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# Physics design of experimental metal fuelled fast reactor cores for full scale demonstration

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ABSTRACT

Fast breeder reactors based on metal fuel are planned to be in operation for the year beyond 2025 to meet the growing energy demand in India. A road map is laid towards the development of technologies required for launching 1000 MWe commercial metal breeder reactors with closed fuel cycle. Construction of a test reactor with metallic fuel is also envisaged to provide full-scale testing of fuel sub-assemblies planned for a commercial power reactor. Physics design studies have been carried out to arrive at a core configuration for this experimental facility. The aim of this study is to find out minimum power of the core to meet the requirements of safety as well as full-scale demonstration. In addition, fuel sustainability is also a consideration in the design. Two types of metallic fuel pins, viz. a sodium bonded ternary (U–Pu–6% Zr) alloy and a mechanically bonded binary (U–Pu) alloy with 125 μm thickness zirconium liner, are considered for this study. Using the European fast reactor neutronics code system, ERANOS 2.1, four metallic fast reactor cores are optimized and estimated their important steady state parameters. The ABBN-93 system is also used for estimating the important safety parameters. Minimum achievable power from the converter metallic core is 220 MWt. A 320 MWt self-sustaining breeder metal core is recommended for the test facility.

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## 1. Introduction

Fast reactors play a major role in the sustained growth of nuclear power in India. The development of this technology is being carried out at the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. At IGCAR, a 40 MWt Fast Breeder Test Reactor (FBTR) (Srinivasan et al., 2006) was constructed in 1985 by using mixed plutonium uranium carbide fuel. FBTR Mark-I fuel has achieved a burnup of 154 GWd/t without any clad failure. Based on its operation experience and the R&D activities of more than three decades on fast reactors, construction of a mixed oxide, pool type 500 MWe Prototype Fast Breeder Reactor (PFBR) (Chetal et al., 2006) has started at Kalpakkam in 2003, which will be operational in the year 2012. There are also plans to construct 6 more reactors of the same capacity with improved economy and safety features by the year 2023.

To meet the growing demand for electricity in India, studies (Grover and Chandra, 2006) have shown that the share of nuclear power has to be increased from the current 3% to 20% by the year 2050. It is possible through the introduction of 1000 MWe metal FBRs with higher breeding ratio beyond 2025. Several R&D programs have been initiated at IGCAR for establishing the technology of closed metal fuel cycle with emphasis on fuel fabrication and reprocessing. Irradiation of metallic fuel pins (Clement Ravichandar, 2008) and testing of metal fuel sub-assemblies are planned in FBTR. It is to be noted that due to smaller core height of FBTR, these test results are not directly applicable to the design of a commercial power reactor, which has a core height of about 100 cm. It is therefore planned to construct an experimental reactor with metallic fuel core for testing the power reactor metal fuel sub-assemblies (Chetal, 2009).

Metal fuels were chosen as the driver fuel in the early experimental reactors, viz. EBR-I, EBR-II, Fermi-1, Dounreay Fast Reactor (DFR), but in late 1960s worldwide interest turned towards ceramic fuels before its full potential could be achieved. The main reason for departing from metallic fuels was burnup limitation in the initial designs (International Atomic Energy Agency, 2003). There is a global lack of expertise with metal fuels and the limited data available today is based on the experiments carried out in EBR-II and FFTF reactors (Hofman et al., 1997). The irradiation tests in EBR-II reactor have demonstrated that accommodation of radial swelling and fission gas release from the fuel into the plenum enables high burnup in metallic fuels. To allow for swelling, the smeared density is reduced to 75%. The major concern of metallic fuels is its poor chemical compatibility with the steel cladding because of eutectic formation at the operating temperature. To prevent fuel-clad chemical interaction (FCCI), Zr is added in the fuel that inhibits the inter-diffusion of fuel and clad constituents by forming a diffusion

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barrier at the fuel-clad interface. It also helps to increase the solidus temperature of the fuel (Pahl et al., 1990). Addition of Zr increases the melting point of the fuel alloy and improves its dimensional stability during irradiation. Large amount of data has been generated with 10 wt% Zr in the U–Pu–Zr alloy. From the neutronics point of view, less content of Zr is preferred due to its parasitic neutron capture, which reduces the breeding gain of the fuel. Based on the limited but satisfactory experience, 6% Zr in the fuel is preferred in the Indian nuclear power programme with the objective of higher breeding ratio.

Metal fuels have some superior properties compared to other fuel types. They have high density, higher thermal conductivity and higher coefficient of linear expansion inducing very significant safety benefits. The burnup swing in a metal core is less due to higher in-core breeding. But it has reduced Doppler constant relative to oxide cores due to lower fuel temperature change from shutdown to full power. It has been reported (Dubberley et al., 2000) that with high internal breeding ratio, it is possible to achieve near zero burnup swing in a cycle with metal reactors. These facts favor reduced absorber rod worth for the shutdown system. Major disadvantage of metal fuel is the higher sodium void coefficient compared to oxide fuels (Yokoyama et al., 2005; Riyas and Mohanakrishnan, 2008). However, the inherent passive safety potential of metal reactors is superior to other types of reactors which have been demonstrated in several tests carried out in EBR-II. The important tests included loss of flow (LOF) and loss of heat sink tests including a LOF test from 100% power without scram (Chang, 2007). In addition, tests carried out in EBR-II and FFTF under Integral Fast Reactor (IFR) programme (Walters et al., 1984; Hofman, 1980; Chang, 1989; Crawford et al., 2007) have shown that metal fuel is a viable fast reactor fuel to achieve high burnup of about 200 GWd/t. However, there is some perception that the excellent irradiation performance of EBR-II fuel pin is due to its smaller size (4.4 mm diameter and 34.3 cm length) (Carmack et al., 2009; Hofman et al., 1997). But, many long fuel pins (360 cm) have been irradiated in FFTF and achieved burnup more than 10 at% without any breach (Walters et al., 1984). As the interest in fast reactors declined in the 80s, R&D programs stagnated and no commercial size metal-fuelled reactor is constructed.

