b) top view

METHODOLOGY OF ANALYSIS

Since the fuel assembly first-order natural frequency is 10 Hz, as listed in tab. 6, it is less than the zero-period acceleration 33 Hz, so the seismic calculation of equivalent static method could not be applied. The finite element method (FEM), based software ANSYS, has been used in this analysis. After modeling in 3-D with necessary details, the models were then discretized with a higher-order 20-node 3-D solid element (SOLID95) to tolerate irregular configurations of geometry without loss of certainty. The SOLID95 is compatible with displacement shapes and is appropriate for curved borders [16]. The model was then investigated by static (pressure and weight) and dynamic (OBE and SSE) analysis, loads are applied and results are compared with the allowable limits defined by code.

Determination of LBE added mass effect

The calculation of added mass effect generally involves varying engineering judgments regarding the considerations of geometry, adjacent members, certain irregularities, *etc*. These factors significantly vary from situation to situation, in some cases; a preliminary analysis must be done. Theoretically, potential flow theory has been quite successful for determination of added mass effect in a lot of cases, especially where the geometry is not complex. The effect of added mass, for single isolated members, has been thoroughly investigated analytically and experimentally. The natural frequency of a structure immersed in, or in contact with a liquid, decreases significantly compared to that in vacuum. This is referred to as fluid-structure interaction (FSI). A lot of work has been done to find approximate solutions to determine the added mass effect in order to predict the change in natural frequency of a vibrating structure in a liquid [17].

Fuel assemblies of LMFR submerged in liquid LBE may vibrate under the influence of an earthquake, which might lead to a structural damage of fuel assembly, or deformation of the core and affects the structural integrity of the system. The high density of LBE makes the vibration of fuel assemblies severely nonlinear. So, the seismically induced fluid-structure interaction is of great importance. The calculation of added mass is a simplified dynamic analysis and was initially proposed by Westergaard. This theory considers the hydrodynamic pressure of water to the structure in terms of equivalent mass. The equivalent mass principle has been extensively used in many fields.

For ease and simplification of calculations, the fuel assembly is considered to be hexagonal finite length prism of uniform cross-section. For the upper

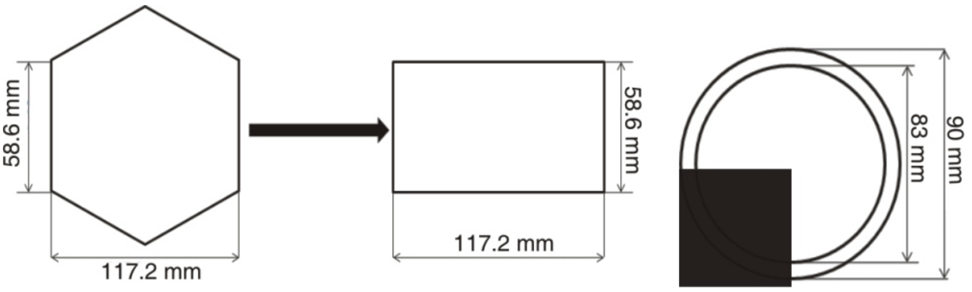

Figure 2. Upper and lower cross-section of the fuel assembly

part of fuel assembly, the equivalent cross-section method has been used for simplification, as the two sides of the rectangle are resembling the hexagon, the hexagon to edge distance was taken as the longer side of the rectangle, while the opposite side is used as the short side of the rectangle as shown in fig. 2. For the lower part of fuel assembly (spike), simply the inside and outside diameters were considered.

The fluid was assumed to be incompressible with no swirling flow. Since the slenderness ratio of the fuel assembly is greater than 40, so it can be assumed to be infinitely long and the effect of fluid along the length direction can be ignored. In this approach, the model can be simplified into two dimensions. The coolant flows through the assembly and also through the spacing between them. To consider the effect of fluid, consider the following variables for derivation. Φ_1 and Φ_2 (area potential functions for left and right faces); a and b (half of the long and short sides of the rectangle) and L (gap between fuel assemblies). In this way the continuity equation for the left area face can be written as

$$\frac{\partial^2 \Phi_1}{\partial_{x^2}} \quad \frac{\partial^2 \Phi_1}{\partial_{y^2}} \quad 0 \qquad (1)$$

Following variables were considered in the further derivation, m – the mass of the fuel assembly, m_c – the added mass due to the fluid, ρ – the density of the fluid, F – the force of the fluid on both sides of fuel assembly, p – the pressure, k – the spring constant, $\varepsilon'(t)$ and $\varepsilon''(t)$ – the first and second-order displacement of the fuel assembly and t – the time. Also, the subscripts 1 and 2 represents the left and the right areas of the fuel assembly, therefore, we have the following form of continuity equation with boundary conditions

$$\left.\frac{\partial \Phi_1}{\partial_x}\right|_{x \;\; a \;\; l} \quad 0$$

$$\left.\frac{\partial \Phi_1}{\partial_x}\right|_{x \;\; a} \quad \varepsilon\ (t) \qquad (2)$$

$$\left.\frac{\partial \Phi_1}{\partial_y}\right|_{y \;\; 0} \quad 0$$

$$\left.\frac{\partial \Phi_1}{\partial_y}\right|_{y \;\; 0} \quad \frac{b}{L}\varepsilon\ (t)$$

Solving eqs. (1) and (2)

$$\Phi_1 \quad \frac{\varepsilon\ (t)}{2L}(x^2 \quad y^2) \quad \frac{\varepsilon\ (t)x}{L}(a \quad L) \qquad (3)$$

