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Analysis of fixation method of fuel assembly for lead-alloy cooled reactor*

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As a potential candidate for generation IV reactors, lead-alloy cooled reactor has attracted much attentions in recent years. The China LEAd-based research Reactor (CLEAR) is proposed as the primary choice for the accelerator driven subcritical system project launched by Chinese Academy of Sciences. Lead-bismuth eutectic (LBE) is selected as the coolant of CLEAR owing to its efficient heat conductivity properties and high production rate of neutrons. In order to compensate the buoyancy due to the high density of lead-alloy, fixation methods of fuel assembly (FA) have become a research hotspot worldwide. In this paper, we report an integrated system of ballast and fuel element for CLEAR FA. It guarantees the correct positioning of each FA in normal and refueling operations. Force calculation and temperature analysis prove that the FA will be stable and safe under CLEAR operation conditions.

Keywords: Lead-alloy cooled reactor, Fuel assembly (FA), Fixation methods, Ballast

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I. INTRODUCTION

The Accelerator Driven subcritical System (ADS) is an advanced nuclear energy system for transmutation of long-lived radioactive nuclear wastes and fission fuel breeding [1, 2]. The lead-alloy of lead-bismuth eutectic (LBE) is advantageous in its high production rate of neutrons, efficient heat removal properties, thermal hydraulics and safety characteristics etc. Therefore, LBE-cooled reactor is designed as a main candidate for the subcritical reactor of ADS [3]. In 2011, CAS launched the ADS project and the China LEAd-based research Reactor (CLEAR) proposed by the Institute of Nuclear Energy Safety Technology (INEST) was selected as the reference reactor [4].

Fuel assembly (FA) is a key component in lead-alloy cooled reactor. A conventional FA would float in the liquid lead-alloy due to the high density, and this problem can be solved by a FA-fixation method to compensate the buoyancy force. Typical fixation methods worldwide include ballast and locking device [5–9]. With a locking device, it is not necessary to increase the FA and core volume, but this causes difficulties in positioning the FA accurately to the lower grid plate in refueling, hence the needs of structure modification of transfer machine gripper and lower grid plate. Considering that the service life of FA in lead-alloy cooled reactor is longer than commercial reactors, no sufficient experimental and operation data can be used to prove its structural stability and reliability.

The density of an FA added with ballast is larger than LBE, so the FA can be easily installed into the correct position and will not float in abnormal operating conditions. The ballast is of inherent safety. It requests no changes in structures of transfer machine gripper and other coupling components, and is simple to be implemented. However, its disadvantage is that volume of the ballast-added FA increases dramatically.

II. TYPICAL STRUCTURE DESIGN AND FIXATION METHOD OF FAS

A. Buoyancy problems

The force analysis of the CLEAR FA (without ballast) is shown in Fig. 1. The direction of total force of the FA in water is the same as gravity, whereas the direction of total force of the FA in LBE is the same as buoyancy, hence the need of a specific design to solve the problem of floating FA in the coolant.

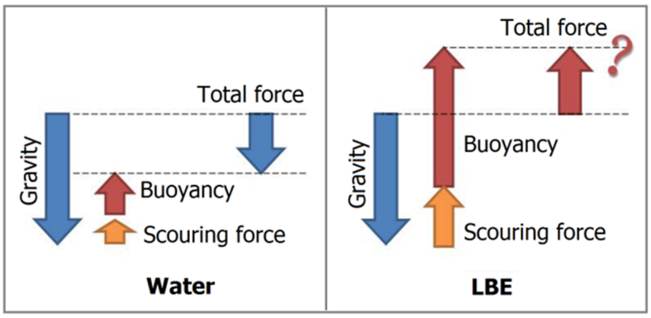

Fig. 1. (Color online) Force analysis of the FA (without ballast).