The objective of the present study is to design an experimental metal FBR core for full-scale testing of a 1000 MWe metal FBR. Full-size fuel sub-assembly with 100 cm fuel column is used. This test reactor is to be planned to have a co-located fuel reprocessing plant. The aim of this study is to find out the minimum power for the test facility to meet the requirements of safety as well as full-scale demonstration. In addition, fuel sustainability is also a consideration in the design. The design of fuel sub-assemblies for this test facility is made with two types of metallic fuel pins, viz. a sodium-bonded ternary fuel pin of U–22% Pu–6% Zr alloy and a mechanically bonded pin of U–Pu alloy with 125 μm Zr liner on the inner clad (Clement Ravichandar et al., 2007). The Zr liner provided for the binary fuel prevents the fuel-clad chemical interaction (FCCI). The isotopic compositions (in atom percent) of $^{239}$Pu, $^{240}$Pu, $^{241}$Pu and $^{242}$Pu in the fuel are 68.79, 24.6, 5.26 and 1.35 respectively. The reactor power is first optimized with minimum fuel mass. The core parameters correspond to a typical commercial power reactor. Fuel cycle sustainability is judged based on breeding ratio rather than on full-scale burnup studies. Controllability of the core with two shutdown systems is also investigated. Kinetics parameters affecting the reactor safety are also computed. The neutronics calculations have been carried out with the latest European fast reactor core simulation code system called ERANOS 2.1 (Gérald Rimpault et al., 2002; Ruggieri et al., 2006). JEFF-3.1 based cross section library is used for most of the neutronics calculations. The ABBN-93 system (Manturov, 1997; Devan, 1999) is used for estimating the temperature and power coefficients.

**Table 1**
Design parameters of a fuel and blanket sub-assembly.

| Parameters | Fuel | Blanket |
|---|---|---|
| Fuel pin diameter (mm) | 6.6 | 14.33 |
| Fuel column length (mm) | 1000 | 1600 |
| Clad thickness (mm) | 0.45 | 0.60 |
| Sub-assembly pitch (mm) | 135 | 135 |
| Pins per sub-assembly | 217 | 61 |
| Spacer wire diameter (mm) | 1.65 | 1.2 |
| Hexcan width across flats/thickness (mm) | 131.3/3.2 | 131.3/3.2 |

Section 2 discusses about the physics optimization studies carried out towards the design of an experimental metal fast reactor. In Section 2.1, the design criteria and the various constraints imposed on the optimization studies are discussed. A small description about the two designs of metallic fuel pins is given in Section 2.2. Section 2.3 briefly discusses about the nuclear data and the neutronics codes system used for the study. The method of FBR core simulation with ERANOS 2.1 system at IGCAR is also briefly outlined. Details of the optimized 4 metal FBR cores are given in Section 2.4. The core parameters are briefly discussed in Section 3. Finally, a design is recommended for the metal experimental reactor, which provides minimum fuel inventory, self-sustainability and controllability, for full-scale testing of a commercial FBR.

## 2. Physics design of metal fuelled fast reactor cores

### 2.1. Design criteria

The design of a fast reactor core involves the optimization of various core parameters, viz. plutonium enrichment, power, linear heat rating (LHR), burnup, cycle length, breeding ratio, absorber rod worth, sodium void coefficient etc. It is often difficult to achieve the optimum value for all the above parameters because they are, in general, inter-dependent. A series of neutronics calculations were performed in an iterative manner to arrive at an optimized core configuration.

The shutdown system contains two independent and diverse systems, namely CSR and DSR. The CSR system is used for reactor start up, control of reactor power, controlled shutdown and SCRAM of the reactor. The DSR system is not used for any reactivity control and is used only to SCRAM the reactor. The rods in DSR system are in fully raised position during reactor operation. The number of absorber rods and their location in the core are decided to provide the safe shutdown of the reactor during normal and accidental conditions, as required by the AERB (Atomic Energy Regulatory Board, 1990).

A lower limit of 23% plutonium is chosen with 6% Zr in the ternary fuel for this study. Fuel enrichment is adjusted to obtain peak LHR of 450 W/cm. The cycle length is fixed in the range of 300 effective full power days (efpd) such that burnup of 100–150 GWd/t is achieved. The excess reactivity of the core is adjusted to obtain the above cycle length. The shutdown capability of absorber rods during normal and all the postulated accidental conditions are also demonstrated.

### 2.2. Design data

The geometrical data of pin and SA are similar to that of PFBR (Table 1). The mechanically and sodium bonded metallic fuel pins used are given in Figs. 1 and 2. The first pin is mechanically bonded binary fuel having a Zr liner (125 μm) between fuel and the clad, whereas the second one is the sodium bonded ternary fuel. The fuel slug is put inside a modified 9Cr–1Mo steel (T91) clad of 6.6 mm outer diameter. The mechanically bonded pin uses fuel with 85% smeared density. It is expected that the fuel swelling can be accom-

