Relationship between Core Size, Coolant Choice, Fuel Type, and Neutron Flux in a Fast Irradiation Test Reactor

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Abstract

Currently, the United States has no domestic capability for large volume irradiation testing in a fast-spectrum system to support the development of advanced fuels or materials. The recently-proposed Global Nuclear Energy Partnership includes provisions for a sodium-cooled Advanced Burner Test Reactor which could provide this testing capability. In addition to sodium, lead-bismuth eutectic and helium coolants are being considered for future energy systems. In this paper, sodium, lead-bismuth eutectic, and helium-cooled systems are evaluated to determine the impact on fast flux and fuel enrichment resulting from varying core diameter, fuel volume fraction, fuel type, and coolant. While fast flux is most strongly influenced by core diameter at fixed power, fuel enrichment is a more complicated function of all four parameters. In the end, the combination of high fast flux and low enrichment can best be achieved by a sodium-cooled system.

KEYWORDS: fast test reactor, irradiation, sodium, lead-bismuth, LBE, helium

1.0 Introduction

An element of the recently-proposed Global Nuclear Energy Partnership (GNEP) is the efficient and effective management of nuclear waste by consuming actinide elements in an Advanced Burner Reactor (ABR). In a two-phase approach, the Advanced Burner Test Reactor (ABTR) would first prove the concept of effectively burning actinides and additionally support the development and qualification of fuels and materials for the ABR. In addition to GNEP, ten nations have agreed on a framework for international cooperation in research for an advanced generation of nuclear energy systems, known as Generation IV. These ten nations have joined together to form the Generation IV International Forum (GIF) to develop future-generation nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide competitively priced and reliable energy while addressing nuclear safety, nuclear waste, proliferation of nuclear materials, and public concerns and perceptions on nuclear power. Sodium, lead or lead-bismuth, and helium-cooled fast reactors are prominent reactor types under consideration as Generation IV nuclear energy systems. These reactor types offer high fuel utilization and the potential for effective actinide management. Despite the prospects of the ABTR, the United States currently has no capability for irradiation testing of large volumes of fuels or materials in a fast-spectrum system to support the domestic development of these fast reactor systems.

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A fast irradiation test reactor would be able to provide fuel and material irradiation testing in a fast neutron spectrum. In this paper, sodium, lead-bismuth eutectic (LBE) and helium-cooled systems are considered for their potential to provide a fast neutron flux over a substantial irradiation volume. Using a fixed core power of 100 MWth, a series of parametric core designs were evaluated to determine the impact on fast flux and fuel enrichment resulting from varying core diameter, fuel volume fraction, fuel type, and coolant. In summary, the average fast flux in a central experimental assembly position is most strongly influenced by core diameter (i.e. power density). With the exception of the LBE cases, the dependence of the fast neutron flux on other factors is relatively insignificant. As a result, the highest experimental fast flux will be obtained with the smallest, most compact, highest power density core, regardless of other factors. However, to accomplish this with a reasonably-low fissile enrichment, a low leakage core with a high fuel volume fraction and low coolant volume fraction is needed.

2.0 Methodology

Neutronics and fuel cycle analyses were carried out using the DIF3D/REBUS3 fuel cycle analysis code.[1,2] A fixed, equilibrium fuel cycle based on a three-batch core with six month refueling intervals was imposed on all core designs considered. Room temperature assembly dimensions are listed in Table 1 for each of the three fast reactor coolant options. For modeling purposes, all active-core material compositions and dimensions were evaluated at a core-average temperature of 425°C. Flux calculations were carried out using the hexagonal-z nodal diffusion theory option of DIF3D. The fresh fuel charge enrichment was determined so that the reactor had an end-of-equilibrium-cycle (EOEC) eigenvalue of 1.0. The axial height of each active core was fixed at 100 cm. Experimental fast flux was averaged over the active height of one or more empty, central assemblies. The composition of the experimental assemblies consists of the assembly duct and coolant only.

A total of 28 configurations were evaluated and are summarized in Table 2. Since the goal of this study is to identify the sensitivity of flux and enrichment to various design parameters, no assessment has been made as to the viability of the different configurations that were evaluated. For example, in the 91-pin LBE case (described below) the peak coolant velocity is expected to exceed a 2 m/s limit.[3] Overall, however, the cases presented here have relatively low power densities, and thermal limits should not be a concern.

