

## Analysis of fixation method of fuel assembly for lead-alloy cooled reactor (Postprint)

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### Abstract

As a potential candidate for generation IV reactors, lead-alloy cooled reactors have attracted considerable attention 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 the Chinese Academy of Sciences. Lead-bismuth eutectic (LBE) is selected as the coolant for CLEAR owing to its efficient thermal conductivity and high neutron yield. To compensate for the buoyancy caused by the high density of lead-alloy, fixation methods for fuel assemblies (FA) have become a research hotspot worldwide. This paper reports an integrated ballast and fuel element system for CLEAR FAs. It ensures the correct positioning of each FA during normal and refueling operations. Force calculations and temperature analysis demonstrate that the FA will remain stable and safe under CLEAR operating conditions.

### Full Text

#### Analysis of Fixation Method of Fuel Assembly for Lead-Alloy Cooled Reactor

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for the accelerator-driven subcritical system project launched by the Chinese Academy of Sciences. Lead-bismuth eutectic (LBE) is selected as the coolant for CLEAR due to its efficient heat conductivity and high neutron production rate. To compensate for buoyancy caused by the high density of lead-alloy, fixation methods for fuel assemblies (FAs) have become a research hotspot worldwide. This paper reports an integrated ballast and fuel element system for CLEAR FAs that guarantees correct positioning during normal and refueling operations. Force calculations and temperature analysis demonstrate that the FA remains stable and safe under CLEAR operating conditions.

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

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## Introduction

The Accelerator-Driven subcritical System (ADS) represents an advanced nuclear energy concept for transmuting long-lived radioactive waste and breeding fission fuel [1, 2]. Lead-bismuth eutectic (LBE) offers advantages including high neutron production rates, efficient heat removal properties, favorable thermal-hydraulic characteristics, and enhanced safety features. Consequently, LBE-cooled reactors have emerged as a primary candidate for ADS subcritical reactors [3]. In 2011, the Chinese Academy of Sciences launched the ADS project, selecting the China LEAd-based research Reactor (CLEAR)—proposed by the Institute of Nuclear Energy Safety Technology (INEST)—as the reference design [4].

The fuel assembly (FA) constitutes a critical component in lead-alloy cooled reactors. Conventional FAs would float in liquid lead-alloy due to its high density, necessitating specialized fixation methods to counteract buoyancy forces. Current international approaches include ballast systems and mechanical locking devices [5–9]. While locking devices avoid increasing FA and core volume, they complicate precise positioning of FAs onto the lower grid plate during refueling, requiring modifications to the transfer machine gripper and lower grid plate structure. Furthermore, given that FAs in lead-alloy cooled reactors have longer service lives than those in commercial reactors, insufficient experimental and operational data exist to validate their long-term structural stability and reliability.

In contrast, ballast-equipped FAs achieve densities exceeding that of LBE, enabling straightforward installation and preventing flotation during abnormal conditions. Ballast offers inherent safety, requires no structural changes to the transfer machine gripper or other coupling components, and is simple to implement. However, this approach significantly increases FA volume. After evaluating these trade-offs, this paper investigates an integrated ballast and fuel element system for CLEAR FAs.

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## II. Typical Structure Design and Fixation Method of FAs

### A. Buoyancy Problems

Force analysis of the CLEAR FA (without ballast) is illustrated in Fig. 1 [Figure 1: see original paper]. In water, the net force on the FA acts downward with gravity, whereas in LBE, the net force acts upward as buoyancy, necessitating a specific design solution to prevent FA flotation in the coolant.

### B. Fixation Methods of Typical Reactors

In the European Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) project, the core comprises wrapped hexagonal FAs with pins arranged in a triangular lattice. The 171 FAs are subdivided into two radial zones with different plutonium enrichments to ensure effective power flattening, surrounded by two rows of dummy elements serving as reflectors. The ALFRED design employs upper tungsten ballast to maintain correct FA positioning during refueling operations. The high density of lead-alloy generates substantial buoyancy forces that would otherwise cause FA flotation. During normal operation, FAs connect to the upper diagrid plate via preloaded springs, while during refueling, the upper diagrid plate is removed to access each FA's upper head. The upper ballast counterbalances buoyancy forces, preventing positional changes.

