High volume packing fraction TRISO-based fuel in light water reactors*

* This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

Nicholas R. Brown[1,2], Richard Hernandez[1], Andrew T. Nelson[2]

[1]University of Tennessee, Knoxville
[2]Oak Ridge National Laboratory

Corresponding Author: Nicholas R. Brown, nbrown49@utk.edu

Abstract
For nearly a decade fully ceramic microencapsulated (FCM) fuel, with tri-structural isotropic (TRISO) fuel particles in a silicon carbide (SiC) matrix, has been pursued as an accident tolerant fuel in light water reactors. Other examples exist of TRISO-based concepts for light water reactor fuel with different matrix materials. Previous studies assumed TRISO particle volume packing of approximately 0.44 in SiC (or other) matrix, the highest realistic packing fractions possible with conventional manufacturing. Recent advances in advanced manufacturing have yielded development of a fuel form which consists of conventionally manufactured TRISO particles in a 3D-printed SiC matrix with significantly higher possible TRISO packing fractions (0.5-0.7). This increased uranium loading enhances the viability of TRISO-based particle fuel forms in light water reactors. We assessed the viability of high packing fraction TRISO-based particle fuel forms in light water reactors from the perspective of fuel cycle length, achievable fuel burnup, reactivity coefficients, and fuel cycle performance. Higher packing fraction TRISO-based fuel enables either longer cycle lengths (by ~25%) at a constant enrichment or decreased enrichments (by ~25%) at a constant cycle length. Studies of different fuel kernel types (uranium nitride, uranium oxy-carbide, and uranium carbide) yielded similar results, although the cycle length of uranium oxy-carbide was lower than uranium nitride or uranium carbide. We also characterized the production of ^{14}C due to neutron absorption in ^{14}N during operation for uranium mononitride fuel kernels, with the ratio of $^{14}C/N$ being 1-2 atom % at discharge. For the fuel cycle evaluation, the activity of spent nuclear fuel and high-level waste at 100 and 100,000 years was lower than conventional light water reactor fuel. Environmental impact metrics were similar overall, but higher on the front end of the fuel cycle and lower on the back end of the fuel cycle. Reactivity coefficients of higher packing fraction TRISO-based fuel were reasonable when compared with conventional fuels.

Keywords: FCM fuel; accident tolerant fuel; light water reactor; advanced manufacturing

Introduction

The ability to fabricate nuclear fuels with an advanced or additively manufactured matrix or structural material but a conventionally manufactured fuel material presents several potential advantages [1], for example increased margin to fuel failure or an additional barrier to fission product release. Fully ceramic microencapsulated (FCM) [2] fuel, as well as dispersion fuel forms [3], have been considered as light water reactor (LWR) accident tolerant fuel (ATF) over the past decade. FCM fuel is based around the proven tri-structural isotropic (TRISO) fuel particle in a silicon carbide (SiC) matrix, and has also been considered for applications in heavy water moderated reactors [4] and gas cooled reactors [5]. Advantages of the FCM fuel form include enhanced fission product retention, the addition of a new layer of defense in depth (TRISO particles plus the SiC matrix), elimination or reduction of pellet-cladding mechanical interaction (PCMI), and increased fuel discharge burnup. Challenges with FCM fuel are associated with reduced heavy metal loading and a lack of irradiation performance data, including data in accident conditions [6]. Three techniques are used to address the challenges inherent with FCM fuel: higher density fuel kernels (uranium nitride or carbide), the highest possible volume packing of TRISO particles in the matrix, and uranium enrichment of about 19.75% ^{235}U.

In this paper we focus on quantifying the impact of TRISO volume packing on the reactor performance and safety characteristics of FCM fuel, or other TRISO-based fuels, in LWRs. TRISO volume packing fraction means the volume of the TRISO particles divided by the total fuel volume, including the SiC matrix. Two methods could increase the fuel volume packing fraction in TRISO-based fuels: (1) conventional manufacturing approaches with multiple particle sizes and (2) novel approaches based on conventionally manufactured TRISO particles but advanced manufactured matrix materials. We focus on the latter approach in this article, but either approach would be expected to produce similar results and our conclusions are applicable to both scenarios.

We parametrically evaluate the impact of TRISO packing fraction of FCM fuel and similar particle fuels, such as metal matrix microencapsulated (M3) [7] fuel, in LWRs by varying the packing fraction from approximately 0.44-0.74. We investigated the discharge burnup and fuel cycle length of these fuels in LWRs using an approach that we verified was consistent with previous studies [2]. Once we performed a coarse parametric evaluation, we selected several realistic designs assuming ordered particle lattices with packing fractions on the order of 56%. We used these realistic designs to perform a more holistic assessment including reactivity coefficients and a holistic fuel cycle evaluation based on a US Department of Energy Office of Nuclear Energy (DOE-NE) study [8].

Conventional manufacturing approaches have been demonstrated for FCM fuel that yield packing fractions of about 0.34 – 0.40 [9] for a single particle size. Fabrication development of FCM fuel using conventional manufacturing is generally limited to these modest packing fractions because compaction of particles dispersed in a non-consolidated matrix can lead to coatings cracking if particles are in contact and placed under uniaxial stress [10]. Previous evaluations of FCM fuel in LWRs assumed optimistic packing fractions of 0.44 - 0.50 [2], which may stretch the limits of conventional manufacturing. Historically, high volume fractions of TRISO particle packing were achieved in the Fort St Vrain reactor, with TRISO particle volume packing fractions of approximately 0.60 [11]. Four different TRISO particles sizes were used within the Fort St Vrain reactor to achieve such high particle packing, since multiple particle sizes yield higher packing fractions within the same volume.

Recent research and development efforts have been made to demonstrate and deploy advanced manufacturing technologies in nuclear applications, which includes both fission [12] and fusion [13] applications. For example, the Transformational Challenge Reactor (TCR) [14] is a helium-cooled, yttrium-hydride moderated microreactor being designed for the Department of Energy Office of Nuclear Energy (DOE-NE) to demonstrate and deploy advanced manufacturing technologies in nuclear design and manufacturing processes. Capabilities developed within the TCR program for 3D-printed SiC matrix material for FCM fuel with conventionally manufactured TRISO particles [15].