Four different core diameters were used with the sodium-cooled options, and both U-10Zr and U-Pu-10Zr metallic fuel were used within a 91-pin assembly design. An additional case was evaluated by substituting the 61-pin assembly design defined for the LBE cases to evaluate the sensitivity to changes in the fuel volume fraction.

For the LBE-cooled option, three different core diameters were evaluated with U-10Zr fuel in the 61-pin assembly. (Issues of material compatibility are not addressed in this parametric study.) The smallest, seven-ring core was evaluated a second time by substituting the 91-pin assembly design developed for the sodium option to measure the effect of increasing the fuel volume fraction on the LBE cases.

Two different assembly designs, both based on the assembly design developed by Gulf General Atomics in the 1970s for the Gas-Cooled Fast Breeder Reactor,[4] were used to evaluate the helium-cooled options. The primary difference between the "standard" and "compact" cases is the reduced pin and lattice pitch used in the "compact" cases as listed in Table 1. Both designs were used with varying core diameters. For the standard design, both UO_2 and $(U,Pu)O_2$ fuel were used. For the compact design, only UO_2 fuel was used.

Table 1: Assembly Design Parameters for the Sodium, LBE, and Helium Options. The helium option includes "standard" and "compact" variants.

	Sodium	LBE	Helium
Pin Diameter (mm)	8.0	8.0	7.16
Clad Thickness (mm)	0.4	0.5	0.48
Pin Pitch (mm)	8.80	10.75	9.8/8.8
Pins per Assembly	91	61	271
Duct Flat-to-Flat (cm)	9.00	9.00	16.9/15.2
Assembly Lattice Pitch (cm)	9.20	9.20	17.5/15.5
Active Height (cm)	100	100	100
Volume Fractions			
Fuel (smeared)	0.50	0.32	0.31/0.39
Coolant	0.29	0.50	0.53/0.41
Structure	0.21	0.18	0.16/0.20

3.0 Results

In addition to the result presented in Table 2, the fast flux at EOEC, averaged over the central experimental volume is plotted in Figure 1 for all cases. Fissile enrichment requirements are plotted in Figure 2. The obvious trend is that one can achieve higher flux values for smaller (higher power density) cores. Similarly, smaller cores generally have higher fissile enrichment requirements, but the enrichment also depends strongly on fuel type, fuel volume fraction, and coolant.

When considering the uranium-fueled results alone (Figure 1, closed symbols) for sodium and helium, the average fast flux in the central experimental volume shows virtually no dependence on fuel type (metallic or oxide), coolant type (sodium or helium), or fuel volume fraction (standard or compact; 61-pin or 91-pin). Unlike the fast flux, the fissile enrichment depends strongly on fuel volume fraction and coolant.

For any given concept, the *total* flux will be directly proportional to the power density, and inversely proportional to the macroscopic fission cross section, which is related to the fissile inventory. Since the power level and core height have been fixed at 100 MWth and 100 cm in all cases, power density will increase with decreasing core diameter. For a given power density, then, the case with the lowest macroscopic fission cross section (lowest fissile inventory) will tend to have the highest flux. Assuming the flux spectra are similar, these trends will also apply to the *fast* flux. Sensitivities of the fast flux and enrichment to various design options are described in the following sections.

Table 2: Summary of Fissile Enrichment and Fast Flux as a Function of Core Size, Coolant Choice, Fuel Type, and Fuel Volume Fraction.