Similarly, the continuity equation for the right area face can be written as

$$\frac{\partial^2 \Phi_2}{\partial_{x^2}} \quad \frac{\partial^2 \Phi_2}{\partial_{y^2}} \quad 0 \qquad (4)$$

The boundary conditions are as follows

$$\left.\frac{\partial \Phi_2}{\partial_x}\right|_{x \;\; a \;\; l} \quad 0$$

$$\left.\frac{\partial \Phi_2}{\partial_x}\right|_{x \;\; a} \quad \varepsilon\ (t) \qquad (5)$$

$$\left.\frac{\partial \Phi_2}{\partial_y}\right|_{y \;\; 0} \quad 0$$

$$\left.\frac{\partial \Phi_2}{\partial_y}\right|_{y \;\; b} \quad \frac{b}{L}\varepsilon\ (t)$$

Solving eqs. (4) and (5)

$$\Phi_2 \quad \frac{\varepsilon\ (t)}{2L}(\ x^2 \quad y^2) \quad \frac{\varepsilon\ (t)x}{L}(a \quad L) \qquad (6)$$

The equation of motion for the fuel assembly is as follows

$$m\varepsilon\ (t) \quad F \quad k\varepsilon(t) \quad 0 \qquad (7)$$

Since the fuel assembly wrapper cross-section has the geometry of a hollow hexagon, so it can be approximated as a simple rod hinged in the lower core plate and the use of Bernoulli hypothesis is possible for plane cross-sections because the cross-section of wrapper is very small compared to its length. According to Bernoulli's equation, the pressure to which fuel assembly is subjected is

$$p \quad \rho g z \quad \rho \frac{\partial \Phi}{\partial_t} \qquad (8)$$

Substituting eq. (3) into eq. (8)

$$P_{1x \;\; a} \quad \rho g z$$
$$\rho \quad \frac{\varepsilon\ (t)}{2L}(a^2 \quad y^2) \quad \frac{\varepsilon\ (t)a}{L}(a \quad L) \qquad (9)$$

Continuity and Bernoulli's equation in terms of F (force of fluid on both sides of fuel assembly) can be written as

$$F_1 = \int_{-b}^{b} p_1 dy = 2\rho gzb + \frac{\rho \ddot{\varepsilon}(t)}{L}\left(\frac{1}{3}b^3 + a^2 b + 2abL\right) \quad (10)$$

Similarly,

$$F_2 = \int_{-b}^{b} p_2 dy = 2\rho gzb - \frac{\rho \ddot{\varepsilon}(t)}{L}\left(\frac{1}{3}b^3 + a^2 b + 2abL\right) \quad (11)$$

Therefore, the resultant force F would be the difference of force on both sides of the fuel assembly

$$F = F_1 - F_2 \quad (12)$$

which results in

$$F = 2\rho \frac{\ddot{\varepsilon}(t)}{L}\left(\frac{1}{3}b^3 + a^2 b + 2abL\right) \quad (13)$$

Substituting eq. (13) into eq. (7), we get

$$\left[m + \frac{2\rho}{L}\left(\frac{1}{3}b^3 + a^2 b + 2abL\right)\right]\ddot{\varepsilon}(t) + k\varepsilon(t) = 0 \quad (14)$$

Let,

$$m_c = \frac{2\rho}{L}\left(\frac{1}{3}b^3 + a^2 b + 2abL\right) \quad (15)$$

Equation (15) has three variables a, b and L, which are explained as follows:

When $L \to$ zero, a and b are constant, the assemblies are inaccessible and fluid added mass is infinite; when $L \to \infty$, a and b are constant, the fluid added mass is $m_c = 4\rho ab$, which is the same as a single fuel assembly in a large pool, which is the same as potential flow theory. When $b \to$ zero, L and a are constant, fluid added mass is 0. When b or $a \to \infty$, L and a or b are constant, it is equivalent to infinite large plates and thus the added mass is infinite. When $a \to$ zero, L and b are constant, the added mass is given by $m_c = 2\rho b^3/3L$. In summary, when $L \to \infty$, the results of this calculation and results calculated by Westergaard theory ($m_c = 4\rho ab$) are the same.

For the sake of verification, the calculated results presented in tab. 4, were compared with the SYMPHONY test data, Westergaard and CEFR (China Experimental Fast Reactor) for water as working fluid. Afterward, the density of LBE was used to calculate added mass of fluid and used for subsequent analysis.

$$m_{a1} = \frac{2\rho}{L_1}\left(\frac{1}{3}b_1^3 + a_1^2 b_1 + 2a_1 b_1 L_1\right) \quad (16)$$

$$m_{a2} = \frac{2\rho}{L_2}\left(\frac{1}{3}b_2^3 + a_2^2 b_2 + 2a_2 b_2 L_2\right) \quad (17)$$

$$m_a = 1774.8 m_{a1} + 500 m_{a2} \quad (18)$$

Table 2. Calculation parameters for CLEAR-I fuel assembly

Parameter	Definition	Value
m_{a1}	Upper section of fuel assembly	1774.8 mm
m_{a2}	Lower section of fuel assembly	500 mm
ρ	Density of working water	$1.10 \cdot 10^{-6}$ kgmm^{-3}
a_1	Half of the long side of the rectangle	58.6 mm
b_1	Half of the short side of the rectangle	34.2945 mm
L_1	Distance between wrappers	3.5 mm
a_2	Outside diameter of spike	45 mm
b_2	Inside diameter of spike	41.5 mm
L_2	Distance between spikes	30.7 mm
m	Mass of fuel assembly	149.25 kg

Using parameters listed in tab. 2, in eqs. (16)-(18), the calculated added mass was approximately, $m_a = 74.12$ kg ($m_a/m = 0.4965$).