In this paper, we assess the possible application of such novel fuel materials in LWRs. These novel fuels result in increased uranium loading, with packing fractions up to 0.64 achievable with a single TRISO particle size [16]. This greatly increases the potential attractiveness of FCM fuels in LWRs. An example concept for a high packing fraction FCM concept in an LWR is shown in Figure 1(a) and an M3 fuel concept in Figure 1(b). The particles are arranged in an ordered face centered cubic (FCC) lattice with a TRISO volume packing fraction of 0.557 for the FCM fuel and 0.468 for the M3 integral fuel rod.

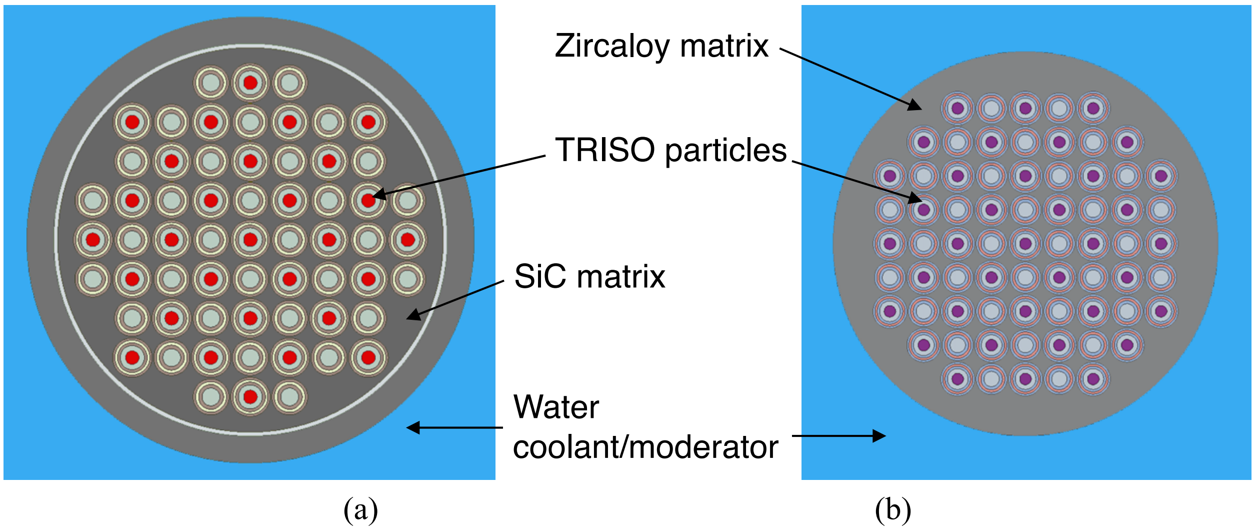


Figure 1. Plan view of an example high packing fraction (a) FCM fuel arrangement in an LWR and (b) M3 integral fuel rod arrangement in an LWR.

Methodology

There were three steps (phases) in our study. The first phase was a verification phase, detailed in this section, where we developed a model and benchmarked it to the data available in the literature [2, 17]. The second phase of the study consisted of a parametric evaluation of fuel cycle length and burnup versus packing fraction and enrichment. We used fixed particle lattices to conduct this parametric study, since past studies have shown these fixed lattices represent very similar behavior to randomly packed particles [2]. The objective of the second phase was to develop a scoping matrix to aid in choosing a set of detailed cases for more detailed investigation. In the third phase, we used several high packing fraction cases for FCM and M3 fuel to study the impact of different kernel materials, including uranium mononitride (UN), uranium monocarbide (UC), and uranium oxy-carbide (UCO) on fuel cycle performance.

In the FCM fuel form what we call UN kernels are composed of mostly uranium mononitride with some minor fraction of uranium monocarbide that typically remains as an impurity following synthesis [18]. By including both UN and UC kernels in our study, we provide insight into the reactor physics and fuel cycle impacts of the admixture of UC in UN ($UC_{1-x}N_x$). The anion purity (x) can vary significantly depending on the fabrication process used. 'High purity' UN typically indicates x of above 0.95, but values of 0.8-0.9 are commonly encountered in the literature including materials subjected to irradiation [18, 19]. We also assessed the buildup of ^{14}C and ^{1}H in the UN fuel kernel during reactor operation due to neutron absorption in $^{14}N(n,p)^{14}C$ reactions. Enrichment of nitrogen in ^{15}N is commonly proposed as a way to get around this [20, 21], but means of fabricating $U^{15}N$ at large scales has not yet been demonstrated. We calculated fuel temperature coefficient (FTC) and moderator temperature coefficient (MTC) and compared to a Design Control Document (DCD) for a modern LWR. Finally, we used the DOE-NE Evaluation and Screening (E&S) study definition [8] to perform a holistic fuel cycle performance assessment, including both front-end and back-end fuel cycle impacts. The E&S study has served as a useful foundation for comparing such parameters for novel fuel or reactor options to well understood analysis examples in different fuel cycles [22, 23].

The U.S. DOE-NE E&S study [8] binned several thousand hypothetical nuclear fuel cycle options into 40 representative Evaluation Groups (EGs). The grouping of the EGs was performed using the basic reactor and fuel cycle characteristics for the fuel cycle option, such as fast or thermal reactor spectrum, critical or subcritical reactor, or the necessity of uranium enrichment at fuel cycle equilibrium. The E&S study used 9 performance criteria with 25 specific metrics to inform on the 9 high-level performance criteria. These performance criteria included important factors like natural resource utilization (NRU), high level waste (HLW) disposed, and radioactivity of discharged material at 100 and 100,000 years. In the case of each EG, a representative analysis example was selected to represent performance of that group. For a once-through fuel cycle with low-enriched uranium, but enrichment greater than 5%, the reactor fuel options considered in this study is EG02 – "Once-through using enriched-U fuel to high burnup in thermal or fast critical reactors." The EG02 AE for the E&S study was a thermal spectrum modular high temperature gas-cooled reactor (mHTGR) with a ^{235}U fuel enrichment of 15.5%, a power output of 350 MWth, and a discharge burnup of 120 GWd/t.

The first phase in our study was to develop lattice physics models for a Westinghouse 17 × 17 fuel assembly. We verified these newly generated models via comparison to results in the literature [2] for two ordered lattice arrangements of TRISO particles, a square lattice and a hexagonal lattice. The fuel assembly model we used is based on the specifications of the AP1000 reactor: 3400 thermal megawatts (MWth), 157 fuel assemblies, and a 14 ft active core height. The fuel pin pitch is 1.26 cm and assembly pitch is 21.42 cm. The model used is an assembly lattice model (see Figure 2) with a "height" of 4.93 cm (to account for the three-dimensional nature of the packed TRISO fuel) and reflective boundary conditions on all six surfaces. The dimensions of the TRISO particles considered in this study, relative to an example Advanced Gas Reactor (AGR) particle, are shown in Table 1. All particle layer dimensions are shown, including the fuel kernel, buffer carbon layer, inner pyrolytic carbon (iPyC) layer, SiC layer, and outer pyrolytic carbon (oPyC) layer. All calculations in this paper use the Serpent [24] Monte Carlo reactor physics code with explicitly modeled double heterogeneity TRISO particles.

