Use of Beryllium Oxide to Shape Power and Reduce Void Reactivity in Gas Cooled Fast Reactors

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Abstract

Use of Beryllium Oxide (BeO) as a diluent is explored as a means for both power shaping and void reactivity reduction in fast reactors. A supercritical carbon dioxide (S-CO_2) cooled fast reactor fueled with Light Water Reactor Transuranics and directly coupled with a Brayton cycle power conversion system is used to investigate the effect of BeO as a diluent. Results show that relatively flat power profiles (peak $\leq$ 1.22) can be maintained throughout core life using a combination of enrichment and diluent zoning, due to the slight moderating effect of the BeO. Combining BeO diluent with the innovative strategy of using a thick volume of S-CO_2 coolant as the radial reflector yields negative void reactivities throughout core life. The ability to maintain negative coolant void reactivity comes from a combination of the effects of spectral softening due to the BeO diluent and the enhanced leakage upon voiding of the S-CO_2 radial reflector.

KEYWORDS: Gas cooled Fast Reactors (GFRs), Beryllium Oxide (BeO), void reactivity, power shaping

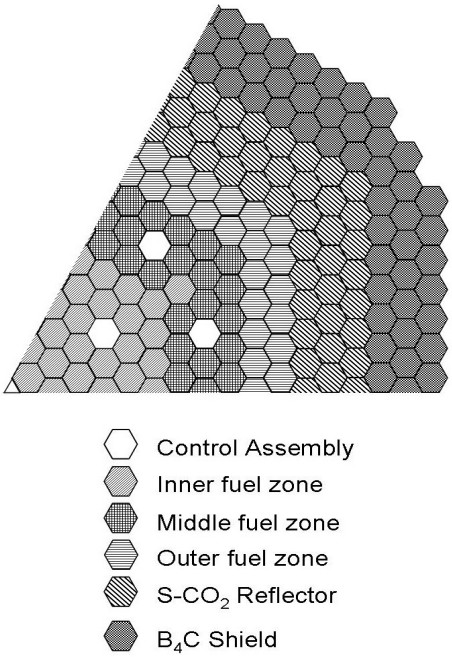
1. Introduction

Motivated by the goals of the Generation-IV International Forum (GIF), an investigation into the feasibility of designing a long-lived Gas-cooled Fast Reactor (GFR) core has been undertaken. Specifically, a GFR cooled by supercritical carbon dioxide (S-CO_2), fueled with Light Water Reactor spent fuel transuranics, and directly coupled with a Brayton cycle is under investigation as part of a Nuclear Energy Research Initiative grant.

Several parameters of the current reference reactor core, listed in Table 1, are of note. First, the long burnup attainable from a single-batch core is ideally suited for a battery-type core. The power shaping results presented later will also support use of this core for such an application. Second, the large burnup is favorable economically. While other factors play a significant part in the overall economic picture, e.g. specific power, a first order economic estimate shows that a large burnup from a single batch core is beneficial from an economic standpoint. Other interesting parameters, i.e. the high fuel volume fraction and the low turbine inlet temperature (coolant outlet temperature), will be discussed later in this paper.

Table 1: Reference GFR Core Design Parameters

1/6th Core Layout



Parameter	Value
Thermal Power	2400 MW_{th}
Specific Power	20.7 kW/kg_{HM}
Power Density	85.4 kW/L
Number of fuel batches	1
Reactivity Limited Burnup	130 MWD/kg 17.2 years
System Pressure	20 MPa
Core Inlet Temperature	485.5°C
Core Outlet Temperature	650°C
Active Core Height	1.54 m
Thermal/Net Efficiency	51/47 [1]
Effective Core Diameter	4.81 m
H/D (active core)	0.32
Fuel Assembly Description	Tube-in-Duct (TID) [2]
Assembly flat-to-flat distance (outer can)	22.7 cm
Coolant hole diameter	0.7 cm
Fuel, volume %	$(U\text{-}TRU)O_2$, 61
Cladding, volume %	ODS MA956, 14
Coolant, volume %	$S\text{-}CO_2$, 25
Reflector	$S\text{-}CO_2$ (radial) Ti (axial)
Shielding (radial and axial)	99 $^{w}/_{o}$ B_4C