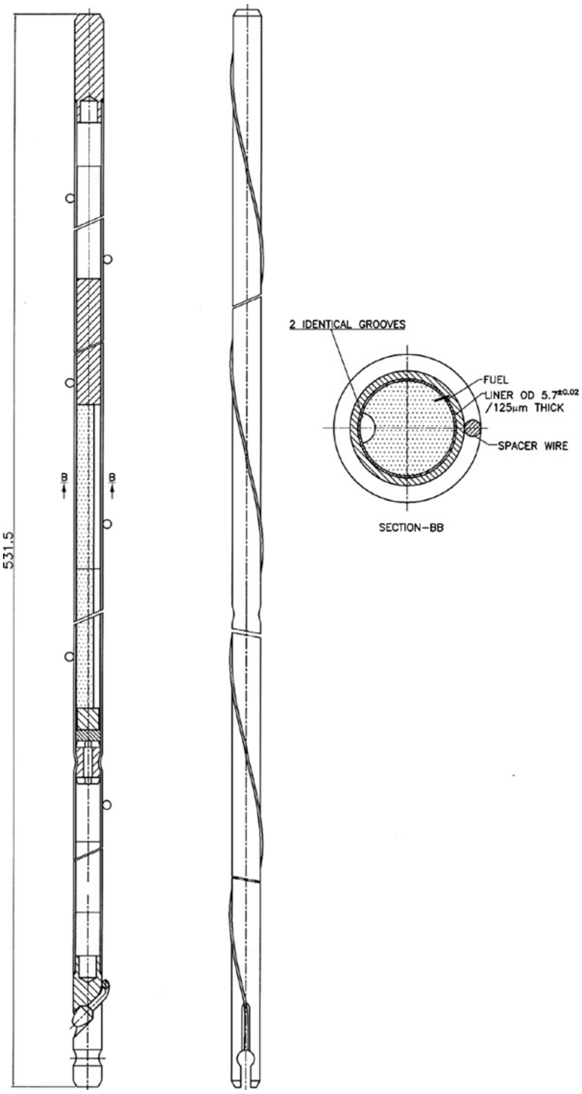


**Fig. 1.** Mechanically bonded metallic fuel pin design.

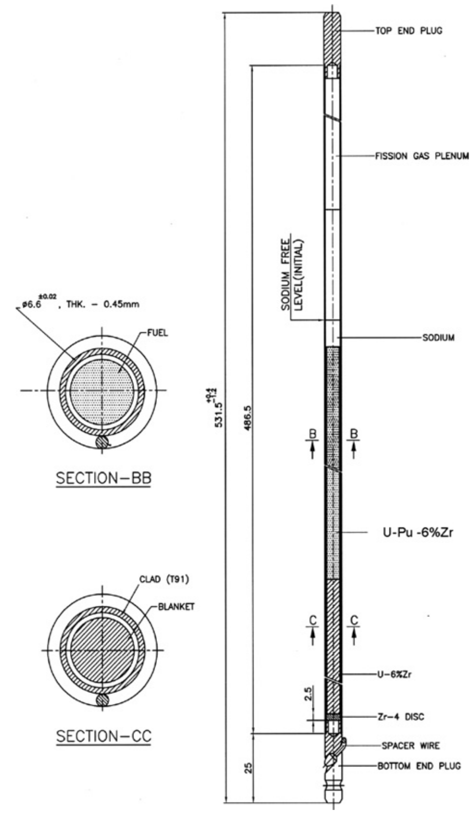


**Fig. 2.** Sodium bonded metallic fuel pin design.

modated with the help of two grooves provided in this design. Sodium bonded ternary fuel pins have a smeared density of 75%. The axial blankets have 80% smeared densities. Nickel reflector similar to that of FBTR is used. The fuel expansion coefficient used is $1.905 \times 10^{-5}$/K. The core inlet and outlet sodium temperatures are 370 and 510 °C respectively. Clad mid wall mean temperature is limited to 650 °C during normal operation. The core height is 100 cm with 30 cm axial blanket at the core top and bottom. The average fuel temperature considered is 750 °C, whereas it is 440 °C for both coolant and structural materials. Fuel centre line temperature is about 850 °C.

### 2.3. Method of calculations

The European Reactor ANalysis Optimized calculation System called ERANOS is used for most of the calculations (Fig. 3). The latest version of this system, ERANOS 2.1, contains cross section libraries based on JEF-2.2, JEFF-3.1 and ENDF/B-VI. It also contains various procedures for the reference and design calculations of Liquid Metal Fast Reactor cores, with extended capabilities for Generation-IV type advanced fast reactors, Accelerator Driven Systems and Gas Cooled Fast Reactors. The cross section libraries were available in different energy group structures for various applications. For fast reactor applications, 33-group library is provided for all the important nuclides. A fine group library in 1968 group structure is also available for 37 nuclides of interest to fast reactors. There are libraries in 172 and 175 energy group structures for thermal spectrum and shielding applications. Fig. 2 gives the flowchart of calculations with ERANOS 2.1 system at IGCAR. The ECCOLIB library based on JEFF3.1 is used for the core calculations. The cell code ECCO (Gérald Rimpault, 2005) is used to prepare the homogenized cross sections. It uses the subgroup method to account the resonance self-shielding effects. The preparation of cross sections for the absorber rod requires a special treatment due to very high coupling of heterogeneous absorber rod to the surrounding core cells. The method used is called the reactivity equivalence method, developed by Rowlands and Eaton in 1978. Based on this method, there is a special procedure available in ERANOS 2.1 to homogenize the absorber rod cross sections which uses 2-D $S_n$ transport theory code BISTRO (Palmiotti et al., 1987) and its associated perturbation modules. Three dimensional diffusion theory calculations are done for estimating the core physics parameters. To estimate the temperature and power coefficients, PREDIS (Harish et al., 1999) code is used.

### 2.4. Optimized metal cores

Based on a series of core optimization studies, 4 small FBR cores were finalized (Figs. 4–7). More details of these cores are given in Table 2. The important core characteristics are given below:

(a) FBR-1: It has 2 enrichment zones. Fuel sub-assemblies contain mechanically bonded pins of U–Pu alloy with a Zr liner. There is no radial blanket.
(b) FBR-2: It has single enrichment core without a radial blanket. It uses mechanically bonded pins of U–Pu alloy with a Zr liner.

