Nuclear Engineering and Design 340 (2018) 122–132

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Fuel geometry options for a moderated low-enriched uranium kilowatt-class space nuclear reactor

Leonardo de Holanda Mencarini[a,b], Jeffrey C. King[a,*]

[a] Nuclear Science and Engineering Program, Colorado School of Mines (CSM), 1500 Illinois St, Hill Hall, 80401 Golden, CO, USA
[b] Subdivisão de Dados Nucleares - Instituto de Estudos Avançados (IEAv), Trevo Coronel Aviador José Alberto Albano do Amarante, n 1, 12228-001 São José dos Campos, SP, Brazil

ABSTRACT

A LEU-fueled space reactor would avoid the security concerns inherent with Highly Enriched Uranium (HEU) fuel and could be attractive to signatory countries of the Non-Proliferation Treaty (NPT) or commercial interests. The HEU-fueled Kilowatt Reactor Using Stirling Technology (KRUSTY) serves as a basis for a similar reactor fueled with LEU fuel. Based on MCNP6™ neutronics performance estimates, the size of a 5 kW_e reactor fueled with 19.75 wt% enriched uranium-10 wt% molybdenum alloy fuel is adjusted to match the excess reactivity of KRUSTY. Then, zirconium hydride moderator is added to the core in four different configurations (a homogeneous fuel/moderator mixture and spherical, disc, and helical fuel geometries) to reduce the mass of uranium required to produce the same excess reactivity, decreasing the size of the reactor. The lowest mass reactor with a given moderator represents a balance between the reflector thickness and core diameter needed to maintain the multiplication factor equal to 1.035, with a H/D ratio of 1.81. All three heterogeneous geometries yield a minimum mass reactor using a moderator/fuel ratio of 80 wt%. The lifetime is directly proportional to the initial amount of fissile material in the core in all the cases. Based on the small differences in estimated masses, but large difference in estimated lifetimes between the 60 wt% and 80 wt% moderated reactors, the 60 wt% moderated systems with disc or helical fuel geometries represent the best balance between total mass and operating lifetime.

1. Introduction

Space nuclear power systems convert the thermal energy released by radioactive decay or nuclear fission to electricity to be used by a spacecraft or other space-based equipment. Some advantages of nuclear energy systems for space applications include: compact size, long operating lifetimes, and operation independent of the distance from the sun or of the orientation to the sun (Buden, 2011a). A Low Enriched Uranium (LEU) fueled space reactor appears to be a realistic option for signatory countries of the Non-Proliferation Treaty (NPT), which ratified the decision to not employ Highly Enriched Uranium (HEU) in future nuclear systems (IAEA, 2001). LEU-fueled reactors could also be of interest to commercial space exploration companies. Kilopower Space Nuclear power systems are interesting because they can fill a gap in available electrical power systems between 1 kW_e and 10 kW_e with operational times in excess of two decades. A small nuclear fission heat source may be an attractive alternative to radioisotope heat sources due to the limited supply of plutonium-238 (the most common RTG fuel) and the inherent security concerns related to plutonium. This work presents a preliminary study of moderator configuration options for a LEU-fueled kilowatt-class space nuclear reactor considering four different geometrical combinations of metallic fuel (U-10Mo) and moderator ($ZrH_{1.5}$) in the core. The study considers potential moderator configurations in terms of the core diameter required to provide a cold, clean multiplication factor (k_{eff}) of 1.035. This comparison illustrates the impact of moderator configuration on the size and performance of a LEU-fueled kilowatt-class space nuclear reactor.

2. Background

The LEU-fueled space nuclear reactor considered in this paper is based on the Kilowatt Reactor Using Stirling TechnologY (KRUSTY) reactor designed by the Los Alamos National Laboratory (Poston et al., 2013). Fig. 1 provides axial and radial cross section views of the KRUSTY reactor geometry. The HEU-fueled KRUSTY reactor consists of six important subsystems - the solid block of uranium-10 wt% molybdenum alloy (U-10Mo) fuel, the beryllium oxide (BeO) reflector, the sodium working fluid heat pipes, the radiation shadow shield, the boron carbide (B_4C) safety rod, and the advanced Stirling convertor engine power subsystem (Chan et al., 2007). The shadow shield consists of lithium hydride (canned in stainless steel) as the neutron shield material and depleted uranium as the gamma shield material.

The KRUSTY core is cast as a single cylinder of U-10Mo with a height-to-diameter (H/D) ratio of 1.81. The U-10Mo alloy provides higher strength and more swelling resistance than pure uranium (Poston et al., 2013). Although not neutronically optimal, a cylinder

---

* Corresponding author.
E-mail addresses: lmencari@mines.edu, mencarini@ieav.cta.br (L.d.H. Mencarini), kingjc@mines.edu (J.C. King).

https://doi.org/10.1016/j.nucengdes.2018.09.017
Received 19 April 2018; Received in revised form 10 September 2018; Accepted 17 September 2018
0029-5493/