The Russian experimental accelerator-driven system (XADS) project features a core with 120 FAs, 162 dummy assemblies, and 12 absorber assemblies. Each FA consists of a hexagonal wrapper tube, operation head, and position spike, anchored to the lower diagrid through a locking device. The operation head connects to a transfer machine gripper—improved based on sodium reactor technology—with the additional capability to push the FA into the LBE and maintain vertical alignment. The transfer machine gripper locks and unlocks the FA to and from the lower diagrid and itself.

In the Belgian Multipurpose Hybrid Research Reactor for High-tech Applications (MYRRHA) project, the fresh core contains 68 FAs inserted from underneath into holes in the core support plate. Each FA includes 91 pins and is retained in position by buoyancy force. The subcritical core is surrounded by a core barrel to prevent FAs from drifting apart. The refueling machine moves vertically approximately 2 meters to extract FAs from the core, with the fuel handling system located underneath the core.

After weighing the advantages and disadvantages of these three core designs (Table 1), we propose an integrated ballast and fuel element system that ensures correct FA positioning during both normal and refueling operations. The following sections describe the FA structural design, with particular emphasis on fixation methods.

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### III. Structure Design of CLEAR FA

#### A. The FA Structure

To reduce technical risk and R&D costs,  $\text{UO}_2$  was selected as the reactor fuel due to its adequate chemical compatibility with lead-alloy coolant. Based on nuclear nonproliferation treaty requirements and China's current situation, the  $\text{UO}_2$  enrichment was designed at 19.75%. The maximum fuel pellet temperature limit is 2300 °C, with a temperature gradient limit of  $4 \times 10^4$  °C/m. Each FA contains 61 fuel pins featuring stainless steel cladding and  $\text{UO}_2$  pellets [10, 11]. Preliminary structural design parameters for the FA under CLEAR service conditions and design load cases are listed in Table 2 .

#### B. The Fixation Method

Ballast was selected as the fixation method for CLEAR FAs. An integrated ballast and fuel element system ensures correct FA positioning during normal and refueling operations, with the ballast design analyzed through detailed assessment of service conditions and accident risks.

**1. Material of the Ballast** Ballast material density must substantially exceed that of LBE coolant, with performance suitable for the lead-alloy cooled reactor environment. Depleted uranium (DU) and tungsten are candidate materials, with densities nearly twice that of LBE. Their physical properties—including high thermal conductivity and low thermal expansion—are appropriate for reactor environments, and both materials exhibit excellent resistance to LBE corrosion and irradiation swelling. The effective multiplication factors ( $k_{\text{eff}}$ ) differ:  $k_{\text{eff}}(\text{W}) = 1470$  pcm and  $k_{\text{eff}}(\text{DU}) = 1638$  pcm, with DU containing 0.7%  $^{235}\text{U}$  enrichment. Consequently, DU was selected as the ballast material for CLEAR-I FAs.

**2. Force Analysis of the Ballast** Force analysis of FAs without and with ballast in LBE coolant is shown in Fig. 2 [Figure 2: see original paper]. For an FA without ballast, the net force in LBE coolant is:

$$F_{total} = |F_b + F_{sf} - G|$$

where  $F_b = \rho_{LBE} \cdot g \cdot V_{FA}$  is buoyancy,  $\rho_{LBE} = 11$  g/cm<sup>3</sup> is LBE density,  $g$  is gravitational acceleration,  $V_{FA}$  is FA volume,  $F_{sf}$  is coolant scouring force from thermal-hydraulic calculations, and  $G$  is FA weight.

With a DU cylinder ballast of radius  $r_{ba} = 5.45$  cm, height  $h_{ba}$ , and weight  $F_{ba}$  (Fig. 2(b)):

$$h_{ba} = \frac{F_{ba}}{S_{ba} \cdot \rho_{DU} \cdot g} = \frac{F'_b + F'_{sf} - G}{\pi r_{ba}^2 \cdot \rho_{DU} \cdot g}$$

where  $S_{ba}$  is ballast cross-section,  $F'_b$  is FA buoyancy,  $F'_{sf}$  is scouring force from thermal-hydraulic calculations, and  $\rho_{DU} = 19.1 \text{ g/cm}^3$  is DU density. Thermal-hydraulic calculations estimated the ballast height at  $h_{ba} = 510 \text{ cm}$  (with  $F_{total} = 0$ ). Two DU ballast versions were considered: Version A places ballast outside the FA, while Version B distributes ballast inside each fuel element.