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TABLE 1. Advantages and disadvantages of the fixation methods

Reactors	ALFRED/ CLEAR-I	XADS	MYRRHA
Fixation methods	Ballast	Locking device	FA-inserted from underneath
Advantages	Inherent safety, Hydraulic autofrettage	No change in FA weight	No change in FA weight
Disadvantages	Weight increase of FA	Relatively short service time	Big change in reactor structure
		Decrease of one fuel rod per FA	
		Special system for installation	

B. Fixation methods of typical reactors

In the European project of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED), the core consists of wrapped hexagonal FAs with pins, arranged in a triangular lattice. The 171 FAs are subdivided into two radial zones with different plutonium enrichment to ensure an effective power flattening, and surrounded by two rows of dummy elements serving as reflector. The ALFRED design uses upper tungsten ballast to guarantee the correct position of each FA in refueling operations. The high density of lead alloy causes a great buoyancy force and leads to the FA floatation. In normal operation, FAs are connected to the upper diagrid plate by preloaded springs; while in refueling operation, the upper diagrid plate is removed in order to reach the upper head of each FA. Thus, the FAs cannot change their position because of the upper ballast counterbalanced the buoyancy force.

In the Russian project of experimental accelerator driven system (XADS), the core includes 120 FAs, 162 dummy assemblies and 12 absorber assemblies. Each FA, consisting of hexagonal wrapper tube, operation head and position spike, is anchored to the lower diagrid through a locking device. The operation head can be connected to the transfer machine gripper, which has been improved referring to the sodium reactor technology and possesses the additional possibility to push the FA inside the LBE and keep its vertical trim. The transfer machine gripper locks/unlocks the FA to/from the lower diagrid, and unlocks/locks the FA from/to itself.

In the Belgian project of Multipurpose Hybrid Research Reactor for High-tech Applications (MYRRHA), the fresh core contains 68 FAs, which are kept to the core support plate by inserting them in holes of the core support plate from underneath. Each FA includes 91 pins and retains at their location by the buoyancy force. The sub-critical core is surrounded by the core barrel to prevent the FAs from moving away from each other. The refueling machine can move up and down for about 2 m, to extract the FAs from the core. The fuel handling system is performed underneath the core.

After weighing advantages and disadvantages of the three core designs (Table 1), an integrated system of ballast and fuel element guaranteed the correct FA-positioning in normal and refueling operations. In this paper, structural design of the FA, especially the fixation methods, will be described.

III. STRUCTURE DESIGN OF CLEAR FA

A. The FA structure

In view of reducing technical risk and R&D cost of FA, UO_2 was chosen as the reactor fuel due to its adequate chemical compatibility with the coolant lead-alloy. Based on the premise of the nuclear nonproliferation treaty and present situation in China, the enrichment of UO_2 was designed as 19.75%. The maximum temperature limit of fuel pellet was 2300 °C, and the temperature gradient limit was 4×10^4 °C/m. Each FA includes 61 fuel pins, featuring a stainless steel cladding and holding UO_2 pellets [10, 11]. Considering service conditions and design load cases in CLEAR, the preliminary structure design parameters of FA are listed in Table 2.

TABLE 2. The design parameters of CLEAR FA [12, 13]

Items	Values
Fuel elements	61
FA length (mm)	2110
FA diameter (mm)	117.2
Fuel material	UO_2 (19.75%)

B. The fixation method

Ballast was chosen as the fixation method for CLEAR FA. An integrated system of ballast and fuel element ensures correct positioning of FAs in normal and refueling operations. The design of ballast was analyzed with a detailed assessment of the service condition and accident risk.

1. Material of the ballast

Density of the ballast material must be much larger than coolant LBE. Performance of the ballast should be suitable for the lead-alloy cooled reactor environment. Thus, depleted uranium (DU) and tungsten are the candidate material for ballast. Their densities are almost twice as large as LBE. Their physical properties, such as high thermal conductivity and low thermal expansion, were suitable for the reactor environment. Most importantly, they are good at resisting LBE corrosion and irradiation swelling. DU and tungsten (W) are of different effective multiplication factors (k_{eff}), calculated at $k_{\mathrm{eff\,(W)}} = 1470\,\mathrm{pcm}$ and $k_{\mathrm{eff\,(DU)}} = 1638\,\mathrm{pcm}$, considering 0.7% of the ^{235}U enrichment in DU. Therefore, DU was chosen as the ballast material of CLEAR-I FA.