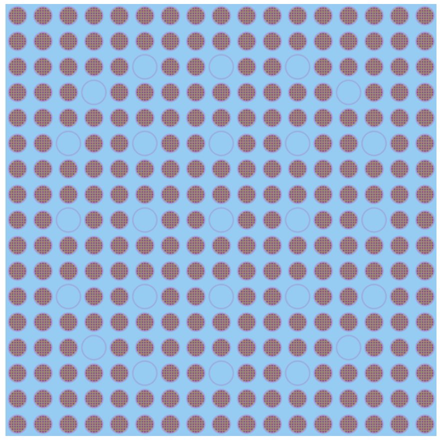


Figure 2. Fuel assembly model considered in the verification study.

Table 1. Parameters of typical TRISO and FCM fuel particles.

Particle Type	TRISO layer radii (cm)				
	Kernel	Buffer	iPyC Layer	SiC Layer	oPyC Layer
Typical TRISO particle (UCO kernel)	0.02125	0.03125	0.03525	0.03875	0.04275
FCM particle (UN, UC, or UCO kernel)	0.0425	0.0475	0.051	0.0545	0.0580

The model was developed and applied for FCM fuel in a LWR with a packing fraction of 0.44. We compared the infinite multiplication factor using two fixed lattice structures (hexagonal and square) in the FCM fuel to values from the literature [2]. We saw excellent agreement between these models and the models in the literature (Figure 3). The fuel residence time is shown in Effective Full Power Days (EFPD). Key differences include the cross-section library, as our current calculations utilized ENDF/B-VII.1 and previous calculations in the literature used ENDF/B-VII.0. Additionally, we did not have the historical model from the literature available to us, so we had to regenerate the assembly model. Both models assumed 0 ppm of boron in the coolant, consistent with the comparison made to the literature.

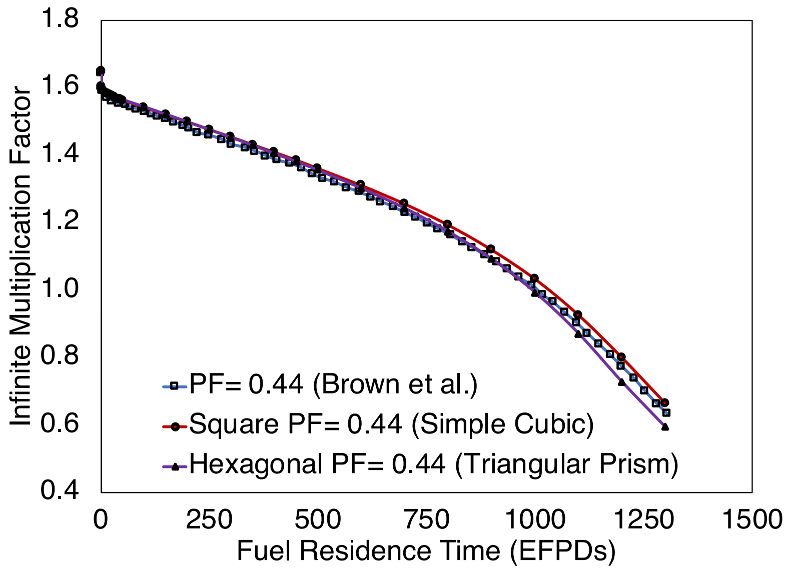


Figure 3. Infinite multiplication factor of FCM verification reactor physics models compared to the literature [2].

For phase 2 of our study, we used body centered cubic (BCC) and FCC fixed particle lattices to determine fuel cycle length and fuel discharge burnup versus TRISO particle volume packing fraction and uranium enrichment. We used the two lattice types to determine whether the fixed lattice structure was obfuscating our results due to self-shielding effects. We also used three different enrichments to understand how the uranium enrichment impacted cycle length and discharge burnup. We allowed particle “cut off” at the boundaries of the FCM pellet in this parametric study, the purpose of which was to scope out the parameter space of cycle length and burnup as a function of enrichment and TRISO volume packing fraction. We used the linear reactivity model to determine cycle length [25]. We were confident in this choice based on the results of a previous study which showed similar results between the linear reactivity model and higher order (quadratic) reactivity models for un-poisoned FCM lattices [2].

Table 2. Parametric study of lattice packing fraction and ^{235}U enrichment.

Parameter	Value
BCC lattice packing fractions (%)	44, 50, 55, 60, 65
FCC lattice packing fractions (%)	44, 50, 55, 60, 65, 70, 74
^{235}U enrichment (%)	10%, 15%, 19.75%

In phase 3 we took realistic FCC lattice designs for FCM (see Figure 1) and also for M3 fuel, with no particle cut-off, and used them to perform calculations with three kernel types (UN, UC, and UCO). We used these realistic models to assess FTC and MTC and compare these safety parameters with the AP1000 DCD [26]. We also assessed ^{14}C and ^{1}H buildup in the UN kernels due to (n,p) reactions in ^{14}N. Finally, we performed an assessment of fuel cycle performance using the metrics of the DOE-NE E&S study.

Results and Discussion

The cycle length and discharge burnup of the different configurations described in Table 2 was assessed using the linear reactivity model. When comparing the FCC and BCC lattice results, we saw negligible differences comparing the two geometries for a constant fuel volume fraction (i.e., for the same volume of fuel in the FCM pellet). Therefore, only the results for the FCC lattices are shown here, with infinite multiplication factor as a function of fuel residence time (at constant power density) shown in Figure 4 for a ^{235}U enrichment of 15%. Contour plots of fuel residence time for a three-batch fuel cycle are shown in Figure 5(a) with units of EFPD and discharge burnup in Figure 5(b) with units of gigawatt day per metric ton of uranium (GWd/t).