Floor response spectrum

The U.S. NRC RG 1.60 spectra are used as the site response spectrum. The design response spectra for the safe shutdown earthquake is characterized by RG 1.60 spectra, the horizontal component of which is scaled to a maximum ground acceleration of 0.3 g and vertical component is scaled to a maximum ground acceleration of 0.217g, considered to be fit for a typical site in China for LMFR. The response spectra for horizontal and vertical components of operating basis earthquake are obtained by dividing the corresponding values of safe shutdown earthquake spectra by 2. Figures 3 and 4 show the acceleration *vs*. frequency curves for OBE and SSE. The spectrum amplification factors for SSE and OBE are all in accord with R.G. 1.60 [18].

Loading combinations

The DP (0.75 MPa) and OP (0.5 MPa) were applied on the outside and inside areas of the fuel assembly. Since the LBE is also flowing through the fuel assembly so, nozzle loads at the entrance and exit were also considered in the analysis. Only those plant operating conditions, involving seismic loadings, were considered. Thus, service levels, having loading combination other than seismic loads, were overlooked as listed in tab. 3. Moreover, in the absence of nozzles, service levels B and C are the same.

RESULTS AND DISCUSSION

The selection of wrapper material for Lead cooled fast reactor (LFR) can be based upon the results of sodium cooled fast reactor (SFR) for most of the re-

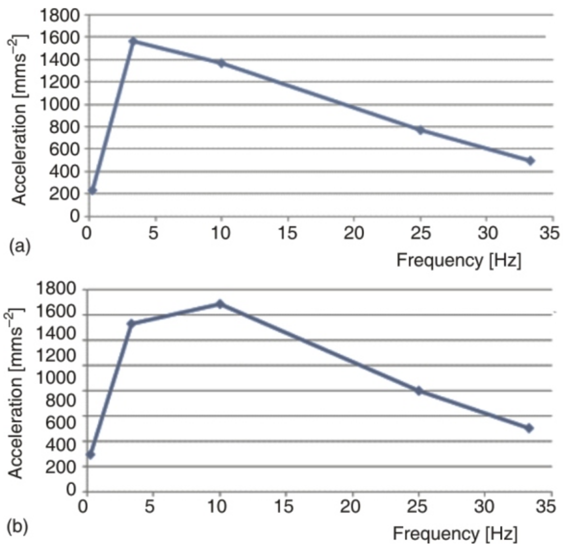

Figure 3. Horizontal (a) and vertical (b) response spectrum for OBE

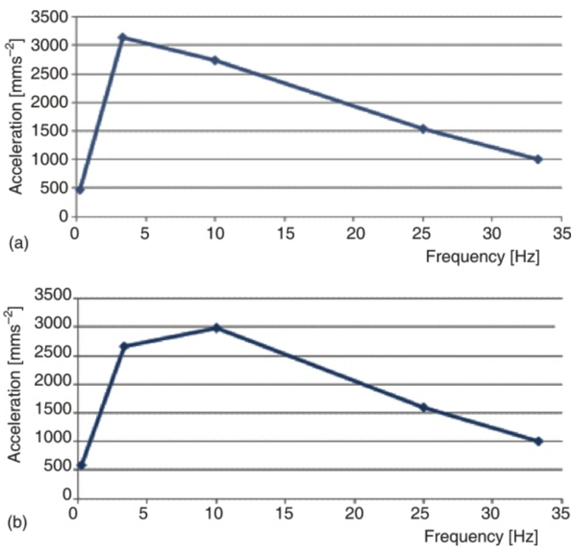

Figure 4. Horizontal (a) and vertical (b) response spectrum for SSE

Table 3. Added mass of LBE comparison with previous researches

Calculation model	Ratio of mass (m_a/m)
SYMPHONY test [19]	0.331
Westergaard [19]	0.227
CEFR (CASTEM) [20]	0.4867
CLEAR-I (working model)	0.4965

quirements, except for a few, those specific to lead coolant. The SS-316L has been considered the proven material for SFR and keeping in view the short-term adoption of a low temperature cycle, simplifies the material selection process. Since the fast reactor fuel operates at high temperature, the required properties and in-service conditions require utmost care in the selection of wrapper material, still a lot of research is underway in the selection of a suitable material for fuel assembly. Following assumptions were made before undergoing any analysis:

The fluid (LBE) is viscous, incompressible and Newtonian, LBE temperature is assumed to be distributed evenly at every point (10 steps) of calculations along with the assumption that fuel assembly is at constant temperature, the rod bundle does not undergo any deformation, and the pitch between rods remain constant in the fuel assembly. The equivalent density method has been used for modeling and analysis of fuel assembly. In order to expedite the analysis model, simplification has been done and the cumulative mass of fuel rods was added to the lower fuel assembly support plate by calculating the equivalent density.

Spike was constrained in all degree of freedom (DOF), as it is inserted in lower diagrid or lower core support plate, while the upper part of fuel assembly (lifting head) was set un-constrained from all directions. In the finite element method, when continuum elements are used, the total stress distribution is obtained. Therefore, to calculate membrane and bending stresses, the stress distribution shall be linearized across the thickness [16]. To check the stress limits, different paths were defined across the thickness and then stresses were linearized and compared with the allowable limits.