Coolant	Fuel Form	Fuel Volume Fraction [a]	Core Diameter [b] (cm)	Fissile Enrichment [c] (%)	Experimental Fast Flux [d] (10^{15} n/cm^2/s)
Sodium	U-10Zr	0.5055	89	23.9	1.09
			101	20.5	0.933
			119	17.8	0.737
			136	16.3	0.605
		0.3203	119	26.5	0.779
	U-Pu-10Zr	0.5055	89	16.2	1.25
			101	13.9	1.06
			119	12.1	0.828
LBE	U-10Zr	0.3203	119	23.9	1.03
			136	21.2	0.851
			154	19.5	0.719
		0.5055	119	16.8	0.884
Helium	UO_2	0.3080	136	39.1	0.639
			170	30.0	0.468
			192	26.5	0.389
			226	23.8	0.292
			259	22.1	0.227
			292	20.9	0.181
		0.3938	150	24.7	0.550
			170	21.9	0.454
			200	19.9	0.339
			229	18.6	0.262
	$(U,Pu)O_2$	0.3080	136	24.9	0.754
			170	19.7	0.545
			192	17.8	0.450
			226	16.3	0.336
			259	15.3	0.259
			292	14.6	0.205

a. Fuel volume fraction represents the smeared volume fraction in driver assemblies only.
b. Core diameter represents a circular area that is equivalent to the combined area occupied by driver assemblies in addition to experimental and control rod positions.
c. For plutonium-fueled cases, fissile enrichment includes contributions from Pu-239 and Pu-241.
d. Experimental fast flux is averaged over the active axial length of the central (group of) experimental position(s).

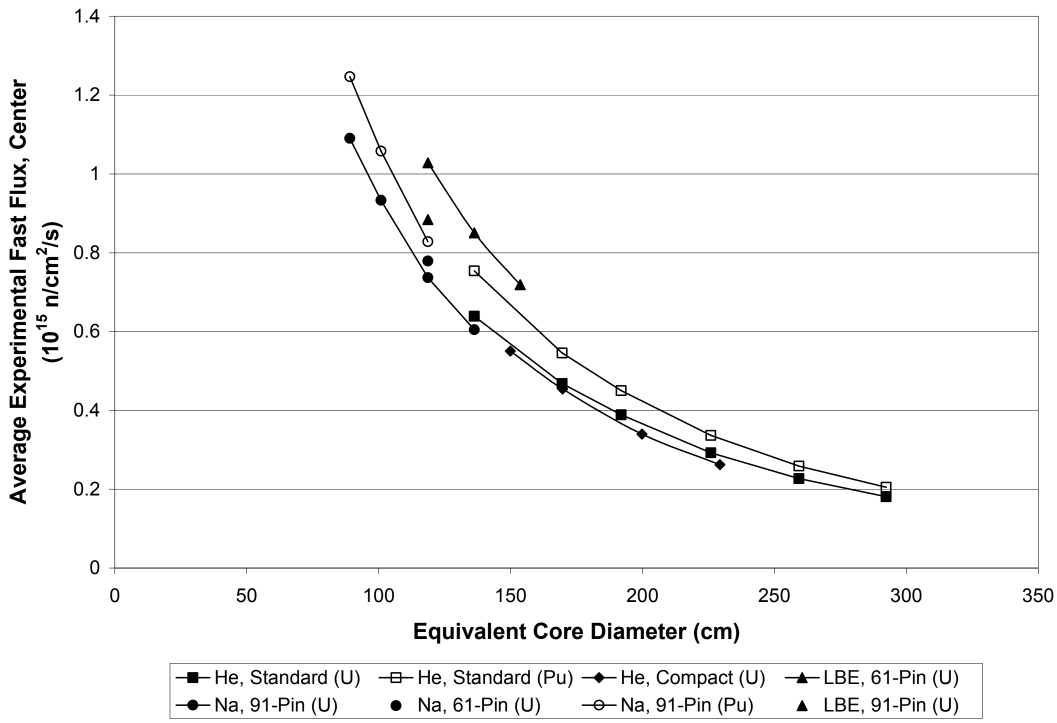

Figure 1: Average Fast Neutron Flux in the Central Experimental Position(s) as a Function of Core Diameter for Various Configuration Options.