While more traditional GFR strategies employ Helium as the coolant, this approach uses $S\text{-}CO_2$ for several reasons. The thermophysical properties of $S\text{-}CO_2$ as a coolant and power cycle working fluid allow for comparable performance to Helium at lower temperatures at the reactor outlet/turbine inlet, i.e. 650°C v. 850°C. This alleviates problems associated with core materials performance at elevated temperature and allows for the use of existing materials. As well, the thermophysical properties of $S\text{-}CO_2$ make it more attractive from a decay heat removal perspective, as a much lower containment pressure is necessary for the promotion of natural circulation than with Helium. [3] Further, much development has been done on the $S\text{-}CO_2$ Brayton Cycle which shows great promise as a Power Conversion System with predicted thermal efficiencies between 45-50%. [1] This provides economic benefits not only from the high thermal efficiency, but also from being able to use a direct cycle. The downside to using $S\text{-}CO_2$ is that it must be kept at a high pressure in order to ensure efficient operation, i.e. 20 MPa v. 8 MPa for Helium, which requires a more robust pressure boundary.

2. Challenges

Among the numerous challenges associated with designing such a fast reactor is devising a core with acceptable power peaking and void reactivity. Power peaking is more limiting in a GFR than in LWRs or liquid metal cooled reactors because of the small heat transfer coefficients achievable with gas coolants; hence, low power peaking is very desirable. While power shaping for thermal reactors can be achieved through conventional methods, i.e. burnable poisons, enrichment zoning, and fuel shuffling, achieving an acceptable power shape throughout core life presents a greater challenge in a fast reactor. With a harder neutron energy spectrum, fast reactors can not use burnable poisons effectively for power shaping, as neutron energies are typically above the range where neutrons are parasitically absorbed at rates comparable to heavy metals. While enrichment zoning is a viable beginning of life (BOL) option, the power shape varies significantly over core life with such a strategy, exceeding desired limits. Frequent fuel shuffling is another solution; however, this penalizes operations and economics.

Positive coolant void reactivity is a perennial concern in fast reactors which imposes a significant design challenge. Previous solutions to this problem have reduced the severity of this problem, but have not eliminated the need for active reactivity insertion mechanisms to compensate for this effect. The larger scope of this work is to design a passively safe GFR. In this paper, keeping coolant void reactivity negative without otherwise seriously compromising core performance will be explored as one means towards achieving this larger goal.

3. Solutions

The approach taken in this work is to blend a material, i.e. a "diluent," into the fuel. The diluent has the effect of both reducing the fuel concentration (minor effect) and softening the neutron energy spectrum (major effect). By varying the concentration of the diluent, it is possible to vary these two effects and hence, effectively shape power. Further, the softening of the neutron spectrum is enough to help reduce the effects of coolant void reactivity, but not so much as to make the reactor epithermal. Spectral softening also has the concurrent benefits of enhancing the negative Doppler reactivity coefficient and enhancing the worth of traditional reactivity control mechanisms, i.e. B_4C control rods. However, there exists a trade-off with respect to spectral softening in a fast reactor, as making Doppler reactivity too negative can have the negative consequence of inserting too much positive reactivity upon core cooldown following an Anticipated Transient Without SCRAM. Another key trade-off that exists with the use of diluent is the displacement of fuel, which when taken alone would have the effect of limiting the reactivity limited lifetime of a given core. However, the diluent will soften the neutron spectrum and push more neutrons into the resonance region, contributing to greater breeding which will counter the loss of fuel effect on reactivity limited burnup.

Central to enabling the success in shaping power and reducing void reactivity is the use of innovative Tube-in Duct (TID) fuel assemblies. [2] A TID fuel assembly is made up of a hexagonal outer can that has tubular coolant channels placed in a triangular lattice within the outer can, with "hex-nut" fuel pellets that fit around each of the coolant channels. Essentially, it is an "inside-out" version of a conventional fast reactor

triangular lattice pin-type assembly, where the fuel and the coolant switch places. The TID fuel assembly allows a higher fuel volume fraction than a comparable pin-type core with the same Pitch to Diameter (P/D) ratio. This is favorable with respect to void reactivity reduction as a higher fuel volume fraction means a lower coolant volume fraction. As a result, the moderation of the coolant plays a much smaller role and its accompanying loss results in a smaller increase in neutron energy upon voiding. Hence, as will be shown later, the magnitude of the coolant void reactivity is smaller. With respect to radial power shaping, the high fuel volume fraction provided by the TID assembly permits the use of diluent in the fuel while still allowing enough of a heavy metal loading to enable not only criticality, but also sufficient conversion ratio during burnup to achieve a sustainable core without the need for external blankets. This provides a proliferation benefit as it causes the weapons-attractive isotopes (e.g. Pu-239) to be intimately mixed with other radioactive transuranics and fission products, making extraction difficult.