Dependence of LBE density and added mass on temperature

Temperature plays a key role in nuclear power plant dynamics; drastic temperature changes produce thermal shock on nuclear power plant components specifically in the core where the temperature changes are severe from startup to upset or faulted conditions. Fast reactors usually operate at very high temperatures as compared to other types of nuclear power plants. Any change in temperature of the core leads to change of many factors including, nevertheless, density of the coolant, dynamic behavior of core components, *etc*. With the increase in temperature from 500 K to 815 K, for every 35 K rise in temperature, the density of LBE decreases by approximately 47 kgm^{-3}, as shown in tab. 4.

The subsequent increase in temperature affects the added mass of LBE on the fuel assembly, for every 47 kgm^{-3} decrease in the density of LBE, there is a linear decrease of 0.866 kg of added mass on fuel assembly, as it can be seen on the graph in fig. 5.

The discussion in the previous sections, along with tab. 5 and fig. 5, can be empirically summed up in the

Table 4. Analysis types, load cases and combination

Service level	Operating condition	Load combination
Level 0	Design	DP + DW
Level A	Normal	OP + DW
Level B	Upset	OP + DW + OBE
Level D	Faulted	OP + DW + SSE

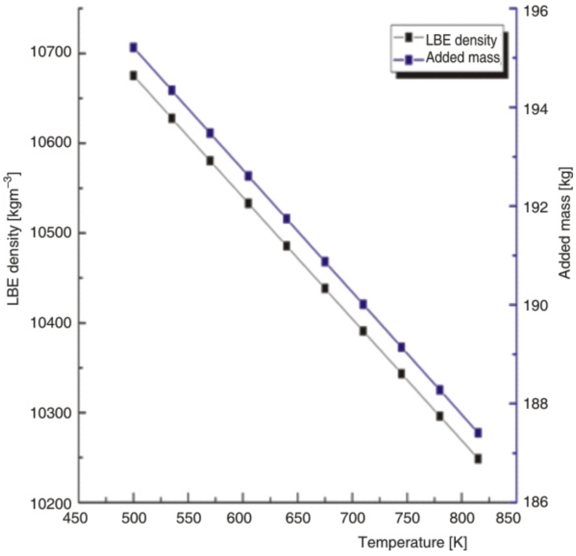

Figure 5. Temperature-dependent profile of LBE density and added mass

form of a linear relationship that is best suited for a rough estimation and approximation of added mass effect.

$$m_a \quad [11096 \quad (1.3236K)]4abL \qquad (19)$$

where m_a is added mass due to LBE, K – the temperature, variables a, b and L were explained previously. Since fast reactors using LBE as coolant, usually employ hexagonal fuel assemblies so, the relationship presented as eq. (16), can be used for approximate estimation of added mass effect at any temperature.

Modal analysis in vacuum and LBE

In order to investigate the vibration of mechanical structures, modal analysis is carried out experimentally or by simulation, which determines eigenvalues and eigenmodes. Finite element method (FEM) is one of the methods for obtaining mode shapes, fig. 6 and natural frequencies, tab. 6. Modal analysis has been compared in vacuum and LBE and it

Table 5. Temperature dependent added mass effect

Temperature [K]	LBE density [kgm^{-3}]	LBE added mass [kg]	Equivlent mass [kg]
500	10675.23	195.21022	344.4672015
535	10627.83389	194.34352	343.6005015
570	10580.43776	193.47682	342.7338015
605	10533.04163	192.61012	341.8671015
640	10485.6455	191.74342	341.0004015
675	10438.24937	190.87672	340.1337015
710	10390.85324	190.01002	339.2670015
745	10343.45711	189.14333	338.4003115
780	10296.06098	188.27663	337.5336115
815	10248.66484	187.40993	336.6669115