**3. Comparison of the Two Ballast Versions** Force analysis results for both versions are presented in Table 3 .

**Version A** ballast (Fig. 3(a) [Figure 3: see original paper]) consists of several DU plates connected to the FA at the coolant entrance. The pressure at the coolant entrance ( $P_{EC}$ ) is:

$$P_{EC} = \frac{F_{cw}}{S_E}$$

where  $F_{cw} = F_b + F_{sf} - G = 600 \text{ N}$  and  $S_E = 2.34 \text{ cm}^2$  is the coolant entrance cross-sectional area, yielding  $P_{EC} = 2.56 \text{ MPa}$ . With a designed refueling cycle of ten years, corrosion at corners will occur due to the small entrance cross-section. Over this period, stainless steel performance degrades significantly, and coolant entrance deformation becomes possible during normal and refueling operations. Additionally, cracks propagate more readily due to stress concentrations at coolant entrance holes.

**Version B** ballast distributes the ballast to each fuel element (Fig. 3(b) [Figure 3: see original paper]). Fuel element design specifications are given in Table 4 . The pressure on a single cladding tube ( $P_{CT}$ ) is:

$$P_{CT} = \frac{f_{cw}}{S_{CT}}$$

where  $f_{cw} = 10.4 \text{ N}$  is the ballast weight per fuel element and  $S_{CT} = 0.1457 \text{ cm}^2$  is the cross-sectional area of one cladding tube, yielding  $P_{CT} = 0.714 \text{ MPa}$ —substantially lower than  $P_{EC}$ . Consequently, Version B offers a much larger safety margin under identical service conditions. After evaluating the pros and cons (Table 5 ), Version B was identified as the most promising design for CLEAR FAs, presenting fewer technological risks.

## IV. Temperature Field Analysis of Ballast

### A. Model of Ballast

Due to the central symmetry of the ballast cross-section, a 1/6 sector was selected for the calculation model [15, 16] (Fig. 4 [Figure 4: see original paper]). The DU pellet uses 15-15Ti cladding with a helium layer between pellet and cladding. Material properties are listed in Table 6 .

### B. Boundary Conditions

Ballast heat transfers from the DU pellet to the cladding via helium, and from the cladding to the LBE coolant [17, 18]. During normal operation, electromagnetic loads are negligible. Ballast service parameters in the lead-alloy cooled reactor are given in Table 7 . Cladding and DU temperatures were obtained using empirical formulas with conservative calculations to ensure adequate safety margins.

### C. Simulation Results of Steady-State Operation

The finite element code ANSYS simulated the ballast model. The temperature field under steady-state operation is shown in Fig. 5(a) [Figure 5: see original paper], with radial ballast pellet temperature distribution in Fig. 5(b) [Figure 5: see original paper]. Based on theoretical and experimental verification, the 15-15Ti operating temperature limit is 550 °C [19, 20]. Simulation results indicate that ballast temperature does not increase dramatically during steady-state operation, and DU does not damage the cladding or other structural materials. The ballast design satisfies all design criteria.

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## V. Conclusion

This paper investigates and designs a fixation ballast structure for FAs in the CLEAR-I lead-alloy cooled reactor. The main conclusions are:

1. Compared to locking devices, ballast offers attractive characteristics including inherent safety and minimal changes to core structure and reactor internals, making it the preferred fixation method for CLEAR-I FAs.
2. Effective multiplication factor calculations demonstrate that DU is superior to tungsten in terms of  $k_{\text{eff}}$  and initial loading capacity, leading to DU' s selection as the ballast material.
3. Force calculations at the coolant entrance show that ballast distributed to each fuel element provides sufficient safety margins under service conditions. Temperature field simulation results confirm that DU and cladding temperatures remain stable and safe during normal operation.

Adequate safety margins must be provided for anticipated accidents; therefore, safety analysis of the ballast under abnormal operating conditions will be addressed in future work.

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