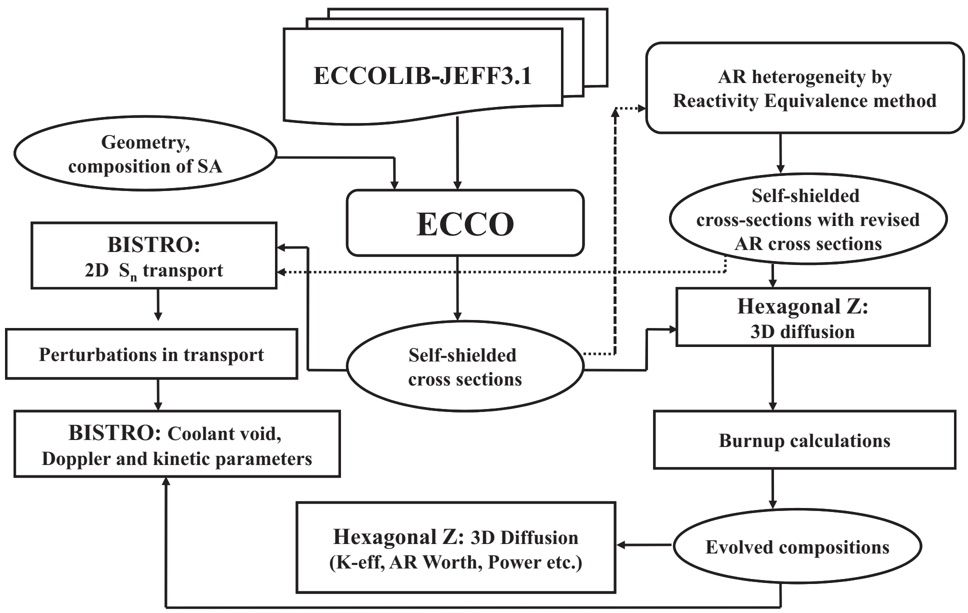


**Fig. 3.** Flowchart of FBR core calculations with ERANOS 2.1 system.

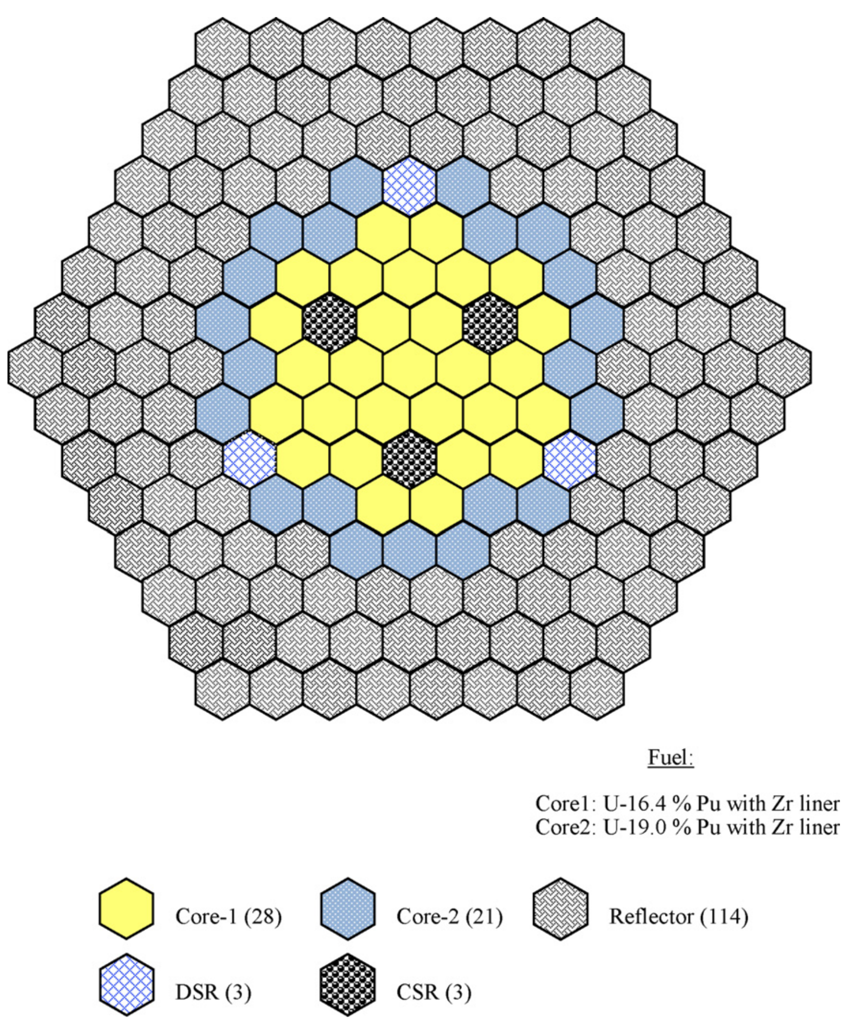


**Fig. 4.** Core configuration of a 300 MWt metal fuelled fast reactor (FBR-1).

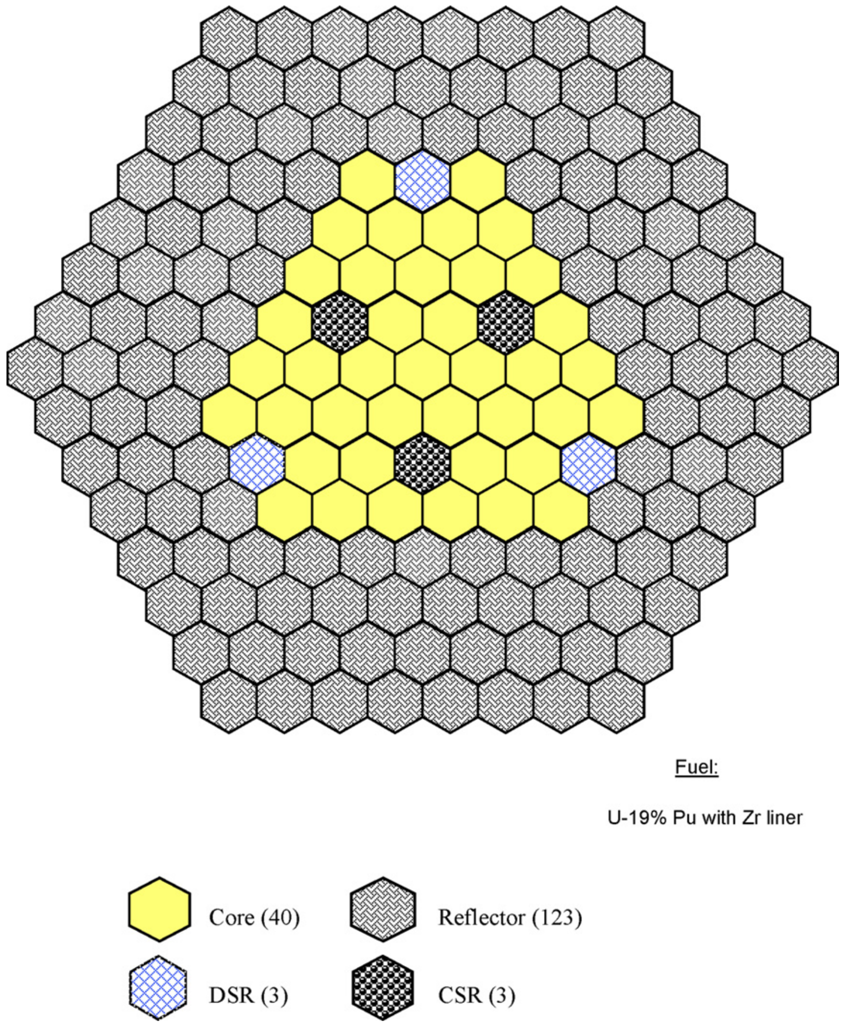


**Fig. 5.** Core configuration of a 220 MWt metal fuelled fast reactor (FBR-2).

(c) FBR-3: It uses sodium bonded fuel pins of U–Pu–6% Zr alloy. The core has single enrichment zone without a radial blanket.
(d) FBR-4: It has a single enrichment with fuel sub-assemblies containing sodium bonded ternary (U–Pu–6% Zr) fuel pins. A radial blanket of U–6% Zr alloy (sodium bonded) is provided to achieve the breeding ratio greater than unity.

## 3. Discussion on core parameters

Fuel enrichment, defined as the fraction of Pu in the mixed fuel (Pu–U), has to ensure a critical core during the entire cycle of operation. It is optimized to obtain the maximum LHR of 450 W/cm even for small cores. The end-of-life core is required to have minimum

**Table 2**
Core specifications of 4 metal fuelled fast reactors.

| Parameters | FBR-1 | FBR-2 | FBR-3 | FBR-4 |