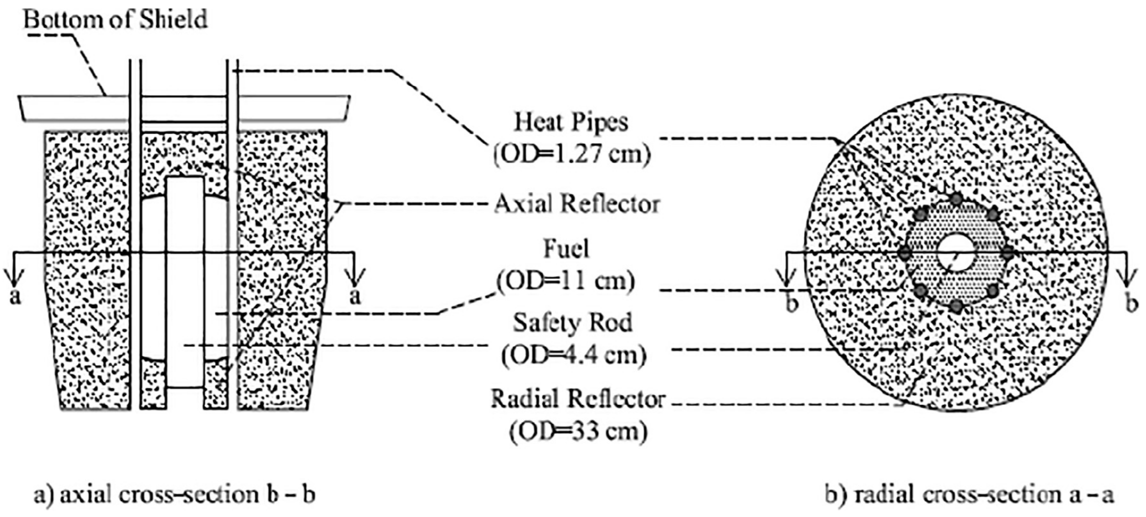

Fig. 1. Axial and radial cross-sections of KRUSTY (adapted from Poston et al., 2013).

with a H/D ratio > 1 is generally preferred in space applications because it reduces shield size, shortens heat conductions paths, and adds more heat transfer area from the fuel to the coolant. A greater core H/D ratio also provides more axial separation/shielding from the high-flux regions of the reactor. A control rod has maximum neutronic worth when in the center of a long H/D ratio core, and a control mechanism aligned with the system/launch axis is generally easier to integrate. Criticality safety is also simpler with a very high worth radial reflector (which is facilitated by a high H/D ratio). The core can thus be highly subcritical during forming, handling, and transport operations, and is more easily designed to remain subcritical in all potential launch accident scenarios (Poston et al., 2013).

A neutron reflector is necessary to maintain a small size system and provide sufficient reactivity worth to meet the launch accident criticality safety requirements. Potential reflector materials include beryllium, beryllium oxide and graphite. In space applications, beryllium oxide is generally preferred as it is a denser, higher worth material per unit thickness than pure beryllium or graphite (Poston et al., 2013).

Heat pipes transfer thermal energy through the evaporation and condensation of a working fluid, with the condensed fluid returned to the evaporator region via capillary action through a wick (Reay and Kew, 2006). Heat pipes can provide heat transfer coefficients orders of magnitude higher than possible through conduction, with no moving parts. A heat pipe reactor eliminates the components that would be needed for a pumped loop, simplifying system integration. The simple reactor geometry in kilopower-class reactors allows the use of simple, straight cylindrical heat pipes; however, there is considerable experience with bent and non-cylindrical heat pipes (Reay and Kew, 2006). Fig. 1 shows the location of the eight heat pipes located at the core periphery in the KRUSTY reactor. At the low thermal power of the KRUSTY reactor (4 kW_t), the heat pipes do not need to be within the fuel, as the thermal resistance in the fuel is low (Poston et al., 2013). This reduces the size and mass of the core, since interior heat pipes would displace fuel from the core and the heat pipe materials would be parasitic neutron absorbers. The lack of internal heat pipe voids also minimizes the potential impact of flooding during an accident, thus simplifying launch safety. Additionally, the radiation streaming paths through the shadow shield offered by ex-core heat pipes will be less significant than the streaming paths resulting from in-core heat pipes.

The radiation shadow shield utilizes lithium hydride (LiH) clad in stainless steel as the neutron shield material and depleted uranium (DU) as the gamma shield material. The LiH is enriched in lithium-6 to reduce the gamma source from neutron capture in the stainless-steel and DU. The reference shield utilizes three layers of LiH and DU, with each layer of LiH being placed in a stainless-steel can (Poston et al., 2013). The shield contains full penetrations for the heat pipes, plus a gap for multi-foil insulation to prevent shield heating and parasitic power loss (Poston et al., 2013).

Fig. 1 also shows the location of the safety rod system, which consists of a 4.4 cm boron carbide (B_4C) control rod that inserts into a hole along the axial core centerline. Prior to launch, the safety rod is fully inserted into the reactor core and maintains the system in a subcritical state during the spacecraft launch and in the event of any launch accident (Poston et al., 2013). Once the spacecraft has achieved a safe orbit, the safety rod is removed to bring the reactor to a critical, power-producing, state. The negative temperature reactivity coefficient resulting from the uranium alloy controls the reactivity of the reactor, maintaining the reactor in a critical state when the safety rod is removed.

Stirling engines use a reciprocating piston driven by thermal power to produce electric power from a linear alternator (Buden, 2011b). Stirling engine power converters scale well at low powers and can yield power conversion efficiencies significantly greater than is possible with the thermoelectric converters used in previous efforts (Poston et al., 2013; Buden, 2011b). High-efficiency free-piston Stirling convertors have been baselined for the initial designs to increase system performance and provide high specific power. Their use benefits from existing flight development of the Sunpower, Inc., 80-We Advanced Stirling Convertor as well as recent successful technology demonstrations of both 1- and 6-kWe convertors developed by Sunpower Inc. (with thermal conversion efficiency up to 40%), for NASA under the current Nuclear Systems Program. The Stirling engine heat acceptor is conductively coupled to the sodium heat pipe condenser and uses the thermal energy from the reactor to thermodynamically drive the power piston and linear alternator (Gibson et al, 2015).

The LEU-fueled space nuclear reactor will consist of these same subsystems, modified to use Low-Enriched Uranium. The LEU-fueled kilowatt-class space nuclear reactors developed in this paper all have the same basic geometry model, shown in Fig. 2. The LEU-fueled models described in this paper provide the option for moderated systems with a thermal fission spectrum instead of the unmoderated fast spectrum system used in KRUSTY.