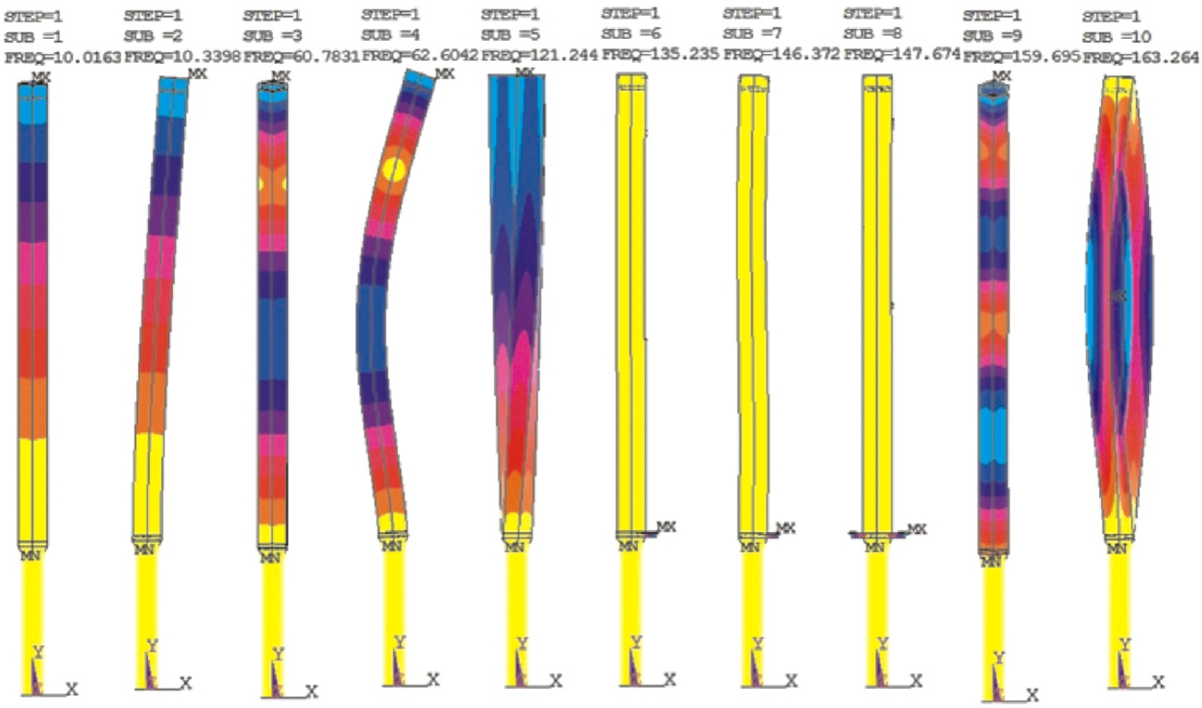

Figure 6. Mode shapes of fuel assembly

Table 6. Natural frequency comparison in Vacuum and LBE

Medium	Mode	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Vacuum	Frequency (Hz)	31.02	32.03	135.23	146.51	147.69	175.8	178.7	184.4	193.53	260.92
LBE	Frequency (Hz)	10.01	10.34	60.78	62.6	121.24	135.24	146.37	147.67	159.7	163.26

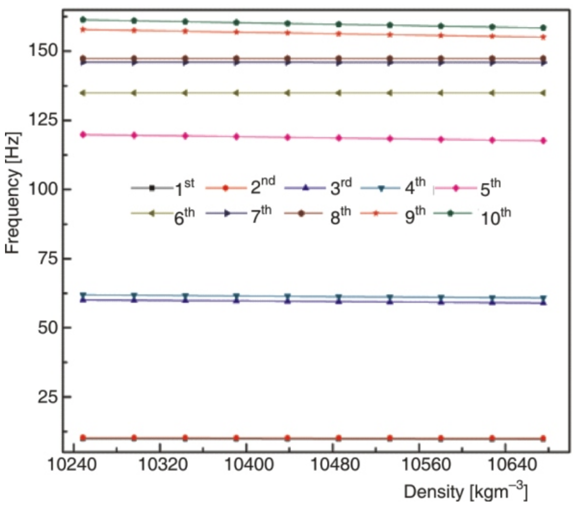

Figure 7. Dependence of frequency on the density of LBE

was found that the added mass effect in the system due to LBE (much higher density as compared to vacuum), is inversely proportional to the natural frequencies.

Moreover, the temperature-dependent behavior of density plays an important role in the natural frequencies of the system. Although the change observed, was not significant enough to modify the system dynamics, still it must be reported in order to design the connecting systems. The results obtained from modal analysis shows very little difference in natural frequencies as the temperature of the system changes. With the increase in temperature from 500 K to 815 K, for every 35 K rise in temperature, the density of LBE decreases by approximately 47 kgm^{-3}. Due to decrease in density, a slight increase in frequency can be observed, since frequency is inversely proportional to density. The overall increase in frequency with the rise in temperature is not more than 0.2 % over the entire temperature range, as it can be seen from the graph in fig. 7.

Temperature-dependent stress behavior of hexagonal wrapper

Fast reactors usually operate at elevated temperatures and the variations in temperature are quite non-uniform, due to which swelling of fuel assembly hexagonal wrapper results, causes significant bowing that leads to possible mechanical interaction between them. In order to ensure safe operation of the core, stress determination is a must for complete wrapper length over the entire possible operating temperature range. Hence, it is important to know the temperature-dependent kinetics of the wrappers.

The integrity of hexagonal wrapper is of the main concern of this study because wrapper is the thinnest and the longest section bearing all mechanical loads. Therefore, to check the stress limits and better understanding of the behavior of wrapper, 20 paths were defined along the full wrapper length. Stress behavior was studied for different plant conditions along the defined paths. The fuel assembly wrapper is usually subjected to various temperature cycles during its residence time in core. The temperature variation is quite large in case of a fast reactor, usually in the range of a few hundred K (500 ~ 800 K).

The effect of temperature on the wrapper is elaborated in the graph presented in fig. 8. With the in-