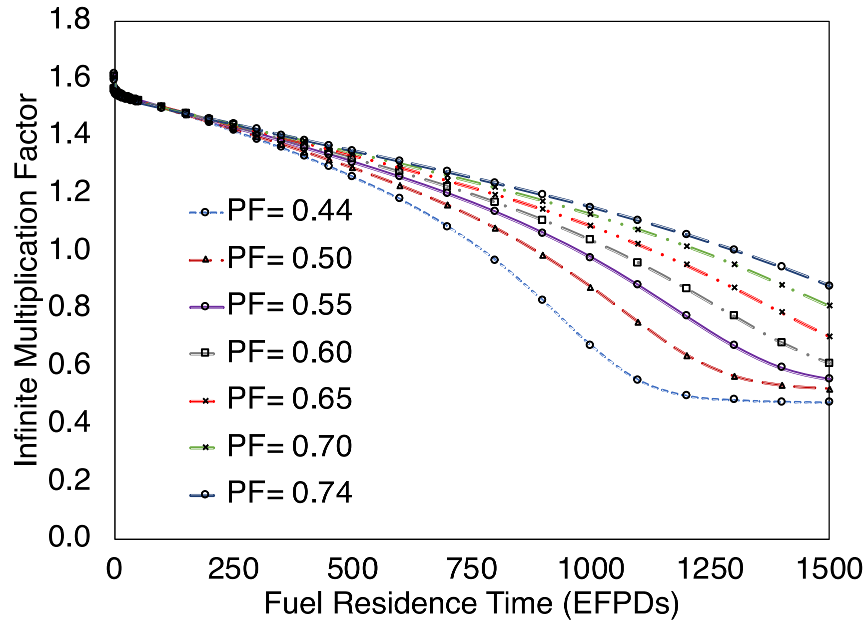


Figure 4. Infinite multiplication factor of high packing fraction FCM fuel with FCC lattices.

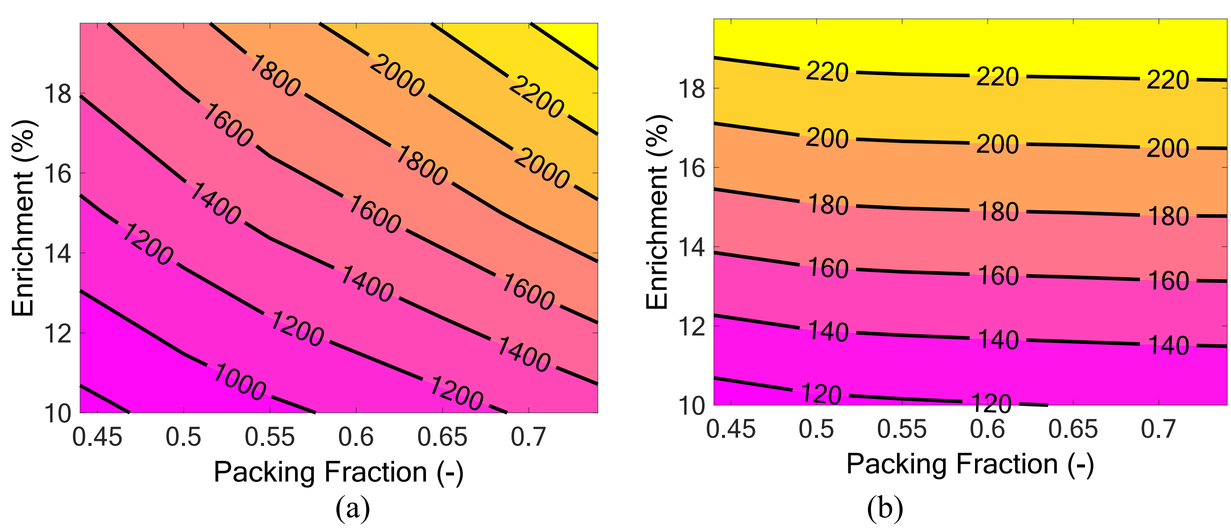


Figure 5. Contour plots for FCM fuel in a three-batch fuel management scheme of (a) cycle length in EFPD and (b) discharge burnup in GWd/t.

These results indicate that high TRISO volume packing fraction (greater than 0.5) particle fuels in LWRs could result in either a 25% increase in achievable cycle length of 25% reduction in enrichment for the same cycle length. This inherently makes these fuel forms more viable and attractive for LWRs.

We also performed a more detailed assessment using two specific configurations shown in Figure 1. We performed the following calculations:

- Evaluation of the type of fuel kernel (UN, UC, or UCO) on cycle length and burnup, at both theoretical density and 15% porosity.
- Assessment of ^{14}C and ^{1}H buildup in the UN kernels due to (n,p) reactions in ^{14}N.
- Determination of reactivity coefficients (FTC and MTC).
- Calculation of natural resource utilization, spent fuel activity, and environmental impact fuel cycle metrics.

The ^{235}U enrichment assumed for these more detailed calculations was 19.75%. First, we evaluated the impact of the fuel kernel type on cycle length and burnup. The UCO kernel fabrication process as developed for AGR specifies a uranium density of no less than 9.1 g U/cm^3 . UCO of full theoretical density comprised of a representative UO_2 / UC_X phase fraction possesses a uranium density of 10.2 g U/cm^3. UC and UN both have significantly higher uranium densities: 13.0 g U/cm^3 for UC and 13.5 g U/cm^3 for UN when both materials are fully dense. These values fall to 11.0 and 11.5 g U/cm^3 if porosity increases to 15%. The porosity value of 15% for both UC and UN was chosen as it is typical for material produced using the standard sol gel / carbothermic reduction / nitridation process without additional processing steps to increase density [27]. As shown in Figure 6, both UC/UCO have initial higher excess reactivity due to higher parasitic neutron absorption in UN fuel (mainly due to ^{14}N). Due to higher fissile content in UN kernels, there is a point where UCO and UC curves cross over the UN k-infinity value, resulting in shorter fuel residence time for those lower density kernels. The three-batch cycle lengths for theoretical density are consistent with those shown in Figure 5(a), with the cycle lengths for the 85% theoretical density cases being (unsurprisingly) approximately 15% shorter. The three-batch discharge burnups are consistent with those shown in Figure 5(b), with the discharge burnup being approximately independent of theoretical density. Both three-batch cycle length and discharge burnup are shown in Table 3. These show that an 18-month (or longer) cycle is possible with high packing fraction FCM or M3 fuel with TRISO kernels of any type.