3. Model description

This work presents a comparison of moderator options for an LEU-fueled alternative to KRUSTY, based on results obtained from Monte Carlo N Particle version 6 (MCNP6™) (Pelowitz, 2013) models. The reactor cores are compared in terms of the minimum core diameter required to provide a cold clean multiplication factor (k_{eff}) of 1.035. For

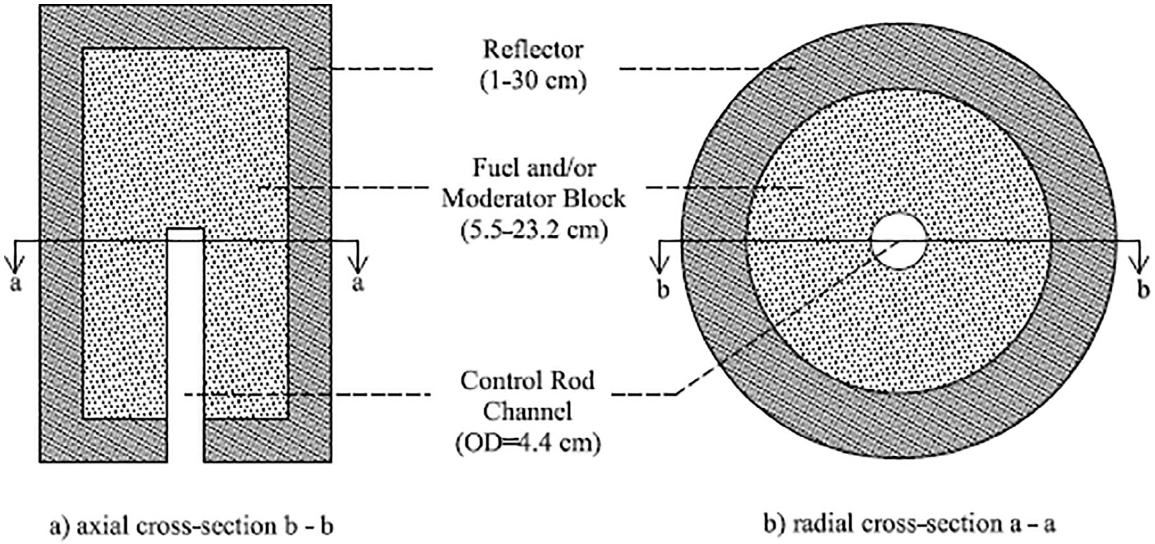

Fig. 2. Axial and radial cross sections of the LEU-fueled reactor.

simplicity, the models omit the heat pipes, the taper of the reflector, and the cladding between the fuel and the moderator. The computational models in this work consider four cases, a homogeneous mixture of fuel and moderator and three heterogeneous fuel and moderator combinations.

In the homogeneously moderated core (Fig. 2), the core consists of a uniform and isotropic mixture of fuel (U-10Mo) and moderator ($ZrH_{1.5}$). In the heterogeneously moderated cores, the first geometry (Fig. 3) consists of spheres of fuel, arranged in a cubic lattice surrounded by moderator. Varying the sphere diameter and spacing provides a specific moderator/fuel ratio. For example, a fuel sphere radius of 0.7 cm, with a square lattice pitch equal to 1.327 cm, provides a 80 wt% moderator/fuel ratio. The second geometry (Fig. 4) considers the fuel and moderator as alternating discs stacked orthogonal to the axis of the control rod. The moderator/fuel ratio is determined by the ratio of the thickness of the fuel and moderator discs. This work considers fuel disk ranging from 0.1 cm to 1.0 cm, in steps of 0.1 cm, while the moderator disc thicknesses vary to provide moderator weight fractions of 30 wt%, 60 wt%, 80 wt% and 90 wt% moderator.

The third geometry (Fig. 5) places the fuel inside the core cylinder as a helix structure. In this geometry, the angle subtended by the fuel sector in each vertical step controls the fuel/moderator ratio. To create the helix, the element disc (fuel plus moderator) in each step is rotated relative to the previous step by an amount equal to the fuel angle (Fig. 5). The fuel sector angle (α in Fig. 5) is defined according the moderator-fuel weight percentage. For example, in a 90 wt% helical moderated system, the fuel sector angle is equal to 6.42° degrees.

Table 1 presents the materials and densities used in each region in the model. The LEU reactor is fueled with 19.75 wt% enriched uranium-10 wt% molybdenum alloy and the zirconium hydride ($ZrH_{1.5}$) acts as a moderator in the system. The choice of zirconium hydride as the moderator in the system is based on the moderator used in the U-ZrH fueled reactors of the Systems for Nuclear Auxiliary Power (SNAP) program (Buden, 2011b); and the present study uses a hydrogen to zirconium ratio of 1.5 for conservatism (Lee et al., 2015).

Beryllium oxide serves as the reflector material and a cylindrical boron carbide (B_4C) control rod in center of the core provides shutdown control (see Figs. 2–5). The control rod is 22 cm long and 4.4 cm in diameter. All of the computational simulations assume that the boron carbide is enriched to 100% boron-10.