Reducing the P/D ratio in pin type cores in order to increase the fuel volume fraction and enjoy neutronic benefits similar to a TID fuel assembly would result in unfavorable thermal hydraulic performance. For a given fuel volume fraction, TID fuel assemblies provide not only lower fuel temperatures, but also significantly lower pressure drops. Further, TID fuel assemblies eliminate the need for wire-wrap or grid spacers, adding an additional benefit from a pressure drop perspective.

4. Tools

Radial power profiles and reactivity parameters, i.e. coolant void reactivity, were calculated using MCNP (Monte Carlo N-Particle) and MCODE (MCNP-ORIGEN DEpletion Program), a code developed at MIT which couples MCNP and ORIGEN in order to do depletion analysis. [4] ENDF/B-VI cross sections were used for all of the calculations. MCNP was chosen for its ability to model the very heterogenous and unique design of our TID fuel assembly, a capability not found in many deterministic codes. It should be noted that MCNP uses Monte Carlo methods in its calculation and is stochastic in nature. Previous work has been done to benchmark the methods used to produce the results in this work against data from the ZPR-9 fast critical assemblies, showing excellent agreement. [5]

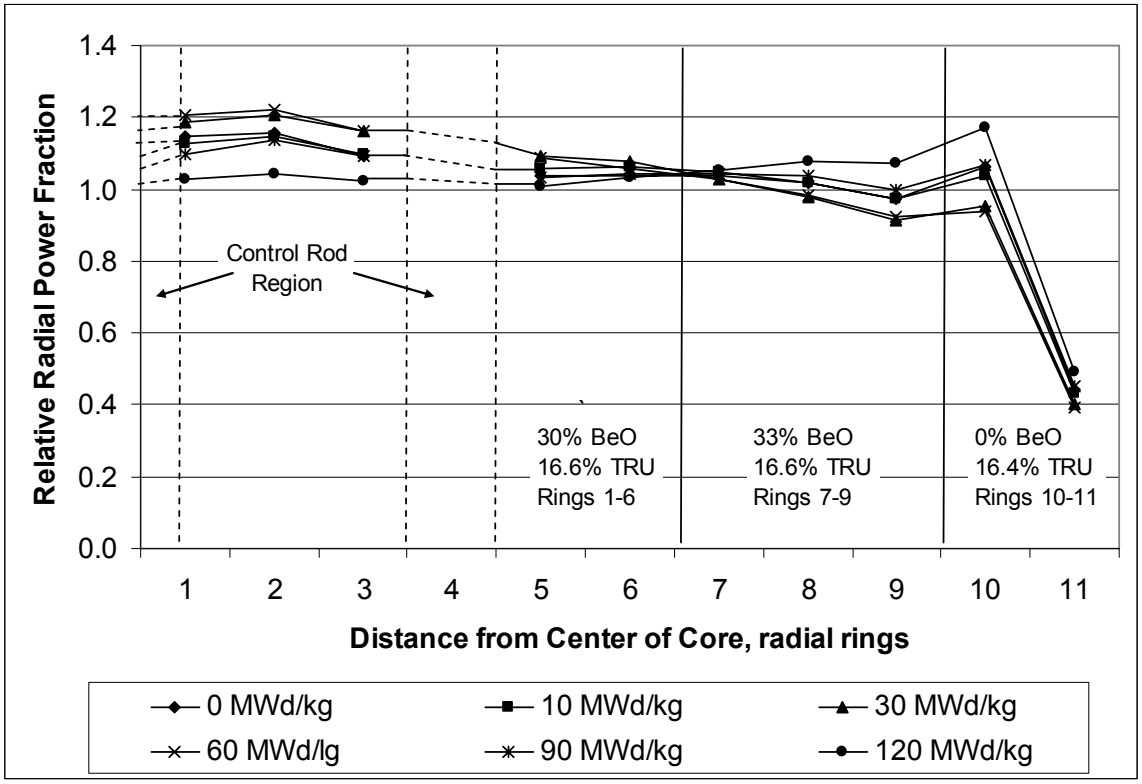
5. Results and Discussion

Work previously done to this end used Silicon Carbide as a diluent. [6] Since then, other candidate diluents have been explored: Beryllium Oxide (BeO) and Titanium Carbide (TiC). While these other diluents have shown comparable effectiveness in shaping power, BeO has demonstrated the greatest effect on reducing void reactivity of all these candidate diluents. As well, BeO has been shown to significantly enhance the thermal conductivity of UO_2 fuel. [7] Since void reactivity concerns create the most stringent design constraint, BeO has been selected as the diluent of choice.