|---|---|---|---|---|
| Power (MWt) | 300 | 220 | 220 | 320 |
| Fuel | U–Pu alloy with Zr liner | U–Pu alloy with Zr liner | U–Pu–6% Zr alloy | U–Pu–6% Zr alloy |
| Fuel density (g/cm$^3$) at 20 °C | 19.05 | 19.05 | 17.1 | 17.1 |
| No. of core zones | 2 | 1 | 1 | 1 |
| Pu enrichment (%) | 16.4/19 | 19 | 23 | 22 |
| Volume fraction (%) | | | | |
| Fuel: fuel/steel/Na/Zr | 32.07/23.9/41.02/3.01 | 32.07/23.9/41.02/3.01 | 35.08/23.9/49.02/0.0[a] | 35.08/23.9/49.02/0.0[a] |
| RB: fuel/steel/Na | – | – | – | 52.33/19.47/38.2 |
| AR: $B_4C$/steel/Na | 28.7/19.0/52.3 | 28.7/19.0/52.3 | 28.7/19.0/52.3 | 28.7/19.0/52.3 |
| Cycle length (days) | 300 | 360 | 300 | 330 |
| No. of batches | 3 | 3 | 3 | 3 |
| No. of CSR/DSR | 3/3 | 3/3 | 3/3 | 4/3 |
| $B_4C$ enrichment (%) | | | | |
| CSR/DSR | 65/65 | 90/65 | 90/65 | 40/20 |

[a] Fuel contains 6 wt% of Zr.

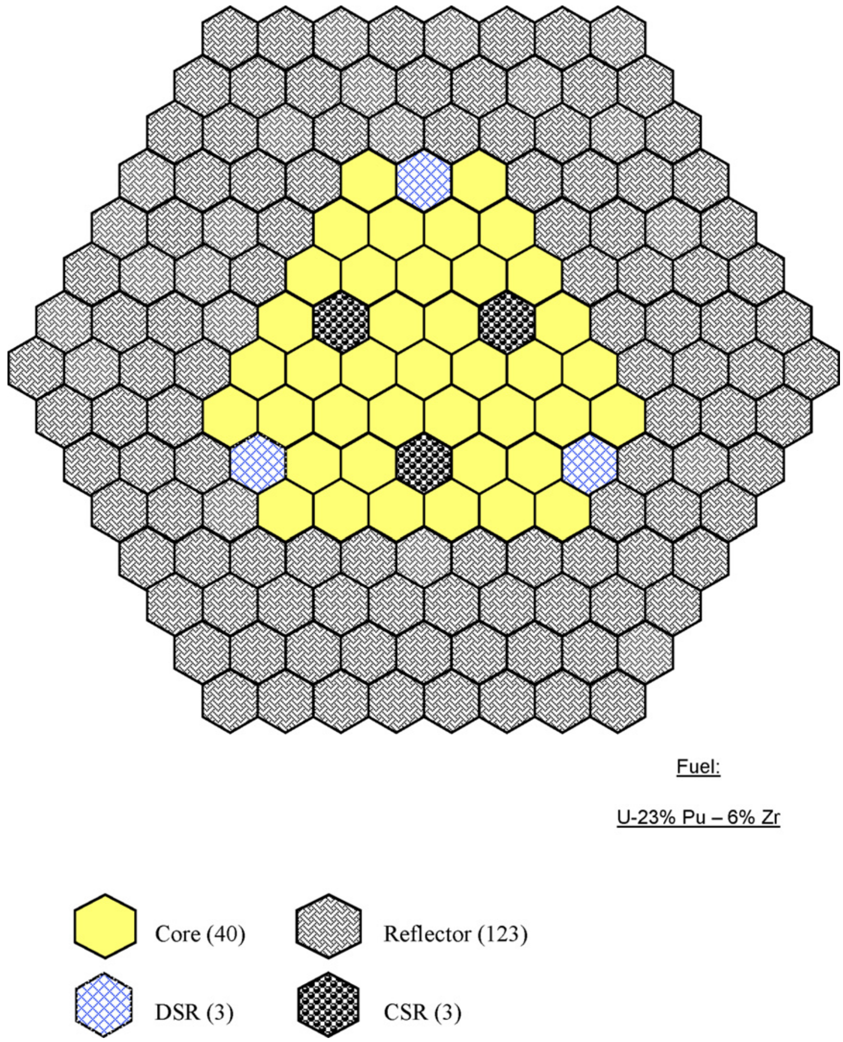


**Fig. 6.** Core configuration of a 220 MWt metal fuelled fast reactor (FBR-3).

reactivity margin of few hundreds of pcm. Maximum enrichment is 23% for FBR-4, and the minimum value is 16.4% for FBR-1.