In all cases, the H/D ratio of the core is 1.81, the same as that in the KRUSTY reactor (Poston et al., 2013). The MCNP6™ computational

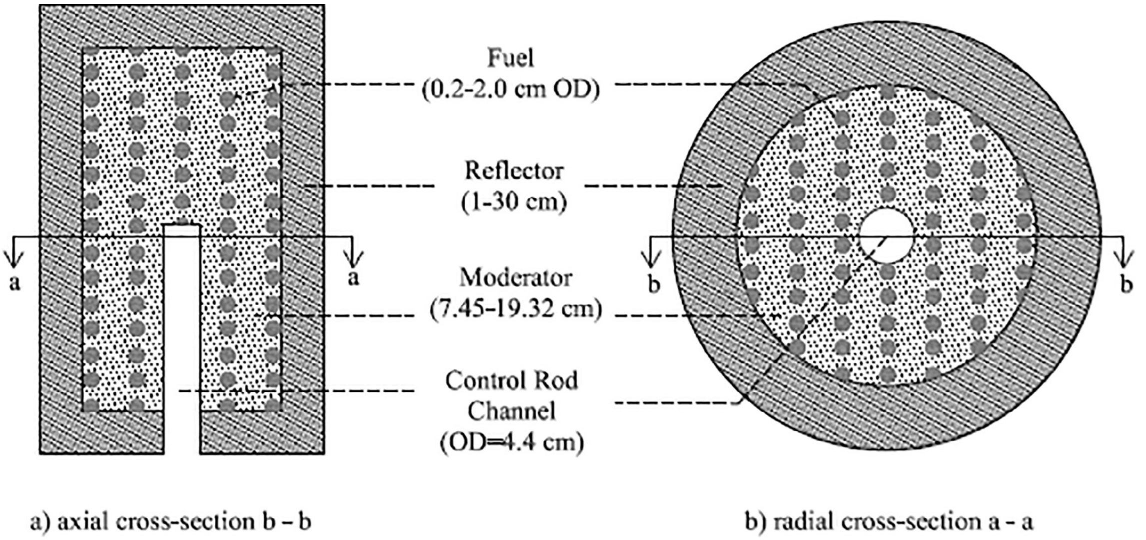

Fig. 3. Axial and radial cross-sections of the LEU-fueled reactor with spherical fuel geometry.

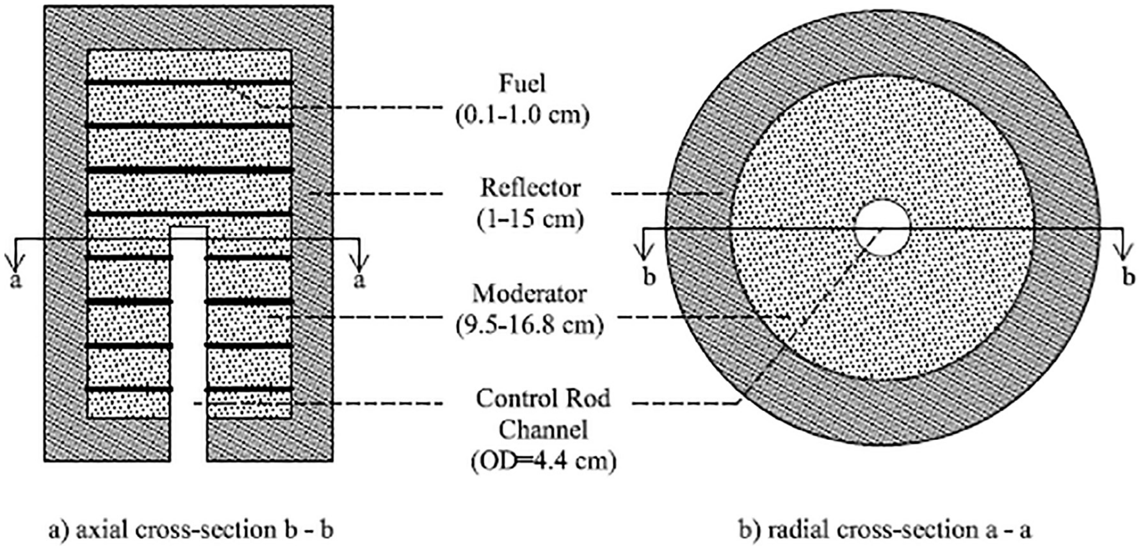

Fig. 4. Axial and radial cross-sections of the LEU-fueled reactor with disc fuel geometry.

code (Pelowitz, 2013) calculated the multiplication factor (k_{eff}) for each case in this study based on 400 active cycles with 10,000 source histories per cycle with 30 cycles skipped before beginning tally accumulation. Each of the simulations used the ENDF/B-VII.1 (.80c) and ENDF/B-VII.0 (0.20 t) nuclear data. All of the model cases considered a reactor temperature of 293 K. The uncertainties associated with the multiplication factor results are less than 0.0005 in all cases.

4. Results

Using MCNP6™ to predict the reactor neutronics performance, this study adjusts the geometry of a LEU reactor fueled with un-moderated 19.75 wt% enriched uranium-10 wt% molybdenum alloy fuel to match the cold-clean multiplication factor of KRUSTY (1.035) (Poston et al., 2013). Then, zirconium hydride moderator is added to the core to reduce the size of the reactor while maintaining the same cold-clean multiplication factor. This work considers core moderator fractions of 0, 30, 60, 80, and 90 wt% moderator. The heterogeneous core models consider three different fuel/moderator geometries inside the core, as described in the previous section. In all cases, the reactor core and reflector are sized to yield a cold-clean multiplication factor of 1.035.

Table 1
Materials for the fuel, moderator, control rod, and reflector in the LEU-fueled reactor models.