2. *Force analysis of the ballast*

The force analysis of FA without and with ballast added in coolant LBE is shown in Fig. 2.

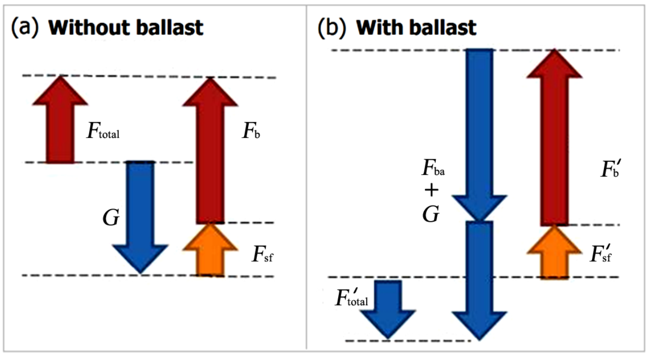


Fig. 2. (Color online) Force analysis of FA without and with ballast in coolant LBE.

From Fig. 2(a), the total force of FA without ballast in coolant LBE is

$$F_{\mathrm{total}} = |F_{\mathrm{b}} + F_{\mathrm{sf}} - G|, \tag{1}$$

where, $F_{\mathrm{b}} = \rho_{\mathrm{LBE}} \cdot g \cdot V_{\mathrm{FA}}$ is the buoyancy, $\rho_{\mathrm{LBE}} = 11\,\mathrm{g\,cm^{-3}}$ is the density of LBE, g is the acceleration of gravity, V_{FA} is the volume of FA; F_{sf} is the coolant scouring force estimated by thermal hydraulics calculations; and G is the gravity of FA.

With the ballast of a DU cylinder in radius of $r_{\mathrm{ba}} = 5.45\,\mathrm{cm}$, height of h_{ba}, and gravity of F_{ba}, we have (Fig. 2(b))

$$h_{\mathrm{ba}} = F_{\mathrm{ba}}/(S_{\mathrm{ba}}\cdot\rho_{\mathrm{DU}}\cdot g) = (F'_{\mathrm{b}}+F'_{\mathrm{sf}}-G)/(\pi r_{\mathrm{ba}}^2\cdot\rho_{\mathrm{DU}}\cdot g), \tag{2}$$

where, S_{ba} is the section of ballast; F'_{b} is the buoyancy of FA; F'_{sf} is the scouring force estimated by thermal hydraulics calculations; and $\rho_{\mathrm{DU}} = 19.1\,\mathrm{g/cm^3}$ is the density of DU. The thermal hydraulic calculation was performed, and the ballast height was estimate at $h_{\mathrm{ba}} = 510\,\mathrm{cm}$ ($F_{\mathrm{total}} = 0$).

DU ballast in two versions was added into the FA to improve comprehensive density and to balance the upward force. Version A ballast was outside the FA, while Version B ballast was inside FA on every fuel element.

3. *Comparison of the two ballast versions*

Force analysis of the two versions were presented in Table 3.