The excess reactivity of the core is computed by taking into account the reactivity loses during reactor operation. During reactor startup, there will be loss of reactivity due to temperature and power rise. There is also reactivity loss due to core burnup. These effects are taken care of by the withdrawal of absorber rods. In addition, the core is required to have some more extra margin of reactivity. It is because the complete movement of CSR at the core top is not allowed in the design and this margin is fixed as 400 pcm. The average reactivity loss due to burnup from BOL to EOEC is taken as twice that of BOL core for one cycle operation. With 10% calculation uncertainty on reactivity loss due to burnup, the required value of multiplication factor at the hot state is given in Table 3. The calculated values of multiplication factors for these optimized cores are also given in Table 3.

The absorber rods in CSR and DSR systems are designed such that they provide a shut down margin (SDM) of at least 10 $ when all rods are available during SCRAM as stipulated by AERB. In accidental situations when some of the rods are not available, the SDM provided by the AR is less than 10 $. It is to be ensured that the reactor can be brought down to cold shutdown state with more than 1 $ sub-criticality margin for the double failure event of non-availability of CSR system when one DSR got stuck while lowering. The absorber rod material in FBR-1 is the 65% enriched $B_4C$ for both CSR and DSR. The enrichments of $B_4C$ in CSR and DSR are respectively 90% and 65% in FBR-2 and 3. For FBR-4, CSR uses $B_4C$ with 40% enrichment, whereas natural $B_4C$ is used in DSR. The absorber rod

**Table 3**
*K*-eff's at the operating condition for BOL core (all rods up).

| Core type | Burnup loss of reactivity per cycle (pcm) | Margin (pcm) | Required | | Calculated *K*-eff[a] |
|---|---|---|---|---|---|
| | | | Excess reactivity (pcm) | *K*-eff | |
| FBR-1 | 3509 | 400 | 7418 | 1.08012 | 1.07466 |
| FBR-2 | 4550 | 400 | 9500 | 1.10499 | 1.10126 |
| FBR-3 | 4886 | 400 | 10,172 | 1.11324 | 1.11577 |
| FBR-4 | 3850 | 400 | 8100 | 1.08814 | 1.09231 |

[a] Neutron transport corrections on *k*-eff accounted.

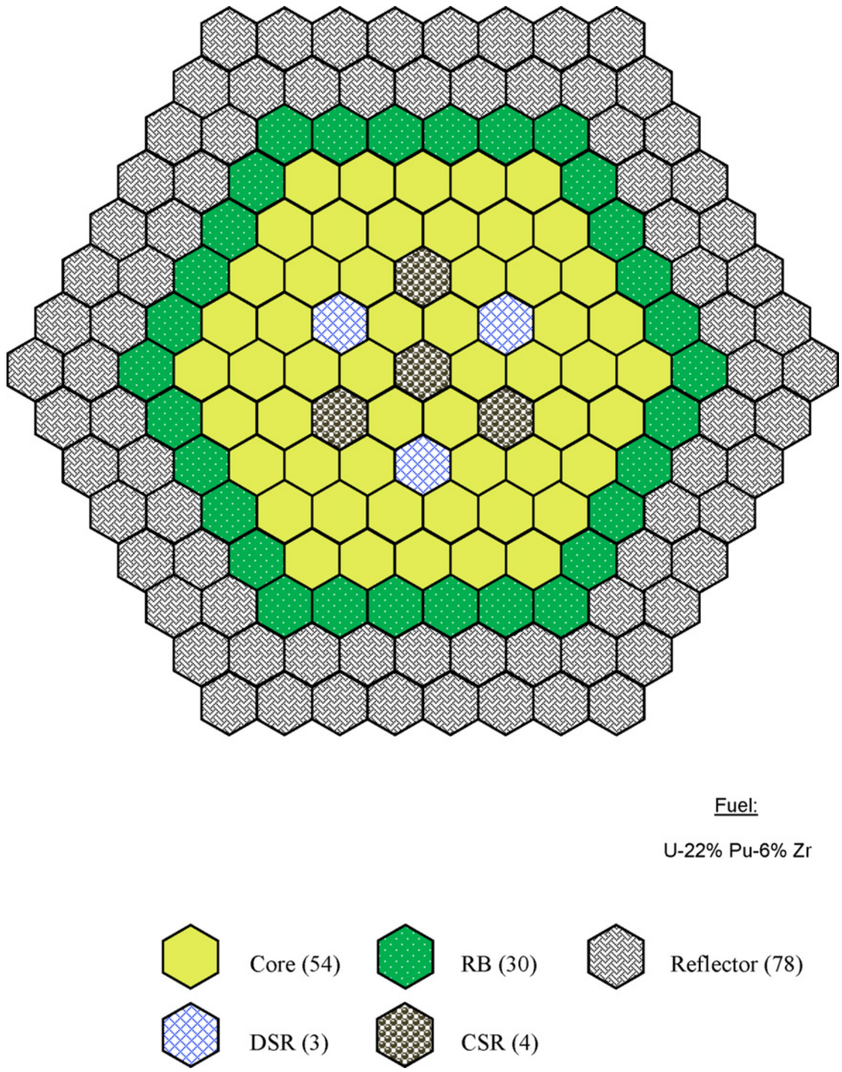


**Fig. 7.** Core configuration of a 320 MWt metal fuelled fast reactor (FBR-4).

worth for the various core states are given in Table 4. Even though, the BOL core has more excess reactivity compared to BOEC core, the absorber rods are designed only to handle the excess reactivity corresponding to that BOEC core. By using diluent sub-assemblies in BOL core, the requirement of additional worth for shutdown system can be controlled.