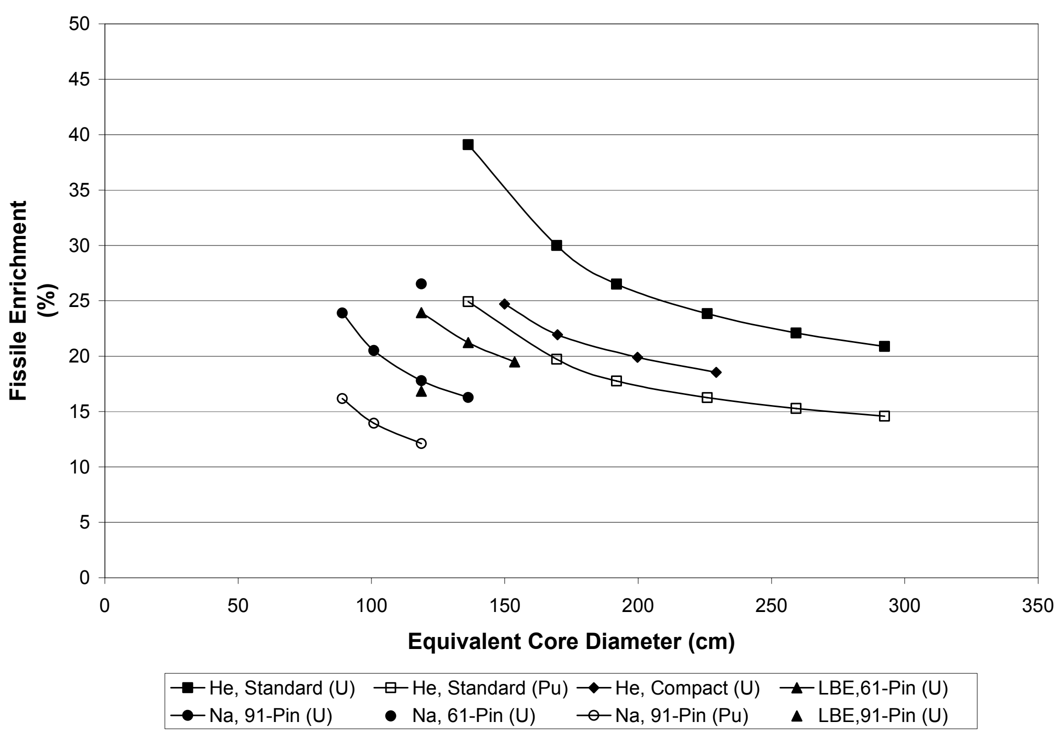

Figure 2: Fissile Enrichment Requirements as a Function of Core Diameter for Various Configuration Options.

3.1 Sensitivity to Fuel Volume Fraction (Sodium Coolant)

The two sodium cases with 119 cm diameters represent different fuel volume fractions through the use of two different assembly designs. Since the core layout is the same in both cases, the average core power density will be the same.

In changing from the 91-pin to the 61-pin assembly design, the U-235 enrichment requirement increased from 17.8% to 26.5% because the smeared fuel volume fraction decreased from 0.50 to 0.32. However, the net effect is that there is a reduction in the fissile inventory resulting in a reduced total fission cross section and an increase in the total (and fast) flux. The total fission cross section decreases by nearly 10%, but the fast flux plotted in Figure 1 shows an increase of just over 5%

The lower fuel volume fraction from the 61-pin assembly design results in higher leakage and lower capture rates. Increased leakage tends to shift the power distribution away from the center of the core. In the inner core region, the power density decreased by more than 4% for the 61-pin case. The higher coolant fraction also leads to a slightly softer spectrum. These effects reduce some of the benefit of the lower fission cross section. In the end, large changes in the fuel volume fraction have only a small effect on the fast flux for the sodium-cooled option.

3.2 Sensitivity to Fuel Volume Fraction (LBE Coolant)

As with the sodium cases, each of the 119 cm diameter LBE cases represent different fuel volume fractions. Again, the average core power density will be the same in both cases, however there is a significant difference in the average fast flux observed in the central experimental volume. The higher fast flux with the 61-pin assembly design is due to the reduction in the total fission cross section.

In going from a 91-pin to a 61-pin assembly design, the smeared fuel volume fraction drops from 0.50 to 0.32 and the U-235 enrichment increases from 16.8% to 23.9% to compensate. Ignoring any other effects, one would expect the fissile inventory to be conserved, but it actually decreases due to spatially-dependent changes in leakage and capture.