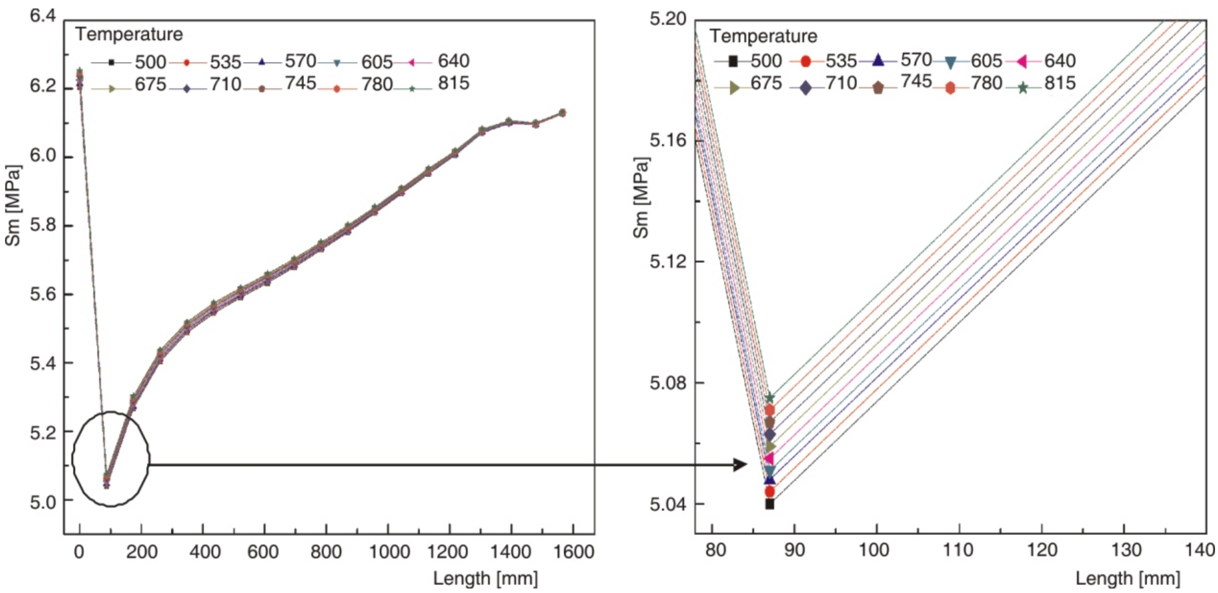

Figure 8. Stresses profile along wrapper length against temperature

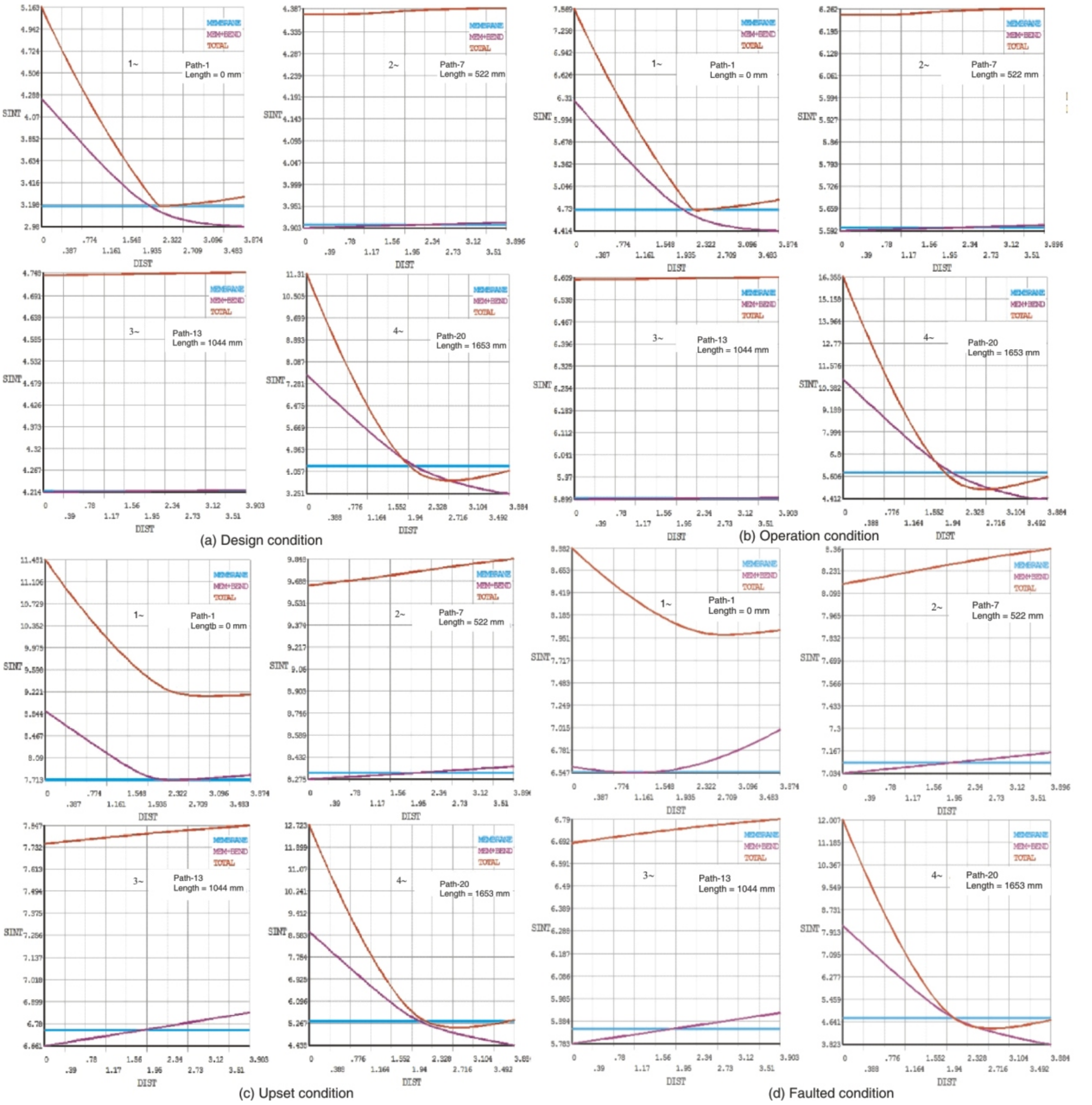

Figure 9. Stress distribution along wrapper length for design and faulted conditions