The Version A ballast (Fig. 3(a)) was made of several DU plates, connected with FA on the entrance of coolant. The pressure at entrance of coolant, P_{EC}, can be calculated by

$$P_{\mathrm{EC}} = F_{\mathrm{cw}}/S_{\mathrm{E}}, \tag{3}$$

TABLE 3. Parameters of force analysis

Designs	V (cm^3)	G (N)	F_{ba} (N)	F_{b} (N)	$F_{\mathrm{sf\_max}}$ (N)
No ballast	10292.5	846.83	0	1109.4	26.25
Ballast A	15657.7	1851.1	1004.3	1687.8	26.25
Ballast B	14512.3	1482.3	635.5	1422.2	26.25

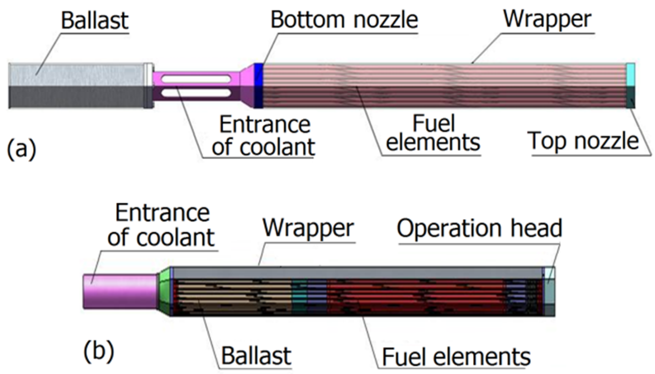


Fig. 3. (Color online) Schematics of the fuel assembly with Version A (a) and Version B (b) ballast.

where, $F_{\mathrm{cw}} = F_{\mathrm{b}} + F_{\mathrm{sf}} - G = 600\,\mathrm{N}$ and $S_{\mathrm{E}} = 2.34\,\mathrm{cm^2}$ is the sectional area of entrance of coolant. So, $P_{\mathrm{EC}} = 2.56\,\mathrm{MPa}$. The refueling cycle was designed at ten years. Corrosion at corner will occur due to the small section area at the entrance of coolant. In the ten years, performance of stainless steel will decrease significantly, and deformation of coolant entrance was possible in normal and refueling operations. In addition, the crack grew much frequently owing to holes at the entrance of coolant.

Figure 3(b) shows the FA structure with the Version B ballast, which is divided to every fuel element. Design specifications of the fuel element are given in Table 4.

TABLE 4. Design specifications (in mm) of CLEAR fuel element

Items	Values
Pin length	1675
Pin diameter	12
Pellet diameter	10.9
Active zone length	800
Ballast length	510
Cladding material	Stainless steel

The pressure of one cladding tube, P_{CT}, can be calculated by

$$P_{\mathrm{CT}} = f_{\mathrm{cw}}/S_{\mathrm{CT}}, \tag{4}$$

where $f_{\mathrm{cw}} = 10.4\,\mathrm{N}$ is the gravity of ballast in one fuel element, and $S_{\mathrm{CT}} = 0.1457\,\mathrm{cm^2}$ is the sectional area of one cladding tube. Thus, $P_{\mathrm{CT}} = 0.714\,\mathrm{MPa}$, being much smaller than P_{EC}. Therefore, under the same service environment, the safety margin of Version B is much larger than that of Version A. After weighting the pros and cons (Table 5), Version B was proposed as the most potential design for CLEAR FA, with fewer technological risks.

TABLE 5. The pros and cons of two versions

Features	Version A	Version B
Force analysis	–, Deformation of coolant entrance occurs.	+, Smaller deformation
Inherent safety	–, FA may float in reactor accidents.	+, FA always sinks under coolant.
Safety margin	–, Crack grows much easier.	+, Service life is longer.

In normal operations, sufficient safety margin of ballast design should be given for service environment [14]. Therefore, safety analysis of the ballast should be carried out.

IV. TEMPERATURE FIELD ANALYSIS OF BALLAST

A. Model of ballast

As cross section of the ballast is central symmetry, 1/6 of the structure was chosen to establish the calculation model [15, 16] (Fig. 4). The DU pellet has a 15-15Ti cladding, with a helium layer between the pellet and cladding. Properties of the materials are given in Table 6.