With a reduction in the fuel volume fraction, leakage increases while neutron capture decreases. When total core leakage and capture rates are combined, one observes no net change between the two assembly designs. However there is change in the spatial dependence that affects the enrichment. Net leakage and capture decrease in the inner regions of the core and increase near the core periphery when the fuel volume fraction is reduced. The reduction in the inner core is more important in its effect on fuel enrichment. With a net reduction of the neutron loss rates in the inner regions of the core, overall fissile inventory decreases to cause a 16.6% reduction in the total fission cross section.

Although the fission cross section has decreased by over 16%, the corresponding increase in the fast flux in the central experimental position is slightly lower at 14%. This difference is caused by a shift in the power distribution between the two cases. Because of increased leakage in the 61-pin design, there is a slight shift in the power distribution towards the outer core which causes a 2% reduction in the flux in the inner core.

When comparing the sodium and LBE cases, there is a larger reduction in the fissile inventory in the LBE case resulting in a larger increase in the fast flux. Furthermore, the effects that compete against this (primarily the shift in the power distribution) are smaller in the LBE case than in the sodium case. Of the three coolants evaluated, LBE exhibits the strongest response to fuel volume fraction for both flux and enrichment.

3.3 Sensitivity to Fuel Volume Fraction (Helium Coolant)

The five-ring standard and six-ring compact helium cases have nearly identical core diameters (~170 cm). If one were to simply preserve fissile inventory in going from the standard to the compact case, the enrichment would be expected to drop from 30% to 24% due to an increase in the smeared fuel volume fraction from 0.31 to 0.39. However, the compact case has significantly less leakage, a higher conversion ratio (0.40 compared to 0.25) and a slightly higher driver assembly volume fraction, so the actual enrichment requirement drops to 22%. This lower-than-expected enrichment would suggest a lower macroscopic fission cross section and higher flux. However, the compact case also has a considerably higher U-238 fission contribution which offsets this. Combined, the two cases have nearly identical macroscopic fission cross sections. (The difference is less than 1%.) As a result, the total flux for the two cases should be very similar.

However, the compact case has a fast flux that is ~3% lower than the standard case. This is simply because the power density is ~3% lower. Because the lattice spacing was reduced in the compact case, the experimental and control-rod positions occupy slightly less space in the compact case. Therefore, with the same core diameter, the compact case has a 3% higher driver assembly volume fraction. This accounts for the differences in the fast flux. From this, one can conclude that fuel volume fraction has a negligible effect on the fast flux for the helium-cooled option.

3.4 Sensitivity to Coolant (Sodium vs. Helium)

The core diameters for the four-ring helium and eight-ring sodium cases are the same. However, different assembly sizes results in a larger driver assembly volume fraction for the sodium case. This leads to a driver power density that is 11% lower in the sodium case. With the higher fuel volume fraction (0.50 vs. 0.31) and a much lower leakage rate, the sodium case has a significantly lower enrichment requirement. This results in a lower total fissile inventory, and the total fission cross section decreases by 10%. The combined effects of power density and fission cross section result in nearly identical *total* flux in both cases (within 2%). However, the average *fast* flux plotted in Figure 1 is from the central experimental volume only. Because these positions are flooded with coolant, two additional competing effects are present.

In the helium case, the low density of the coolant in the central experimental volume results in a harder spectrum compared to the sodium case. However, the leakage fraction in the helium case is also higher, which diminishes this benefit. In the end, the average fast flux in the experimental position is 5% higher in the helium case compared to the sodium case. If the sodium case were reevaluated with a voided (i.e. helium-filled) experimental assembly, the average fast flux would increase slightly as a result of the harder spectrum. More importantly, if the sodium case were evaluated at the same driver power density as the helium case, the fast flux in the sodium case would be approximately 5% higer than in the helium case. But in the end, regardless of significant differences in coolant, geometry, and fuel, the resulting fast flux is similar in the two cases.

3.5 Sensitivity to Coolant (LBE vs. Sodium)

When comparing LBE and sodium cases with identical geometries, the LBE cases result in slightly lower enrichment and higher average fast fluxes in the central experimental volume. This effect is directly related to the different neutronics properties of the two coolants. Although LBE is more parasitic than sodium, it also acts as a better reflector. This results in lower fissile inventory (enrichment) and a lower total fission cross section. Assuming the two cases have similar power densities, the LBE case will have a higher total (and fast) flux.