crease in temperature from 500 to 815 K, the stresses on wrapper specified paths were observed for every 35 K increase in temperature. A constant increase in stress intensity was observed over the entire temperature range under consideration. For example, it can be said that for every 35 K rise in temperature, there is a constant increase in stress on wrapper by a factor of approximately 0.005 MPa, or not more than 0.08 %. It is interesting to note that the effect is at maximum initially at the constrained end fuel assembly, with the increase in height (towards the un-constrained end), the stresses on wrapper still remain constant but, the intensity of stress accumulation, due to change in temperature, reduces uniformly. To summarize the above statement, for the complete length of wrapper, against the complete range of temperature under consideration, from constrained end to free end of fuel assembly, the stresses uniformly ease out. As the temperature increases, the stresses also increase but, as we move towards the free end of wrapper, the increase in stress due to change in temperature decreases and gradually approaches to zero. Or simply, change in temperature doesn't play any significant role in the stresses at the free end of fuel assembly.

Stress distribution for seismic loading and evaluation of results

Stress classification is performed to identify, the *Primary* (P) and *Secondary* (Q) component of stresses, which are related to equilibrium and compatibility equations, respectively. In general, these stresses come from mechanical and thermal loadings respectively and should be linearized to obtain the generalized (P_m) or localized (P_L) component of stresses, bending (P_b) and Peak (F) stresses. Linearization is performed along the cross-section of piping or equipment. The difference between actual and ($P_m + P_b$) stress distributions gives an equilibrium stress distribution, which neither produces net force nor net moment in the considered section, the maximum of which is the *Peak* (F) stress. The maximum stress in a given section usually occurs in internal or external surfaces and it is the sum of P_m (or P_L) + P_b + F.

The maximum stressed nodes, sorted out for ease in the understanding of results, provide a detailed overview for design of LMFR fuel assembly wrapper. Stress distribution or stress contours comparison is elaborated along with the most stressed nodes of fuel assembly wrapper against different loading conditions. A total 20 paths were drawn for determination of different kind of stresses along the wrapper length. For ease in understanding and simplification, graphical comparison has been made in fig. 9 for different plant conditions, only 4 paths are being presented. The lowest (0 mm) and topmost (1653 mm), and middle two (522 mm and 1044 mm) paths along the wrapper length, stresses were then linearized and compared with the allowable limits.

From complete assembly point of view, the stresses were also determined for different plant conditions, and the calculated stresses were compared with the allowable stress limits defined by the code, which is presented in tab. 7.

As shown in fig. 10, the most stressed nodes are near the free end of the fuel assembly fuel plate. The contours were elaborated in terms of stress intensity.