5.1 BeO Effect on Radial Power Shaping

The effect of the BeO diluent on the radial power profile over core life can be seen in Fig. 1. The maximum radial power peak for this core is ~1.22 at 60 MWd/kg. Not only is the relatively flat radial power profile notable, but the ability to keep it roughly constant over core life is also an extraordinary benefit of using a diluent. These results suggest that such a strategy for power shaping would be extremely beneficial in a battery type core, where large burnup with little outside intervention is desired.

Figure 1: Radial Power Profile over Core Life



Similar attempts at power shaping using enrichment zoning have shown that a comparably flat radial power profile is achievable at beginning of life. However, due to the difference in enrichments between zones, the radial power peak shifts between regions over burnup and reaches peaks of up to ~1.5, which are unacceptable from a thermal hydraulics point of view. It should also be noted that the power shapes shown in Fig. 1 are achieved without the use of control rods. Inserting control rods to help control the radial power shape throughout core life is likely to lower the radial power peak even further.

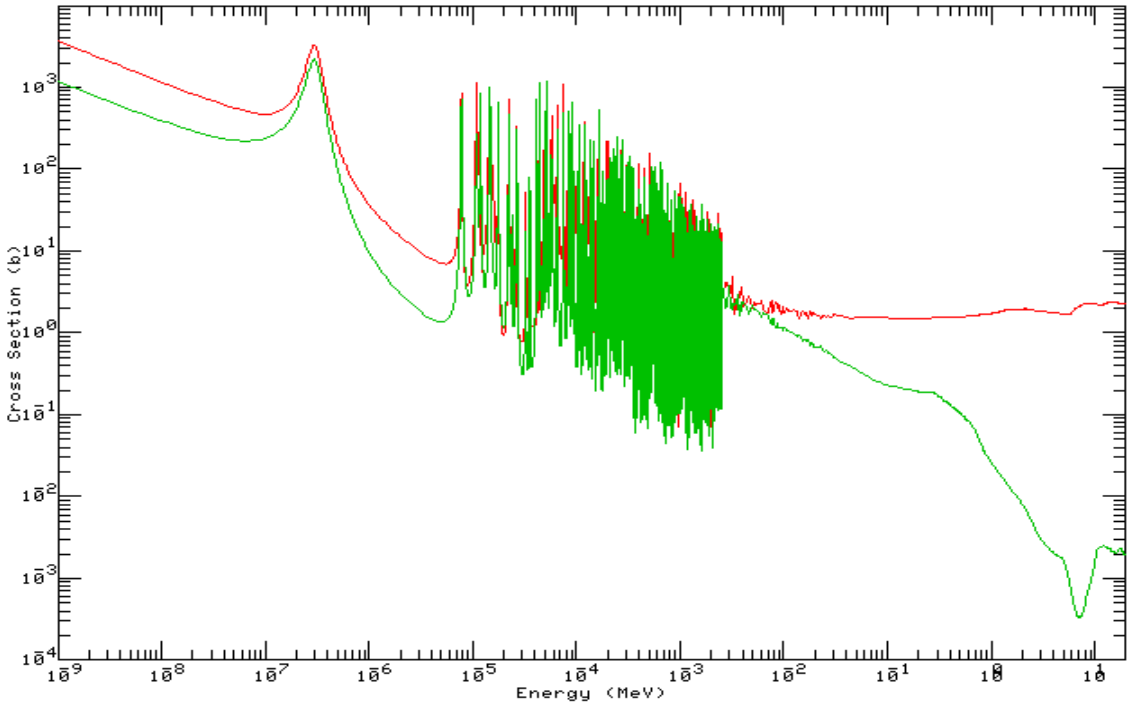
The ability to maintain a relatively constant radial power profile over core life results from the moderating properties of the diluent. The moderation of the diluent is sufficient to lower enough of the neutron population's energy below the fast fission threshold of many of the transuranic nuclides without lowering it so much as to

completely prohibit fast fission. Since the diluent does not get used up like a more traditional burnable poison, it maintains its potency throughout core life.