Region	Material	Density (g/cm^3)
Fuel block	U-10Mo	16.82
Control rod	B_4C	2.40
Moderator	$ZrH_{1.5}$	5.60
Reflector	BeO	3.010

4.1. Unmoderated reactor

The first step in the LEU reactor study adjusted the reflector thickness to maximize the reflector's performance. The initial core diameter (11 cm) from KRUSTY, with a central control rod gap of 4.4 cm OD, was considered as a bare, un-moderated core. Increasing the reflector thickness in 1 cm steps produced Fig. 6. Simply adding reflector thickness is not sufficient to reach a k_{eff} of 1.035 with an LEU-fueled

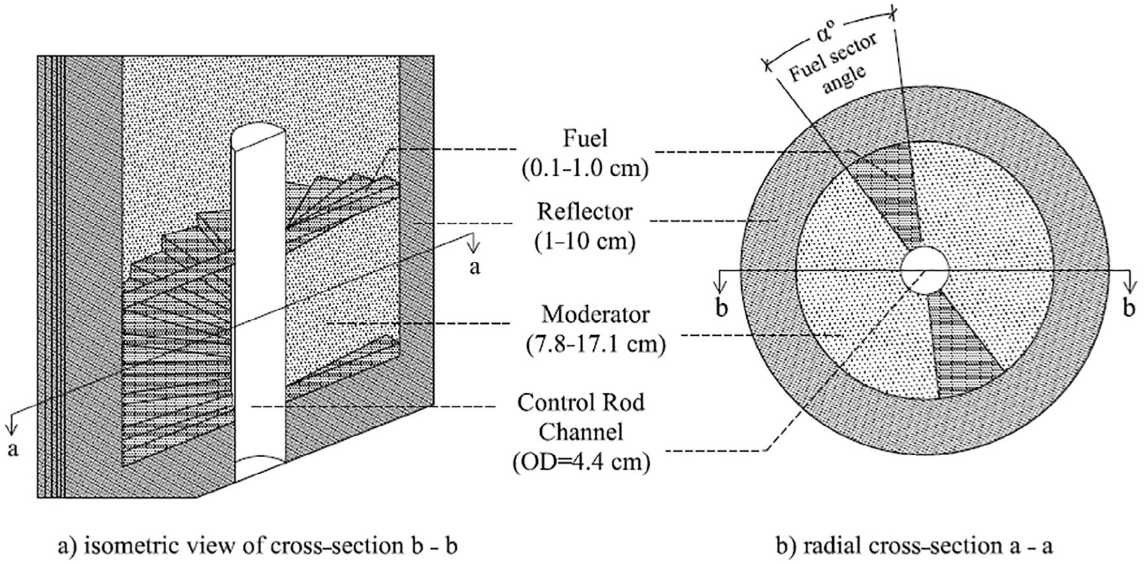

Fig. 5. Isometric and radial cross-sections of the LEU-fueled reactor with helical fuel geometry.

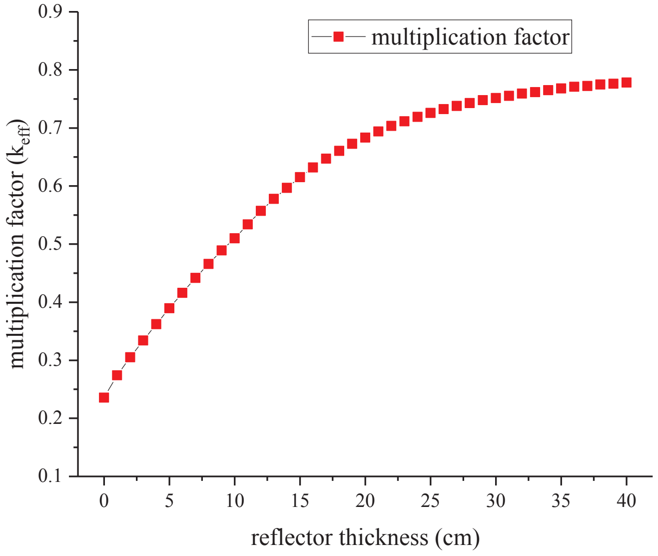

Fig. 6. Multiplication factor as a function of reflector thickness for an unmoderated LEU reactor core with the same dimensions as KRUSTY.

reactor core; and, increasing the reflector thickness more than 30 cm does not result in substantial increases in the multiplication factor. Therefore, 30 cm was the maximum effective reflector thickness for the purposes of the initial reactor sizing study. Considering a constant reflector thickness of 30 cm, increasing the core diameter with a constant H/D ratio equal to 1.81 (the H/D ratio of KRUSTY (Poston et al., 2013)) determines the required reactor size.

Based on Fig. 7, a 17.9 cm diameter LEU core, 32.7 cm in height, with a reflector thickness of 30 cm, provides a beginning of life multiplication factor of 1.035. Changing from 93 wt% enriched HEU to 19.75 wt% enriched LEU fuel resulted in a significant increase in the size of the reactor core (from 20 cm high, 11 cm OD to 32.7 cm high, 17.9 cm OD), with a concurrent increase in total mass, from 98.0 kg to 1,434.5 kg (more than a ten-fold increase), as shown in Table 2. The main source of the mass increase is from the reflector, which is much larger in the LEU case. Interestingly, the total mass of uranium-235 remains relatively constant. Based on these results, an unmoderated LEU-fueled kilopower-class reactor does not seem practical.

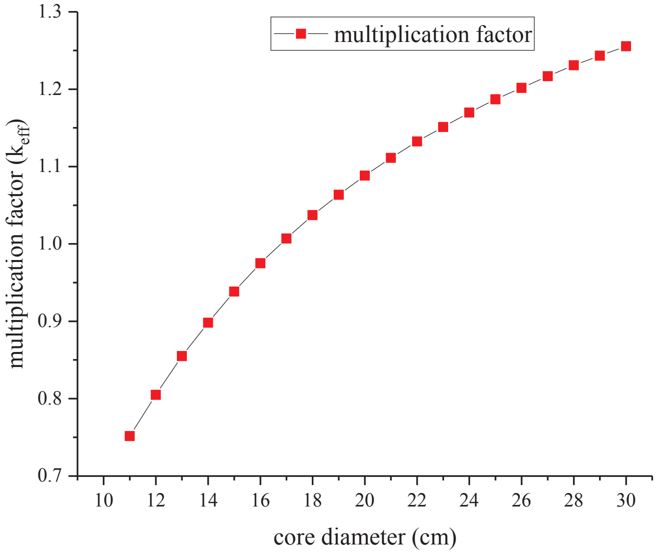

Fig. 7. Multiplication factor as a function of core diameter for the un-moderated LEU reactor with a H/D ratio of 1.81 and a reflector thickness of 30 cm.