Table 5 gives some of the important safety parameters, viz. $\beta_{\mathrm{eff}}$, temperature and power coefficients and sodium void worth. It is seen that except for FBR-1, all cores have net negative sodium void worth. The breakdown of contributions from core and blanket region shows that there is significant negative contribution from voided axial and radial blankets, whereas all cores except FBR-3 have net positive sodium void coefficient from the fissile zone alone. The sodium void coefficient is estimated based on 2-D neutron diffusion theory calculations.

To estimate the SDM, it is necessary to consider the various components of reactivities listed in Table 6. The change of reactivity corresponds to the gain of reactivity while reducing the core temperature from 400 °C to 200 °C at zero power. Similarly, there is a gain of reactivity on reducing the reactor power from maximum to zero power. The calculation uncertainties assumed for temperature and power coefficients are 20%, whereas it is 10% for burnup reactivity loss. AR worth is reduced to account for the computational uncertainties of 15%. All these uncertainties have been included in the calculations such that SDM estimated is the minimum. The minimum cold SDM for different core states are given in Table 7. Results

**Table 4**
Absorber rod worth.

| Absorber rods | Worth (pcm) | | | |
|---|---|---|---|---|
| | FBR-1 | FBR-2 | FBR-3 | FBR-4 |
| All CSR and DSR | 14,668 | 16,313 | 17,502 | 16,692 |
| All CSR | 10,916 | 12,466 | 13,565 | 10,296 |
| All DSR | 3060 | 2801 | 3131 | 8164 |
| All CSR with one rod out | 6593 | 7788 | 8275 | 7508 |
| All DSR with one rod out | 1943 | 1786 | 1993 | 5070 |

**Table 5**
Important safety parameters.

| Core type | $\beta_{eff}$ (pcm) | Temp. coefficient (pcm/°C) | Power coefficient (pcm/MWt) | Sodium void worth (pcm) |
|---|---|---|---|---|
| FBR-1 | 366 | −2.07 | −1.47 | 422 |
| FBR-2 | 380 | −2.16 | −1.84 | −15 |
| FBR-3 | 345 | −2.36 | −1.92 | −485 |
| FBR-4 | 353 | −2.46 | −1.38 | −300 |

**Table 6**
Breakdown of core reactivity for SDM calculations.

| FBR type | Reactivity (pcm)[a] due to change in | | Burnup loss per cycle (pcm)[b] | Reactivity margin (pcm) | Total (pcm) |
|---|---|---|---|---|---|
| | Temperature | Power | | | |
| FBR-1 | 497 | 529 | 3509 | 400 | 4935 |
| FBR-2 | 518 | 486 | 4551 | 400 | 5955 |
| FBR-3 | 566 | 507 | 4886 | 400 | 6359 |
| FBR-4 | 590 | 530 | 3850 | 400 | 5370 |

[a] 20% uncertainty added.
[b] 10% uncertainty added.

**Table 7**
Minimum SDM for different core states at BOL.

| State of the core and availability of AR | SDM at 200 °C (pcm) | | | |
|---|---|---|---|---|
| | FBR-1 | FBR-2 | FBR-3 | FBR-4 |
| All AR | 7532 | 7911 | 8517 | 7805 |
| All CSR | 4343 | 4641 | 5171 | 3381 |
| All DSR | 1575 | 1376 | 1588 | 2905 |
| CSR system with one stuck rod | 669 | 665 | 675 | 1011 |
| DSR system with one stuck rod | 625 | 514 | 621 | 1598 |

showed that both the shutdown systems for all the 4 fast reactor cores are capable of providing safe shutdown during normal and accidental condition.

With respect to breeding ratio (BR), these cores were not optimized. The in-core breeding will be low due to lesser amount of fuel in the core. FBR-4 is found to be a breeder. The conversion/breeding ratios at the end of cycle for the fresh cores are given in Table 8.

The SA-wise power and burnup were estimated for all the cores. It is found that peak LHR achieved in all these 4 cores were close to 450 W/cm. Peak discharge burnup after 3 cycles of operation in