Using diluent for axial power shaping was explored as well. While the power was able to be flattened reasonably well using axially zoned diluent, it must be remembered that the goals with respect to axial and radial power shaping are often different. While a flat radial power profile is desirable from a thermal hydraulics perspective, an inlet-peaked axial power profile is ideal in order to minimize the peak cladding temperature, the most constraining thermal hydraulics limit in our design. Due to the low H/D of our core, zoning of diluent in order to achieve an inlet-peaked power shape proved successful but not ideal. Thermal hydraulic analysis of our inlet-peaked axial power shapes showed only a marginal benefit (<10°C) with respect to peak cladding temperatures when compared to the default chopped cosine axial shape. Considering other effects that such an inlet peaked power profile may have, e.g. rapid burnout of the bottom of the fuel region and subsequent spatial power oscillations throughout core life, the decision was made to only zone diluent radially. However, should a need arise to shape power axially and given that the other constraints can be managed, BeO diluent would serve that need.

5.2 BeO Effect on Coolant Void Reactivity

Figure 2: Microscopic Fission and Capture Cross Sections for Pu-239
(from top to bottom at 1 MeV: fission, capture)



The spectral softening effect resulting from the use of BeO diluent is also beneficial from a void reactivity standpoint. Reactivity in this core is driven primarily by Pu-239, which accounts for ~65-70% of fissions throughout core life. It can be shown that:

$$\Delta\rho_{VOID}\alpha\frac{\sigma_f}{\sigma_c} \quad (1)$$

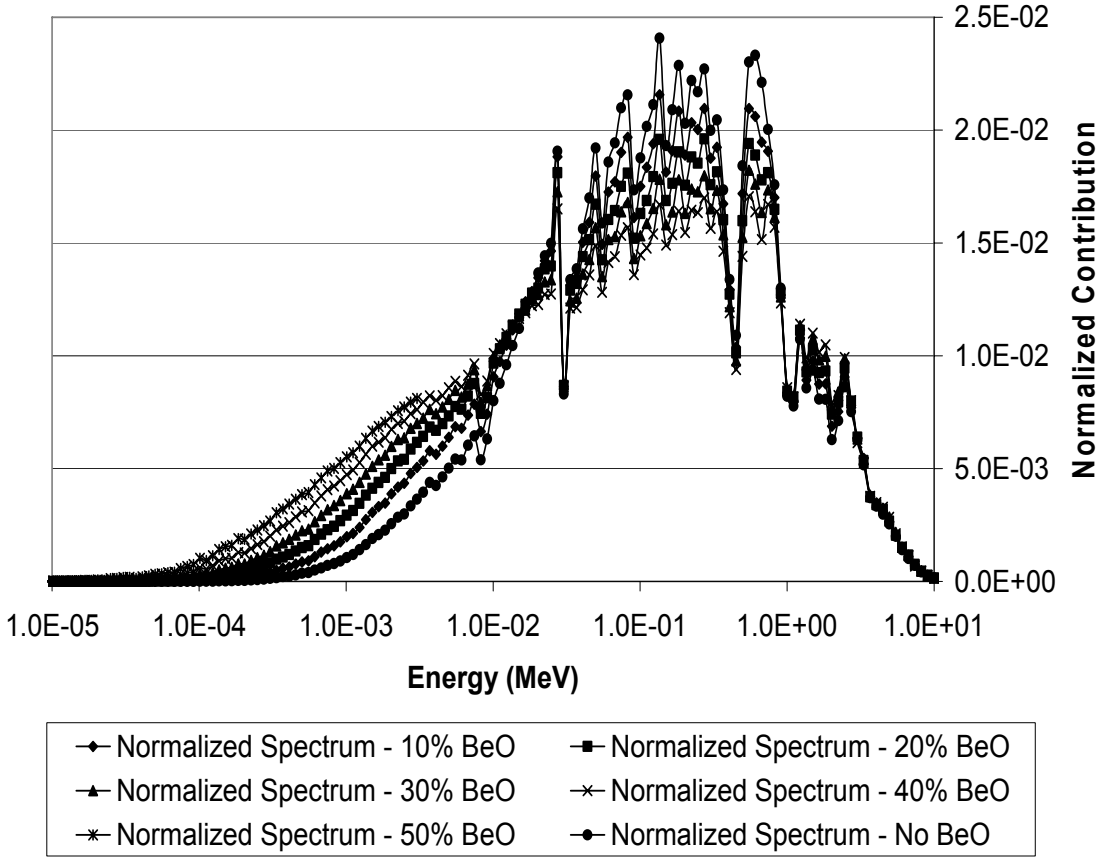
where $\Delta\rho_{VOID}$ = change in void reactivity, σ_f = spectrum and space averaged microscopic fission cross section, σ_c = spectrum and space averaged microscopic capture cross section.