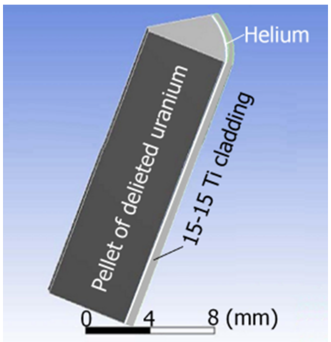


Fig. 4. (Color online) The cross section of the ballast.

TABLE 6. Properties of the ballast materials

Material	DU	15-15Ti	Helium
Density (g/cm^3)	19.1	8	0.1347×10^{-3}
Thermal conductivity (400 °C) (W/(m °C))	29.721	19.3	0.144
Specific heat capacity (J/(kg °C))	140.73	561	3116 (constant volume)

B. Boundary conditions

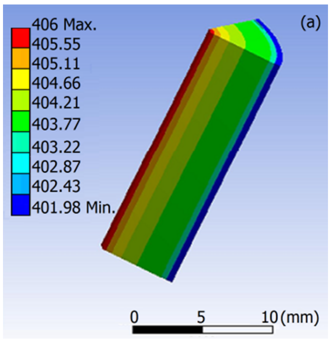
The heat of ballast is transferred from DU pellet to cladding by helium, and the heat of cladding is transferred by the LBE coolant [17, 18]. When the reactor is in normal operation, the electromagnetic load is too small to be considered. Service parameters of the ballast in the lead alloy-cooled reactor are given in Table 7. Temperatures of the cladding and DU were obtained using empirical formulas. To ensure a sufficient safety, they were calculated conservatively.

TABLE 7. Service parameters of the ballast

Parameters	Value
Thermal power of the reactor (MW)	10
Ballast material	DU
Coolant temperature (°C)	400
Heat transfer supervisor of cladding-pellet (W/(m^2 °C))	1000
Maximum linear power density (kW/m)	4.06
Thermal conductivity of 15-15Ti (400 °C) (W/(m °C))	19.3
Average velocity of the coolant (m/s)	0.5

C. The simulation results of steady-state operation

The finite element code ANSYS was used to simulate the ballast calculation model. The temperature field is shown in Fig. 5(a), on the basis of steady-state operation. Figure 5(b) shows the radial temperature of ballast pellet. After an amount of theoretical and experimental verification, the operation temperature limit of 15-15Ti was set to 550 °C [19, 20]. The simulation results show that the ballast temperature did not increase dramatically when the reactor was in steady-state operation. Thus, DU does not introduce damage to the cladding and other structural materials. In summary, the ballast design meets the requirements of design criteria.



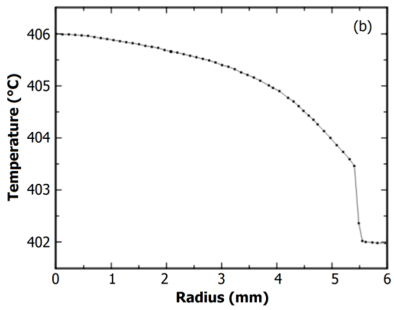


Fig. 5. (Color online) Temperature field of ballast (a) and radial temperature variation of ballast pellet (b).

V. CONCLUSION

In this paper, the structure of fixation ballast for FA in the lead-alloy cooled reactor of CLEAR-I is investigated and designed. The main conclusion can be summarized as follows:

1) Comparing to locking devices, ballast is of attractive characteristics, including inherent safety, small change to core structure and reactor internals, hence the choice of ballast as the fixation method for CLEAR-I FA.

2) Calculation results of $k_{\rm eff}$ show that DU is better than tungsten in terms of the effective multiplication factor and initial loading capacity. So, DU is chosen for the ballast material.

3) The force calculation results of coolant entrance show that the ballast divided into every fuel element has sufficient safety margin under the service environment. The simulation results of temperature field prove that the temperatures of DU and cladding are stable and safe under normal operation condition.

The sufficient safety margin should be given for anticipated accidents, therefore, the safety analysis of ballast in abnormal operating conditions will be given in the near future.

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