Table 2
Homogeneous reactor masses for a multiplication factor of 1.035 for unmoderated HEU and LEU cores.

Region	Component	Uranium enrichment	
		93 wt%‡	19.75 wt%
Core	U_{235}	22.3	23.5
	U_{238}	1.7	95.4
	Mo	2.7	13.2
Reflector	BeO	70.5	1,301.6
Control rod	B_4C	0.8	0.8
Total mass (kg)		98.0	1,434.5

‡ (Poston et al., 2013).

4.2. Moderated reactor

Adding a moderator to the reactor core can reduce the size of an LEU-fueled space reactor system (Bodansky, 2004). In moderated reactors, which are the main type of reactor used for commercial power production, the neutron energy (E) is reduced from the MeV region ($0.1\,\text{MeV} < E \leq 15\,\text{MeV}$) to the thermal region ($E < 1\,\text{eV}$) by successive elastic collisions with light nuclei, possibly preceded by inelastic scattering in uranium (Bodansky, 2004). Reducing the energy of the neutrons to a region where the cross sections are more favorable can decrease the amount of uranium needed to reach criticality (Lee et al., 2015). At a nominal neutron energy of 0.0253 eV, the ratio of the cross section for fission in uranium-235 (583 barns) to capture in uranium-238 (2.68 barns) is greater than 200, making it easier to sustain a chain reaction (Terremoto, 2004). Zirconium-hydride is a well-proven moderator. The SNAP-10A space nuclear reactor, the only space reactor flown by the United States of America in 1965, contained 37 uranium–zirconium hydride fuel elements enriched with uranium-235 (Angelo and Buden, 1985). For conservatism, the LEU reactor models in the present study use a lower fraction of hydrogen ($ZrH_{1.5}$) than reported for SNAP-10A ($ZrH_{1.68}$ – $ZrH_{1.83}$) (Angelo and Buden, 1985). The lower fraction of hydrogen (1.5) accounts for possibility of hydrogen dissociation from the ZrH during the reactor operation. Also, the four models used in this paper assume a maximum operating temperature less than maximum operating temperature of ZrH (1200 K) (Gibson et al, 2015). This reduced operating temperature will reduce power conversion efficiency, but may minimize the dissociation problem related to $ZrH_{1.5}$.

4.2.1. Homogeneously moderated core

Table 3 presents mass estimates for a homogeneously moderated LEU-fuel reactor with a multiplication factor of 1.035 as a function of the weight fraction of the moderator (0, 30, 60, 80 and 90 wt%

Table 3
Homogeneous reactor masses and core diameters for a multiplication factor of 1.035 as a function of moderator fraction.

Region	Component	Moderator Fraction				
		0 wt%	30 wt%	60 wt%	80 wt%	90 wt%
Core masses (kg)	U_{235}	23.5	9.6	2.8	1.2	0.8
	U_{238}	95.4	39.0	11.5	4.7	3.0
	Mo	13.2	5.4	1.6	0.7	0.4
	$ZrH_{1.5}$	0	23.1	24.0	26.3	37.7
Total core mass (kg)		132.1	77.1	39.9	32.9	41.9
Reflector mass (kg)	BeO	1,301.6	1,280.4	1,183.6	1,176.2	1,264.9
Control rod mass (kg)	B_4C	0.8	0.8	0.8	0.8	0.8
Total mass (kg)		1,434.5	1,358.3	1,224.3	1,209.9	1,307.6
Core diameter (cm)		17.90	17.52	15.74	15.60	17.24

moderator). In all cases, the height to diameter ratio (1.81), reflector thickness (30 cm), and materials are the same as the un-moderated LEU reactor in Section 4.1. Adding moderator can significantly reduce the mass of the LEU reactor by 230.3 kg (15.98%), considering the difference between un-moderated reactor and the smallest reactor (containing 80 wt% $ZrH_{1.5}$). These results are considered the upper limit for the mass of the homogeneously moderated systems considered in this paper.

4.2.2. Heterogeneously moderated core

A key question in the development of an LEU-fueled space nuclear reactor is the effect of core heterogeneity on the reactor's multiplication factor. The models and geometries developed during this work considerer three different moderator and fuel geometries, as discussed in Section 3. The heterogeneously moderated reactor provides an example of the impact of combining the fuel and moderator as discrete regions.

The spherical geometry cases in this subsection adjust the pitch and diameter of the fuel spheres arranged in a square lattice filled with moderator to obtain a specified fuel/moderator ratio. The fuel diameters range from 0.2 cm to 2.0 cm, in steps of 0.2 cm, and the fuel pitch varies to provide the moderator weight fractions of 30 wt%, 60 wt %, 80 wt% and 90 wt%.

Table 4 presents the diameters and masses of the smallest homogeneously moderated cores and the smallest heterogeneously moderated cores with spherical geometry. Each case results in a multiplication factor of 1.035 with a 30 cm reflector thickness. For each moderator weight fraction, the heterogeneously moderated cores result in a smaller reactor than is possible with the homogeneously moderated core. A heterogeneously moderated reactor with 60 wt% moderator and fuel spheres with a diameter of 1 cm is the minimum mass core from the options considered in this analysis with a 30 cm reflector thickness. As the moderator ratio increases, the size of the fuel sphere needed achieve the smallest possible core with a multiplication factor of 1.035 decreases. However, above 80 wt% moderator, the decrease in the fuel sphere diameter does not yield better results. In terms of total core mass, the fuel sphere diameter and the weight percentage of the moderator are indirectly proportional in their impact on core diameter.