Coupling this relationship with the behavior of these cross-sections for Pu-239, shown in Fig. 2, shows that as the neutron energy is softened from its undiluted mean value of ~0.4 MeV (for this core design), the capture cross-section increases. Since the fission cross section remains relatively constant over the energy range of interest, Eq (1) shows that there is an accompanying reduction in void reactivity with spectral softening.

5.2.1 Semi-infinite Assembly Study

At first glance, this spectral softening effect is a benefit from a void reactivity standpoint. However, there are several other key effects that must be considered. In order to assess the effect of spectral softening on beginning of life (BOL) void reactivity, end of life (EOL) void reactivity, reactivity swing, and reactivity limited

Figure 3: Neutron Energy Spectra as a function of BeO Concentration



burnup, a semi-infinite assembly (mirror boundary conditions radially, normal boundary conditions axially) was analyzed with varying BeO concentration. The BeO concentration is proportional to the amount of spectral softening: the higher the BeO concentration, the softer the spectrum. Fig. 3 shows the effect of spectral softening as the BeO concentration is increased. Note that the mean energy of the undiluted spectrum is ~0.4 MeV and that this spectrum closely resembles that of the delayed neutron spectrum.

At the beginning of core life (BOL), a concurrent effect of spectral softening, i.e. increasing BeO concentration, is to increase the fraction of Pu-239 fissions in the core. This increase stems from the significant reduction of σ_f for U-238, which displays a threshold behavior at approximately 1-2MeV. Since U-238 accounts for 15-20% of fissions at BOL (second only to Pu-239 at 60-75%), the significant reduction in σ_f of U-238 results in an increase in the core fission contribution from Pu-239. Hence, while softening the energy spectrum may reduce the magnitude of positive void reactivity, it also has the effect of increasing the amount of Pu-239 fissioning in the core, which increases the contribution of Pu-239 to positive void reactivity. This trade-off results in a saturation effect of void reactivity with respect to spectral softening at BOL, as spectral softening initially reduces void reactivity significantly (i.e. the direct spectral softening effect on void reactivity dominates), but then gives diminishing returns as the neutron spectrum gets softer (i.e. the effect of increasing fission fraction of Pu-239 begins to play a more dominant role).

While spectral softening tends to increase the fission fraction of Pu-239 at BOL, the same effect does not occur at end of core life (EOL). Throughout burnup, the softer spectrum leads to more neutrons in the resonance region, increasing the amount of higher mass number actinides that are bred, specifically Pu-241. The increase in the contribution to fission of Pu-241 balances the reduction of fission in U-238 with spectral softening at EOL, keeping the fission fraction of Pu-239 relatively constant with respect to neutron spectrum energy. Hence, the spectral softening at EOL only has the effect of reducing void reactivity. While this bodes well from a safety standpoint, the spectral softening that leads to a favorable EOL void reactivity must be balanced with the other byproducts of spectral softening in a fast reactor, e.g. the effect on reactivity limited burnup. Several other effects also play a minor role in the effect of spectral softening on void reactivity at all times in life: the reduction in fission neutron yield per absorption (η) in the energy region of interest with spectral softening and the smaller effect of the loss of S-CO_2 upon voiding due to an already softer spectrum.