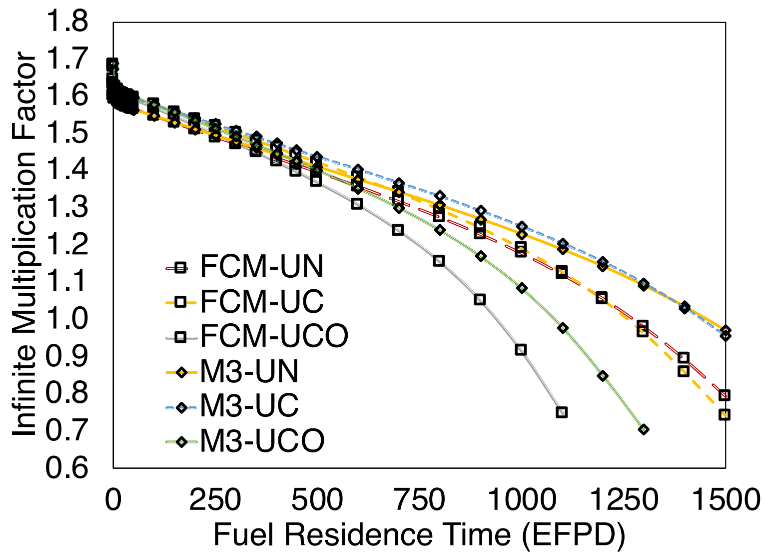


Figure 6. Infinite multiplication factor of high packing fraction FCM fuel and M3 fuel with different fuel kernel types.

Table 3. Selected length and discharge burnup results of the fuel kernel options for 19.75% ^{235}U enrichment.

Kernel Type		UN	UC	UCO
Density (kg/m^3)		14.31	13.6	10.9
M3 Fuel	Fuel Residence Time (EFPD)	2182.1	2162.3	1622.0
	Discharge Burnup (GWd/t)	237.8	246.0	243.8
FCM Fuel	Fuel Residence Time (EFPD)	1914.3	1892.1	1409.6
	Discharge Burnup (GWd/t)	236.0	242.0	239.7

Because UN kernels in FCM fuel are commonly ($UC_{1-x}N_x$) and therefore contain some residual carbon, we performed calculations to understand how much ^{14}C would buildup in the UN kernel. There were two motivations for this. The first motivation was to provide information that could be used to understand the impact on the thermodynamics in the kernel during operation. The second motivation was that ^{14}C is a large contributor to radioactivity at 1,000-10,000 years, so we need to understand the buildup rate of ^{14}C to quantify the contribution of UN and UC fraction to radioactivity. The ratio of ^{14}C to nitrogen (^{14}N + ^{15}N) versus fuel residence time is shown in Figure 7(a) and the total mass fraction of ^{14}N and ^{14}C in the fuel versus fuel residence time is shown in Figure 7(b). The expected buildup of ^{14}C relative to (^{14}N + ^{15}N) is between 1 and 2 atom %. Carbon-14 buildup due to transmutation of 1 atom % equals 500 weight parts per million, which is on the order of ($UC_{1-x}N_x$) carbon impurity levels attainable by modern state of the art fabrication processes [28].

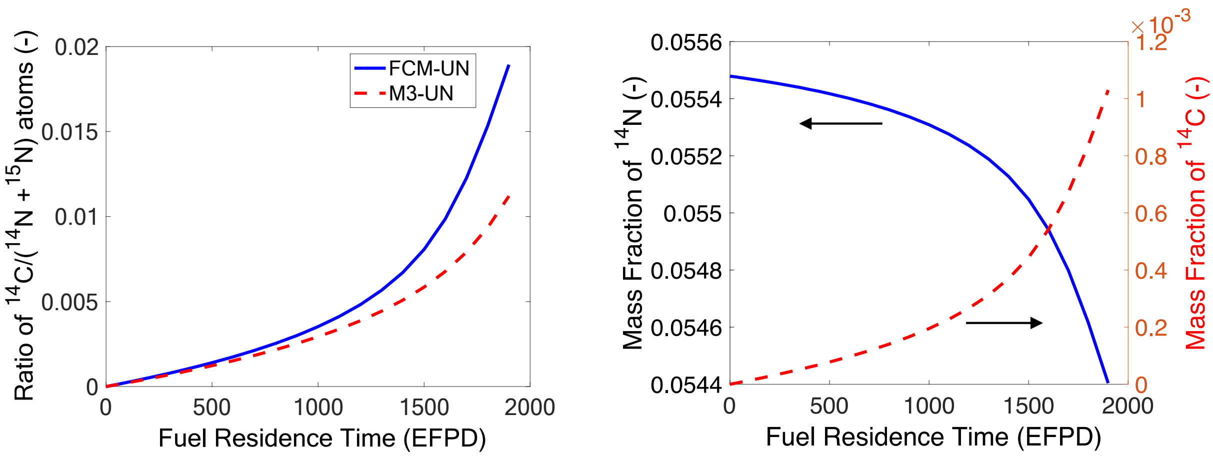
The impact of the ^{14}C buildup on radioactivity after discharge is shown in Figure 8. The radioactivity is calculated according to the standardized assumptions for radioactivity calculation in the E&S study. Specifically, the radioactivity is normalized per unit energy generation, assuming a thermal efficiency (ratio of electric to thermal power) of 33%, and losses of 0.2% in fuel fabrication. To convert the radioactivity from the Serpent code, in Becquerels (Bq) per cm, to the units used in the E&S study, Curies (Ci) per GWe-year, the following equation was used:

$$Activity\left(\frac{Ci}{GWe-yr}\right) = \frac{Activity\left(\frac{Bq}{cm}\right) * \left(\frac{1\ Ci}{3.7E10\ Bq}\right) * Mass\ Flow\ (\frac{t}{GWe-yr})}{Fissile\ Mass\ (\frac{t}{cm})} \tag{1}$$

Where the mass flow given in equation 1 is defined as:

$$\text{Mass Flow}\left(\frac{\text{t}}{\text{GWe}-\text{yr}}\right) = \frac{\text{Power}_{\text{thermal}}(\text{MW})}{\text{Burnup}\left(\frac{\text{GWd}}{\text{t}}\right) * \text{Power}_{\text{electric}}(\text{MW})} * 365.25\frac{\text{days}}{\text{yr}} \tag{2}$$

For FCM fuel with UN kernels versus UC kernels at 10,000 years, the radioactivity of the UN kernel option is ~2.7 times higher than the UC kernel option.