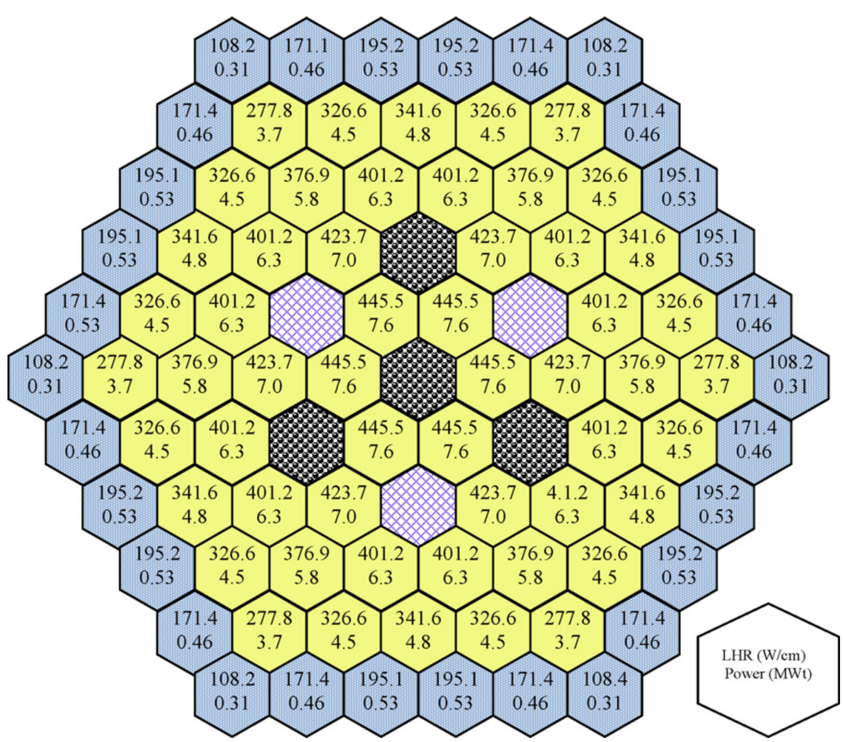


**Fig. 8.** SA power and peak LHR for BOL core of FBR-4 (all rods up): 320 MWt.

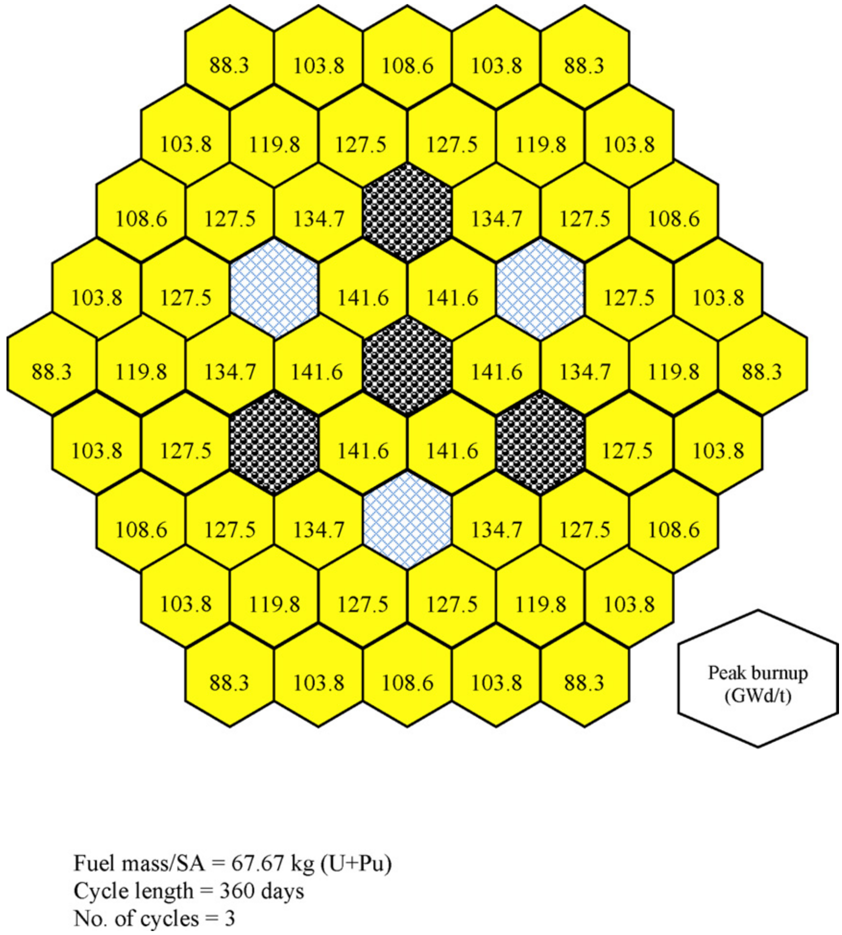


**Fig. 9.** Peak burnup in core SAs after three cycles for FBR-4 (all rods up): 320 MWt.

**Table 8**
Breeding ratio for EOL core.

| Reactor type | BR |
|---|---|
| FBR-1 | 0.870 |
| FBR-2 | 0.748 |
| FBR-3 | 0.638 |
| FBR-4 | 1.076 |

FBR-1, 2, 3 and 4 are 116, 129, 127 and 142 GWd/t respectively. Small adjustment in the burnup is possible by extending or reducing the cycle length. The power and burnup distributions for FBR-4 are given in Figs. 8 and 9 respectively.

## 4. Summary and conclusions

To meet the growing energy demand in India, the rapid growth of fast reactors with high breeding gain is proposed by the Department of Atomic Energy and they have drawn up a road map to achieve this task through the deployment of metallic fuel reactors of 1000 MWe beyond the year 2025. A comprehensive program has been started in India for mastering the various technologies of metal fast breeder reactors with closed fuel cycle. It includes fuel fabrication (sodium and mechanically bonded), full-scale irradiation of fuel sub-assemblies under operating conditions of a power reactor and reprocessing based on electro-refining method. Construction of a small experimental fast breeder facility is envisaged to provide the necessary inputs to the above program. The physics design studies were made with two types of fuel pins, viz., sodium-bonded U–Pu–6% Zr alloy and a mechanically bonded U–Pu alloy with 125 μm Zr liner.

Most of the neutronics calculations have been carried out with the European code system called ERANOS 2.1. The 33-group 3-D diffusion theory calculations using JEFF-3.1 cross sections are done for estimating the core parameters. The ECCO code is used to perform the self-shielding calculations by sub-group method. Absorber rod heterogeneity is accounted based on reactivity equivalence method. ABBN-93 system, coupled with the PREDIS code, is used to estimate the temperature and power coefficients.

Neutronics calculations have been performed in an iterative manner and 4 fast reactor cores (FBR-1, 2, 3 and 4) are optimized. The design constraints imposed are: reduced mass for plutonium, peak LHR of 450 W/cm, peak burnup of 100–150 GWd/t and full-size fuel sub-assembly with 100 cm fuel column. Two shutdown systems capable of providing safe shutdown during normal and one-stuck rod condition have been designed. It is found that the FBR-4 is the only breeder reactor whereas as the other three cores are converters. Minimum power achievable is found to be 220 MWt in converters with full-scale fuel SA. The cores of FBR-2 and 3 can be considered for the experimental facility, if minimum power and fuel inventory are the consideration, one with Zr liner and the latter with 6% Zr in the fuel. However, by considering the fuel sustainability, a 320 MWt breeder core (FBR-4) is designed for the test facility.

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