Decreasing the fuel sphere diameter and increasing the moderator fraction leads to a minimum core diameter at 80 wt% moderator.

Based on the results in this section, a highly moderated system can result in a reduction in the total mass of the system; however, the LEU system is still significantly heavier than the HEU system, largely due to the mass of the reflector. The next subsection demonstrates that balancing the size of the core and the size of the reflector can result in a significantly smaller LEU-fueled reactor.

4.3. Reactor core and reflector size optimization

The results obtained in the previous sub-sections were calculated with a fixed 30 cm reflector thickness. As indicated in Fig. 6 the multiplication factor does not show significant increase after 30 cm thickness. Therefore, 30 cm was the most effective reflector thickness for the purposes of the initial reactor sizing study; however, the lowest mass reactor will be a balance between reflector thickness and reactor diameter. Section 4.3 considers this balance in detail, using a range of reflector thicknesses from 1 cm to 30 cm, in steps of 1 cm. To compensate for the less effective reflector, the study increased the core diameter needed to maintain the cold-clean multiplication factor equal to 1.035, with a H/D ratio of 1.81. Increasing the amount of fissionable material inside the core also extended the lifetime of the reactor system, as will be shown in Section 4.4.

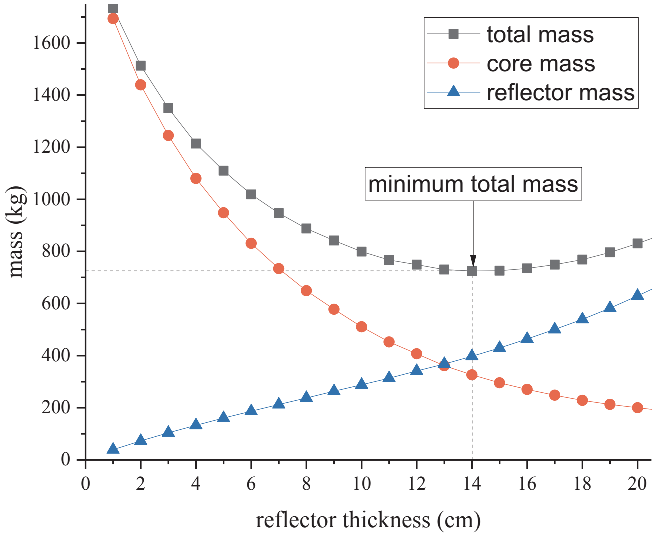

Fig. 8. Fuel and reflector mass as a function of reflector thickness for an un-moderated LEU reactor with a multiplication factor of 1.035.

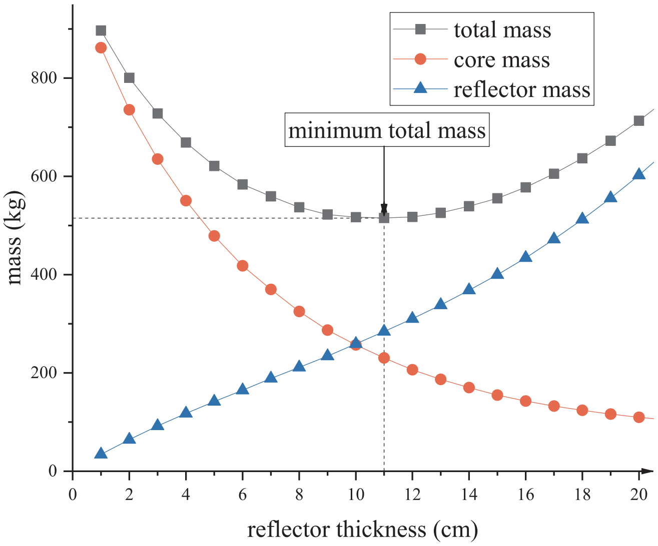

Fig. 9. Fuel and reflector mass as a function of reflector thickness for a LEU-fueled, 30 wt% homogeneously moderated reactor, with a multiplication factor of 1.035.

Table 4
Minimum mass heterogeneously and homogeneously moderated reactors with a reflector diameter of 30 cm and multiplication factor of 1.035.

Moderator Ratio (wt%)	Minimum mass homogeneous core		Minimum mass heterogeneous core			
	Core diameter (cm)	Mass (kg)	Core diameter (cm)	Fuel diameter (cm)	Pitch (cm)	Mass (kg)
30	17.5	1,359.4	15.9	2.0	2.12	1,250.9
60	15.7	1,225.4	14.9	1.0	1.42	1,174.8
80	15.6	1,211.0	15.3	0.2	0.38	1,193.2
90	17.2	1,308.7	17.1	0.2	0.47	1,300.6

Table 5
Dimensions and masses of the minimum mass homogeneously moderated reactors.

Moderator ratio (wt%)	Core diameter (cm)	Coremass (kg)	Reflector thickness (cm)	Reflector mass (kg)	Control rod mass (kg)	Total mass (kg)
30	24.98	230.3	11	284.3	08	515.4
60	23.82	144.9	7	135.4	0.8	281.1
80	24.06	126.4	5	87.3	0.8	214.5
90	25.53	140.6	5	96.6	0.8	238.0

Table 6
Dimensions and masses of the minimum mass heterogeneously moderated reactors with spherical geometry.