(a) (b)

Figure 7. Plots of ^{14}C generation due to (n,p) reaction in ^{14}N: (a) ratio of ^{14}C/(^{14}N+^{15}N) atoms for both FCM and M3 fuel and (b) mass fraction of ^{14}N and ^{14}C in fuel mixture for FCM fuel.

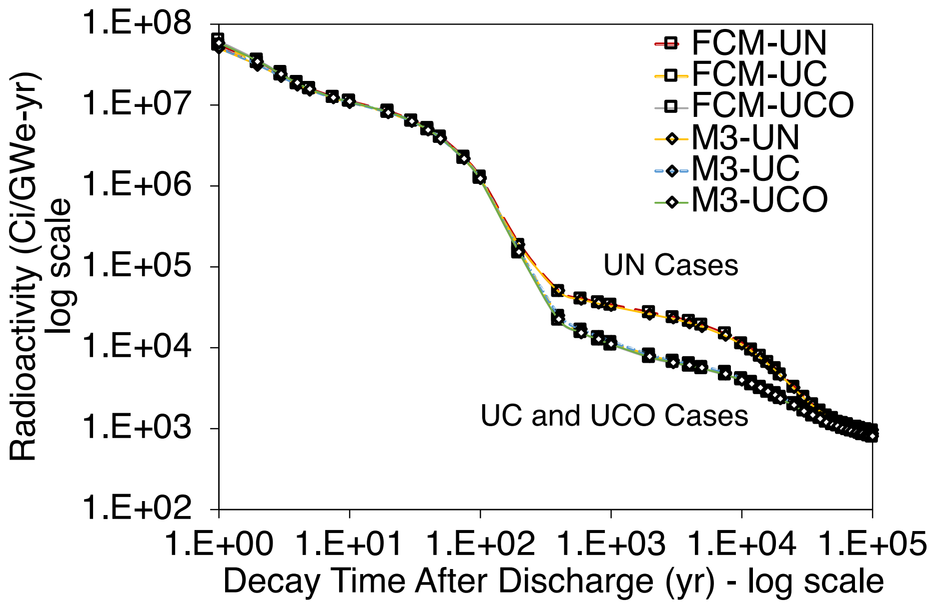


Figure 8. Energy normalized long term radioactivity of fuel options.

The uranium natural resource required and mass of spent nuclear fuel (SNF) and high-level waste (HLW) of the different options considered in this study is compared to two reference cases from the E&S study, a LWR with less than 5% ^{235}U enrichment (EG01) and a mHTGR with 15.5% ^{235}U enrichment (EG02), from the E&S study in Table 4. In all cases the SNF and HLW disposed is less for the options considered in this study relative to the EG01 and EG02 reference cases. The required uranium natural resource is similar to the options in the E&S study, but slightly higher than EG01.

Table 4. Mass of SNF and HLW disposed and natural resource required for the 19.75% enriched FCM and M3 cases considered in this study compared to the E&S study.

Reactor Fuel Type	SNF+HLW Disposed (t/GWe-yr)	Natural Resource Required (t/GWe-yr)
EG 01 (LWR, 5% enriched)	21.92	188.6
EG 02 (mHTGR, 15.5% enriched)	6.09	201.8
FCM Fuel UN TRISO	4.69	198.8
FCM Fuel UC TRISO	4.57	193.9
FCM Fuel UCO TRISO	4.62	195.7
M3 Fuel UN TRISO	4.65	197.2
M3 Fuel UC TRISO	4.50	190.7
M3 Fuel UCO TRISO	4.54	192.4

The radioactivity shown in Figure 9 is about 7% less than the reference LWR case (EG01) from the E&S study at 100 years and 45% less than the reference LWR case at 100,000 years (see Table 5). This difference is due to the higher discharge burnup (~240 GWd/t for FCM and M3 versus 50 GWd/t for EG01) and lower ^{238}U mass, which drives reduced actinide buildup. The reduced actinide buildup results in lower long-term activity at 100,000 years. Calculations were also performed for the energy normalized volume of low-level waste metrics from the E&S study. The volume of low-level waste disposed per unit energy generated was very similar to the EG01 reference case, so the results are not shown.

Table 5. Radioactivity at 100 and 100,000 years for the 19.75% enriched FCM and M3 cases considered in this study compared to the E&S study.

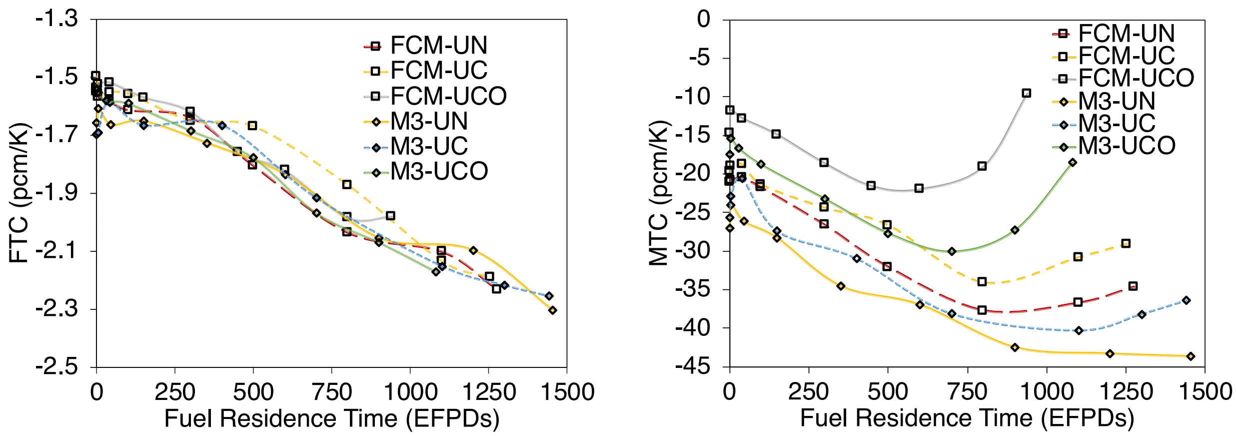
Reactor Fuel Type	Radioactivity 100 years (Ci/GWe-yr)	Radioactivity 100,000 years (Ci/GWe-yr)
EG 01 (LWR, 5% enriched)	1.34E+06	1.65E+03
EG 02 (mHTGR, 15.5% enriched)	1.43E+06	2.05E+03
FCM Fuel UN TRISO	1.25E+06	9.07E+02
FCM Fuel UC TRISO	1.21E+06	8.32E+02
FCM Fuel UCO TRISO	1.21E+06	7.80E+02
M3 Fuel UN TRISO	1.24E+06	9.49E+02
M3 Fuel UC TRISO	1.20E+06	8.55E+02
M3 Fuel UCO TRISO	1.20E+06	7.91E+02