As stated earlier in this report, the cases evaluated for the parametric study have not been assessed as to their viability. In the case of the LBE option, there is a tradeoff between fuel enrichment and coolant velocity. Both are strongly dependent on fuel (and therefore coolant) volume fractions. Using the same assembly designs, more realistic, 250 MWth options for sodium and LBE were evaluated with the additional constraints that fissile uranium enrichment be at or below 20% and that the peak coolant velocity be at or below 2 m/s for LBE. The results for these two cases are summarized in Table 3.

As a result of the constraint on coolant velocity, the LBE option is larger, has a lower power density, higher enrichment, and higher heavy metal inventory in order to achieve a similar fast flux as the sodium option. The advantages that the LBE cases showed in Figures 1 and 2 in terms of fast flux and enrichment have been lost due to this constraint.

Table 3: Results for Sodium and LBE Coolant Options at 250 MWth.

	Sodium	LBE
Thermal Power (MW)	250	250
Coolant Velocity (m/s)	8.3	2.0
Average Experimental Fast Flux (10^{15} n/cm^2/s)	**1.83**	**1.79**
Number of Driver Assemblies	**135**	**237**
Pins per Assembly	91	61
Equivalent Core Diameter (cm)	**119**	**154**
Active Height (cm)	100	100
Fissile Enrichment (%)	**18.3**	**20.0**
Heavy Metal Inventory (kgHM)	**5138**	**5716**

3.6 Sensitivity to Fissile Isotope (U-235 vs. Pu-239)

To assess the impact of using plutonium instead of uranium as the fissile material, several sodium and helium-cooled cases were reevaluated using weapons plutonium as the external fissile feed stream in the fuel cycle model. The use of Pu-239 instead of U-235 results in some important changes.

The energy released per fission from Pu-239 is about 3% higher than for U-235. Therefore, for the same core power level, the fission rate will be about 3% lower. However, a more important effect is the eta (η) of Pu-239 compared to U-235. η represents the number of neutrons produced by fission per neutron absorbed in a fissile isotope. Although the value of η varies on a case-by-case basis, it typically has a value of 2.5 for Pu-239 and 2.0 for U-235. Because Pu-239 produces more excess neutrons, lower enrichments are possible, which results in a lower total fission cross section and higher overall flux.

For the very large helium cases, the fissile enrichment is fairly low, and a sizeable contribution to fission comes from U-238. As core size is reduced and the fissile plutonium enrichment increases, the contribution from U-238 decreases, and the benefit of the higher value for η increases. As seen in Figure 1, the fast flux from the plutonium cases increases faster than the uranium cases as the core diameter is decreased.

Because the uranium enrichment in the sodium cases is already significantly lower than in the helium cases, the additional reduction in fissile enrichment that is observed when switching to plutonium fuel is also smaller. As a result, the increase in the fast flux is not as large as in the helium cases, but it is significant nonetheless.

4.0 Conclusions

It is clear that in order to achieve a high fast flux, one must develop a core with a high power density, regardless of other factors such as coolant, fuel form, and fuel volume fraction. However, in order to limit fuel enrichment requirements, a high heavy metal loading is needed in a core with reduced leakage. High heavy metal loadings can best be achieved with metallic fuel and a high fuel volume fraction. Reducing core leakage can be achieved with a high fuel volume fraction and an effective reflector. Further increases in flux levels can be achieved by utilizing plutonium-based fuels, but this benefit can be obtained regardless of the option under consideration.

Because of their superior thermophysical properties, liquid metal coolants are an obvious choice for removing heat from a high power density core with a high fuel volume fraction and low coolant volume fraction. In the absence of any other considerations, LBE provides an advantage over sodium in that it is an effective reflector and reduces core leakage. This in turn reduces enrichment requirements and enhances the experimental flux. However, LBE is subject to flow velocity limitations, which leads to increased coolant volume fractions. As a result, one can expect sodium and LBE cases to be similar in their abilities to deliver a desired flux level, but the LBE case will likely have a larger core, higher enrichment, and higher heavy metal inventory.

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