It has been shown that as the spectrum softens, reactivity swing and reactivity limited burnup both decrease. Both have been shown to be (nearly) inversely linearly related to BeO concentration in the semi-infinite assembly studies referenced earlier. While a decrease in reactivity swing is favorable from a safety and control standpoint, a reduction in reactivity limited burnup is disadvantageous from an economics standpoint. Since the BOL and EOL void reactivities, reactivity limited burnup, and reactivity swing are all influenced by the hardness of the neutron energy spectrum in different ways, careful selection of the amount of BeO diluent used in such a core design is important in order to optimize all of the tradeoffs among these parameters.

5.2.2 Whole Core Study

Previous studies using more traditional schemes for a radial reflector (e.g. Ti or TiC) show that using BeO diluent in the whole core model yields coolant void reactivities of ≤ \$1. While void reactivities of ≤ \$1 are respectable from a prompt criticality standpoint, the emphasis placed on safety by the goals of the GIF motivate investigation into lowering void reactivity even further. The ideal goal is to make void reactivity negative throughout core life (i.e. ≤ \$0), so that an advanced reactor would not have to rely on active reactivity control systems to assure safety. The results from the semi-infinite assembly work show that increasing diluent concentration above the concentrations used in this study will not yield any further benefit without significant detriment elsewhere. Further, even if other limits were disregarded, negative coolant void reactivities would not be achievable using only BeO diluent. Hence, another approach, in combination with using BeO diluent, is necessary in order to continue to lower void reactivity.

Understanding that one of the parameters that control void reactivity is leakage and realizing that the Loss of Coolant Accident (LOCA) presents the most limiting scenario from a void reactivity standpoint, an innovative yet simple radial reflector strategy is proposed. Using a radial reflector that is made of the S-CO_2 coolant (shown in Table 1), coolant void reactivities that are negative throughout core life are achievable, shown in Table 2. Note that the coolant void reactivity reaches a maximum at the most reactive time in core life (Middle of Life or MOL) and its behavior mimics that of the Pu-239 inventory.

Achieving a negative coolant void reactivity throughout core life is possible since this core design is a relatively low leakage design (compared to other fast reactors), owing to its large size and use of high fuel volume fraction Tube-in-Duct fuel assemblies. Hence, replacing a solid radial reflector, e.g. TiC or Ti, with S-CO_2 does not significantly increase the critical enrichment (core-averaged 16.5$^{w}/_{o}$ TRU for TiC/Ti radially reflected case v. 16.53$^{w}/_{o}$ TRU for S-CO_2 radially reflected case) and results in a loss of only ~\$4.6 of core reactivity. Since the reflector is the coolant, when a LOCA occurs, the reflector "disappears," leakage is enhanced, and negative reactivity is inserted.

Table 2: Void Reactivity at BOL and EOL for the Reference Core Design

Time in Life	keff, nominal (unrodded)	keff, voided	Void Δk	STDEV (σ)	Effective Delayed Neutron Fraction (β)	STDEV (σ)	Void ¢	σ ¢
BOL	1.02136	1.01948	-0.00181	2.19E-04	0.0046	1.7E-04	**-39**	**5**
MOL	1.03197	1.03149	-0.00045	1.98E-04	0.0042	1.9E-04	**-11**	**5**
EOL	1.00044	0.99886	-0.00158	1.72E-04	0.0044	2.1E-04	**-36**	**4**

6. Conclusions

Use of BeO diluent in GFRs has been shown to be effective in both shaping power and reducing coolant void reactivity. These beneficial effects are a direct result of the softening of the neutron spectrum. While this has traditionally been viewed as

detrimental in a fast reactor, the spectral softening is enough to gain these benefits without losing the characteristics of a fast reactor, i.e. making the reactor epithermal. Using BeO diluent alone, void reactivities ≤ \$1 are possible; combining the use of diluent with an innovative radial reflector strategy makes negative void reactivities, i.e. ≤ \$0, throughout core life possible. Furthermore, the radial power profile remains flat over core life without fuel shuffling, making battery type operation for up to nearly 20 years feasible. Future work includes integrating these results with an ongoing thermal-hydraulics analysis, as well as assessing the suitability of such a strategy from a materials (i.e. reactor pressure vessel fluence) and economics perspective.

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