We also performed calculations for the environmental impact metrics from the E&S, namely land use per unit energy, water use per unit energy, CO_2 emissions (primarily from uranium mining and enrichment) per unit energy, and worker radiation dose per unit energy. All relevant values were similar to the EG01 reference case and are shown in Table 6. Although the magnitude of the environmental impacts is very similar, we did note in the calculations how the relative impact of the environmental impacts shifts from the back end of the fuel cycle in the EG01 case to the front end of the fuel cycle in the FCM and M3 cases we considered. Specifically, the front end of the fuel cycle had greater impacts in the FCM and M3 cases (due to greater natural resource and enrichment requirements) and the back end of the fuel cycle had greater impacts in the EG01 case (due to greater radioactivity and mass of waste disposed).

Table 6. Environmental impact metrics for the 19.75% enriched FCM and M3 cases considered in this study compared to the E&S study.

Metric	FCM Fuel			M3 FUEL			EG01 Reference	EG02 Reference
	UN	UC	UCO	UN	UC	UCO		
Land Use (km^2/GWe-yr)	0.162	0.160	0.161	0.162	0.159	0.159	0.175	0.21
Water Use (ML/GWe-yr)	23896	23891	23893	23895	23888	23890	23891	23994
CO_2 Emissions (kt/GWe-yr)	39.2	38.5	38.8	39.0	38.1	38.3	44.1	54.9
Worker Rad Rose (person-Sv/GWe-yr)	1.081	1.075	1.079	1.082	1.07	1.073	1.10	1.28

We calculated the FTC and MTC and compared to the AP1000 DCD [26]. The FTC was calculated with a 300 K perturbation of fuel temperature from 900 K to 1200 K. The MTC used a 10 K perturbation of coolant temperature, including both the coolant density and spectral effect. For FTC the values are shown in Figure 9(a) and compare well with both past studies [2, 7] and the acceptable AP1000 DCD values of -1.8 to -6.3 percent millirho (pcm)/K. The FTC per fuel volume for the FCM and M3 fuel options, which is the truly important factor in terms of prompt inherent feedback, is significantly higher than the value in pcm/K. The MTC is also similar to past studies at lower volume packing. Both ranges of reactivity coefficients appear reasonable, and safe LWR core designs could be developed with these reactivity coefficients.



(a) (b)

Figure 9. Reactivity temperature coefficients: (a) FTC and (b) MTC.

Conclusions

The inherent potential benefit of an added layer of defense in depth in FCM and M3 fuel forms is a direct tradeoff with their reduced loading of fuel meat. The recently developed capability to increase volume packing fraction of particles fuel with an advanced manufactured matrix and conventionally manufactured TRISO particles significantly increases the attractiveness of FCM (or similar particle fuel) fuel in LWRs. Volume packing fractions of about 0.55 enable the ability to run the reactor for about 25% longer or to reduce enrichment by about 25% relative to previous, potentially optimistic, assumptions about volume packing fraction (0.44) in conventionally manufactured FCM fuel. FCM fuel with higher volume packing fraction of particles has reactor performance and safety characteristics that are more similar to conventional fuels that past studies of lower packing fraction FCM fuels.

In terms of fuel kernel materials, both UN and UC are significantly more attractive than UCO due to their higher fissile density. A porosity of 15% in the fuel kernels, relative to fully dense kernels, results in approximately a 15% decrease in cycle length. In other words, development of kernel production processes that can reduce the porosity 15% can thereby gain increases in cycle length of 15%.

The UN particle kernels proposed for FCM fuel contain carbon impurities from fabrication, resulting in ($UC_{1-x}N_x$). Our calculations show that there are no neutronic or fuel cycle impediments are observed as a function of *x*, or even kernels composed primarily of UC, in FCM fuel. Additionally, 1-2 atom % of ^{14}C is expected to build up in UN kernels due to the (n,p) reaction in ^{14}N. This contributes significantly to a radioactivity about 2.7 times higher at 10,000 years versus the use of UC kernels. This would also mean the buildup of 1-2 atom% of hydrogen gas in the particle kernels. The use of UC kernels would result in comparable cycle lengths and discharge burnups to UN kernels. Nitrogen enrichment in ^{15}N would mitigate, to some extent, the challenges with production of ^{14}C and ^{1}H in UN kernels, as would an increased fraction of UC in the fuel kernels.

Our fuel cycle assessment showed results similar to other recent studies on high assay low enriched uranium fuel [23]. Specifically, short-term (100 year) radioactivity is similar to reference LWR and mHTGR cases and long-term radioactivity is lower (~45%) than reference LWR and mHTGR cases. The difference at 100,000 years is due to the higher discharge burnup (~240 GWd/t for FCM and M3 versus 50 GWd/t for the LWR reference case) and lower ^{238}U mass, which drives reduced actinide buildup.

Reactivity coefficients (FTC and MTC) were consistent with previous studies that assumed lower volume packing fractions. They were also consistent with the DCD of the reference reactor system. We expect a safe PWR core design to be possible with these fuel concepts.

CRediT authorship contribution statement
Nicholas R. Brown: Conceptualization, Methodology, Writing – original draft, Supervision; Richard Hernandez: Formal Analysis, Investigation, Software; Andrew T. Nelson: Conceptualization, Funding Acquisition, Writing – review and editing

Acknowledgements
This work was supported by the United States Department of Energy Advanced Fuels Campaign.