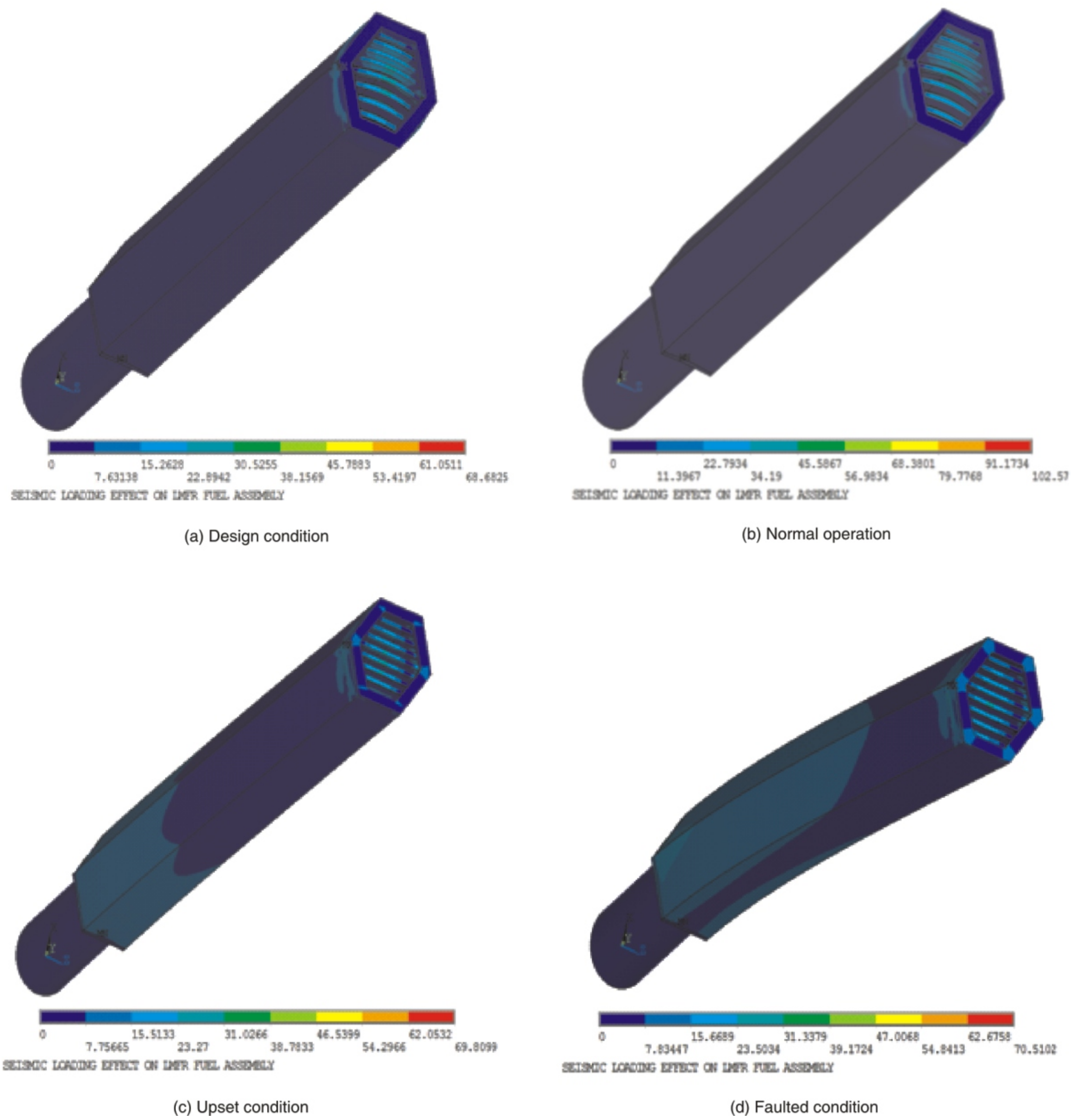

Figure 10. Stress intensity contour for different plant conditions

Table 7. Stress evaluation of fuel assembly under different plant conditions

Service level	Stress intensity (MPa)	Ratio (calculated/allowable)	Displacement (mm)
Design (1.5 S_m = 180)	102.57	0.57	0.12
Normal (3 S_m = 360)	68.6825	0.19	0.08
Upset (3 S_m = 360)	69.8096	0.19	0.70
Faulted (3.6 S_m = 432)	70.5104	0.16	1.16

Where, stress intensity is twice the maximum shear stress, defined as the difference between algebraically largest and smallest principal stress at a given position.

CONCLUSIONS

These results provide a detailed insight for design of LMFR fuel assembly considering different aspects and provide guidelines for further analysis. Wrapper integrity was verified over the entire operating temperature range and the effect of temperature variation on stresses on wrapper is elaborated. The stress ratios calculated are within the allowable limits for different loading combinations and hence, it is concluded that fuel assembly design is adequate to bear the anticipated loads and will perform functions during all plant conditions. Following are the key findings of this study:

- A simple empirical relationship is presented for estimation of added mass effect for LBE type fast reactors, which is best suited for a rough estimation and approximation of the added mass effect.
- Added mass calculations were verified with the SYMPHONY test data, Westergaard and CEFR for water as working fluid.
- With the increase in temperature from 500 K to 815 K, the density of LBE decreases by approximately 47 kgm^{-3} for every 35 K rise in temperature, a slight increase in frequency, not more than 0.2 % over the entire frequency range was observed.
- With the increase in temperature from 500 to 815 K, a constant increase on stress intensity was observed, for every 35 K rise in temperature, there is a constant increase in stress on wrapper by a factor of approximately 0.005 MPa or not more than 0.08%, from constrained end to free end of fuel assembly, the stresses uniformly ease out.
- The stress distribution is elaborated along with the most stressed nodes of fuel assembly wrapper against design, normal, upset and faulted conditions.
- Maximum stress ratios of 0.51 in case of design condition and maximum displacement of 1.16 mm (pitch 3.5 mm) in case of faulted condition was computed on fuel assembly and these values are within the allowable limits defined by Code

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AUTHORS' CONTRIBUTIONS

The modeling, calculations and manuscript preparation were done by M. Khizer. Y. Guowei assessed in verifying the geometric details related to the model. Z. Yong being the corresponding author guided throughout this study, verified the process and the results. W. Qingsheng contributed to improving the presentation of this manuscript, whereas W. Yican provided the comprehensive guidelines and idea about this research.

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ПРОЦЕНА СТРУКТУРАЛНО СЕИЗМИЧКИХ КАРАКТЕРИСТИКА ОМОТАЧА LMFR ХЕКСАГОНАЛНОГ ГОРИВНОГ СКЛОПА У ОПСЕГУ РАДНИХ ТЕМПЕРАТУРНОМ

Утврђен је структурни интегритет скопа брзог реактора са течним металом за различите параметре узимајући у обзир оптимални дизајн горива. Обављено је аналитичко израчунавање додатног масеног ефекта услед олово бизмутног еутектитка и верификација помоћу претодно приказаних теорија. Гаранција интегритета омотача хексагоналног горивног склопа обезбеђена је у читавом опсегу радних температура. Детаљно је проучаван утицај температуре и накнадне промене додатне масе олово бизмутног еутектика, ефекат на природне фреквенције и ефекат напрезања на омотачу. Приказан је једноставан емпиријски однос за процену ефекта додатне масе брзих реактора типа олово бизмутног еутектика за било коју жељену температуру. Наведе је приступ за процену перформанси горивног склопа брзог реактора и приказани су израчунати резултати. Нуклеарна сеизмичка правила захтевају да системи и компоненте које су важне за сигурност морају бити у стању да поднесу ефекте земљотреса и њихов интегритет и функционалност треба да буду гарантовани. Облици режима, природне фреквенције, напрезања на омотачу и сеизмички аспект такође су узети у обзир помоћу ANSYS. Упоређена је модална анализа у вакууму и оловно бизмутном еутектику користећи израчунату додатну масу.

Кључне речи: брзи реактор са течним металом, горивни склоп, сеизмичка анализа, додатна маса, температура