---

[1] Gorton, J.P., Schappel, D., Nelson, A.T. and Brown, N.R., 2020. Impact of uranium oxide (UO2) fuel with molybdenum (Mo) inserts on pressurized water reactor performance and safety. *Journal of Nuclear Materials*, *542*, p.152492.
[2] Brown, N.R., Ludewig, H., Aronson, A., Raitses, G. and Todosow, M., 2013. Neutronic evaluation of a PWR with fully ceramic microencapsulated fuel. Part I: Lattice benchmarking, cycle length, and reactivity coefficients. *Annals of Nuclear Energy*, *62*, pp.538-547.
[3] Capps, N., Schappel, D. and Nelson, A., 2020. Initial development of an RIA envelope for dispersed nuclear fuel. *Annals of Nuclear Energy*, *148*, p.107719.
[4] Hartanto, D., Kim, Y. and Venneri, F., 2015. Neutronics evaluation of a super-deep-burn with TRU fully ceramic microencapsulated (FCM) fuel in CANDU. *Progress in Nuclear Energy*, *83*, pp.261-269.
[5] Lu, C. and Brown, N.R., 2019. Fully ceramic microencapsulated fuel in prismatic high-temperature gas-cooled reactors: Design basis accidents and fuel cycle cost. *Nuclear Engineering and Design*, *347*, pp.108-121.
[6] Brown, N.R., 2020. A review of in-pile fuel safety tests of TRISO fuel forms and future testing opportunities in non-HTGR applications. *Journal of Nuclear Materials*, *534*, p.152139.
[7] Fratoni, M. and Terrani, K.A., 2017. PWR core design with Metal Matrix Micro-encapsulated (M3) fuel. *Progress in Nuclear Energy*, *100*, pp.419-426.
[8] Wigeland, R., Taiwo, T., Ludewig, H., Todosow, M., Halsey, W., Gehin, J., Jubin, R.,

Buelt, J., Stockinger, S., Jenni, K., Oakley, B., 2014. Nuclear Fuel Cycle Evaluation and Screening—Final Report, INL/EXT-14-31465 FCRD-FCO-2014-000106. Idaho National Laboratory (October 8). <https://fuelcycleevaluation.inl.gov/Shared%20Documents/ES%20Main%20Report.pdf>.

[9] Ang, C., Snead, L. and Kato, Y., 2020. A logical approach for zero-rupture Fully Ceramic Microencapsulated (FCM) fuels via pressure-assisted sintering route. *Journal of Nuclear Materials*, *531*, p.151987.

[10] Morris, R.N. and Pappano, P.J., 2007. Estimation of maximum coated particle fuel compact packing fraction. *Journal of Nuclear Materials*, *361*(1), pp.18-29.

[11] Pavlou, A.T., Betzler, B.R., Burke, T.P., Lee, J.C., Martin, W.R., Pappo, W.N. and Sunny, E.E., 2012, July. Eigenvalue sensitivity studies for the Fort St. Vrain high temperature gas-cooled reactor to account for fabrication and modeling uncertainties. In *Proc. American Nuclear Society Reactor Physics Topical Meeting, PHYSOR-2012, Knoxville, TN, April*(Vol. 1).

[12] Lou, X. and Gandy, D., 2019. Advanced manufacturing for nuclear energy. *JOM*, *71*(8), pp.2834-2836.

[13] Sridharan, N. and Field, K., 2019. A road map for the advanced manufacturing of ferritic-martensitic steels. *Fusion Science and Technology*, *75*(4), pp.264-274.

[14] Kile, R.F., Wysocki, A.J., Betzler, B.R. and Brown, N.R., 2021. Transformational challenge reactor analysis to inform preconceptual core design decisions: Sensitivity study of transient analysis in a hydride-moderated microreactor. *Nuclear Engineering and Design*, *376*, p.111122.

[15] Trammell, M.P., Jolly, B.C., Richardson, M.D., Schumacher, A.T., Terrani, K.A., 2019. Advanced Nuclear Fuel Fabrication: Particle Fuel Concept for TCR. *ORNL*, p.1216.

[16] Terrani, K.A., Jolly, B.C., Trammell, M.P., Vasudevamurthy, G., Schappel, D., Ade, B., Helmreich, G.W., Wang, H., Rossy, A.M., Betzler, B.R. and Nelson, A.T., 2021. Architecture and properties of TCR fuel form. *Journal of Nuclear Materials*, 547, p.152781.

[17] Brown, N.R., Ludewig, H., Aronson, A., Raitses, G. and Todosow, M., 2013. Neutronic evaluation of a PWR with fully ceramic microencapsulated fuel. Part II: Nodal core calculations and preliminary study of thermal hydraulic feedback. *Annals of Nuclear Energy*, *62*, pp.548-557.

[18] Harp, J.M., Morris, R.N., Petrie, C.M., Burns, J.R. and Terrani, K.A., 2021. Postirradiation examination from separate effects irradiation testing of uranium nitride kernels and coated particles. *Journal of Nuclear Materials*, *544*, p.152696.

[19] Lindemer, T.B., Voit, S.L., Silva, C.M., Besmann, T.M. and Hunt, R.D., 2014. Carbothermic synthesis of 820 μm uranium nitride kernels: Literature review, thermodynamics, analysis, and related experiments. *Journal of nuclear materials*, *448*(1-3), pp.404-411.

[20] Brown, N.R., Aronson, A., Todosow, M., Brito, R. and McClellan, K.J., 2014. Neutronic performance of uranium nitride composite fuels in a PWR. *Nuclear Engineering and Design*, *275*, pp.393-407.

[21] Gorton, J.P., Collins, B.S., Nelson, A.T. and Brown, N.R., 2019. Reactor performance and safety characteristics of ThN-UN fuel concepts in a PWR. *Nuclear Engineering and Design*, *355*, p.110317.

[22] Heidet, F., Brown, N.R. and Tahar, M.H., 2015. Accelerator–reactor coupling for energy production in advanced nuclear fuel cycles. *Reviews of Accelerator Science and Technology*, pp.99-114.

[23] Hernandez, R. and Brown, N.R., 2020. Potential fuel cycle performance of floating small modular light water reactors of Russian origin. *Annals of Nuclear Energy*, *144*, p.107555.

[24] Leppänen, J., 2010. Performance of Woodcock delta-tracking in lattice physics applications using the Serpent Monte Carlo reactor physics burnup calculation code. *Annals of Nuclear Energy*, *37*(5), pp.715-722.
[25] Driscoll, M.J., Downar, T.J. and Pilat, E.E., 1990. *The linear reactivity model for nuclear fuel management*. Amer Nuclear Society.
[26] United States Nuclear Regulatory Commission. ‘‘Issued design certification: Advanced Passive 1000 (AP1000).” Retrieved from https://www.nrc.gov/ reactors/new-reactors/design-cert/ap1000.html.
[27] McMurray, J.W., Kiggans, J.O., Helmreich, G.W. and Terrani, K.A., 2018. Production of near-full density uranium nitride microspheres with a hot isostatic press. *Journal of the American Ceramic Society*, *101*(10), pp.4492-4497.
[28] Parkison, A., 2020. *Fabrication of uranium nitride* (No. 10,562,771). Los Alamos National Lab.(LANL), Los Alamos, NM (United States).