Moderator Ratio (wt%)	Core diameter (cm)	Core mass (kg)	Fuel diameter (cm)	Reflector thickness (cm)	Reflector mass (kg)	Control rod mass (kg)	Total mass (kg)
30	23.04	179.9	2.0	9	185.5	0.8	366.2
60	22.34	119.0	1.0	6	98.5	0.8	218.3
80	23.06	111.0	0.2	5	81.2	0.8	193.0
90	24.88	130.0	0.2	5	92.4	0.8	223.2

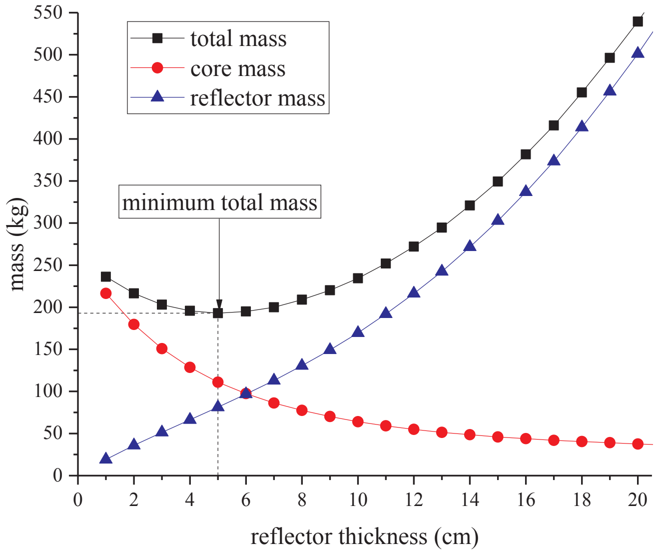

Fig. 10. Fuel and reflector mass as a function of reflector thickness for an LEU-fueled, 80 wt% heterogeneously moderated reactor, with spherical fuel geometry and a multiplication factor of 1.035.

4.3.1. *Mass optimization of the unmoderated reactor*

Fig. 8 indicates the core and reflector masses required to produce a cold clean multiplication factor of 1.035 with an unmoderated LEU-fueled reactor, as a function of reflector thickness. For the unmoderated LEU reactor, the minimum total mass point corresponds to a 14 cm reflector thickness. With a 14 cm reflector thickness, the total mass is equal to 725 kg, 709.5 kg (49.46%) less than the minimum mass unmoderated reactor with a 30 cm reflector thickness (Section 4.2.1.). However, the total mass of the unmoderated LEU reactor is still almost six times the KRUSTY mass (725 kg vs ~ 122 kg, respectively).

4.3.2. *Mass optimization of the homogeneously moderated reactor*

In the homogeneously moderated core, the fuel (U-10Mo), and moderator ($ZrH_{1.5}$) are uniformly mixed, forming a single, homogeneous material. Fig. 9 shows the optimization of the homogeneous moderator system containing 30 wt% moderator. In Fig. 9, the total mass minimum point is found considering the 11 cm reflector thickness, making a minimum total mass equal to 515.4 kg, reducing the total mass in 844.0 kg (62.09%) from the result obtained with the 30 cm reflector thickness discussed on 4.2.1. Table 5 presents the dimensions and masses of the minimum mass homogeneously moderated LEU-fueled reactors, considering moderator ratios of 30, 60, 80, and 90 wt% moderator.

In the homogeneous 30 wt% moderator model, the total mass minimum point corresponds to a 11 cm reflector thickness, making a minimum total mass equal to 515.4 kg, reducing the total mass 842.9 kg (62.06%), compared to the 30 wt% moderated homogeneous core with a 30 cm reflector (1358.3 kg, Table 4).

The 60 wt% homogeneously moderated reactor has a minimum mass of 281.1 kg with a 7 cm thick reflector, while the homogeneous 80 wt% and 90 wt% moderated reactors achieve a minimum total masses with 5 cm thick reflectors. The 80 wt% reactor has the lowest minimum mass (214.5 kg) of all the homogeneous systems. Also, the lowest mass homogeneously moderated LEU-fueled reactor is 510.5 kg less massive than the unmoderated LEU-fueled reactor considered in Section 4.3.1 (214.5 kg versus 725 kg, respectively).

4.3.3. *Mass optimization of the heterogeneously moderated reactor with spherical geometry*

The same process used to optimize the homogeneously moderated cores (reducing the reflector thickness and increasing the diameter of the core while keeping the fuel diameter equal to that listed in Table 4 for each moderator ratio) provides the minimum mass heterogeneously moderated reactors with spherical fuel geometry presented in Table 6.

Fig. 10 shows the core, reflector, and total masses of the heterogeneous moderator system containing 80 wt% moderator and a fuel sphere diameter of 0.2 cm, as a function of reflector thickness for the heterogeneously moderated LEU-fueled reactor with a multiplication factor of 1.035. In parallel to the reactors with 30 cm thick reflectors (Section 4.2.2), small fuel spheres are preferred in highly moderated cases while larger fuel spheres are preferred in less moderated cases. However, the results obtained using the heterogeneously moderated spherical geometry (Table 6) are less massive than their correspondents in the homogeneously moderated cases (Table 5).

4.3.4. *Mass optimization of the heterogeneously moderated reactor with disc geometry*

The disc geometry considered in this study would result in simple-to-fabricate fuel and moderator components that could be easily and repeatably assembled. Fig. 11 shows the core, reflector, and total masses calculated for the heterogeneously moderated system with disc fuel geometry containing 60 wt% moderator and 0.3 cm fuel disc thickness. The minimum total mass results from a 6 cm reflector thickness; corresponding a minimum total mass of 224.0 kg. This is 5.7 kg (2.61%) more than the minimum total mass resulting from the equivalent spherical fuel geometry with 60 wt% moderator (218.3 kg).

Table 7 presents the minimum mass values obtained using the disc fuel geometry. Based on the 30 wt% moderator disc geometry results, the minimum total mass point is achieved with a 8 cm reflector thickness, a fuel disc thickness equal to 1.0 cm, and a minimum total mass

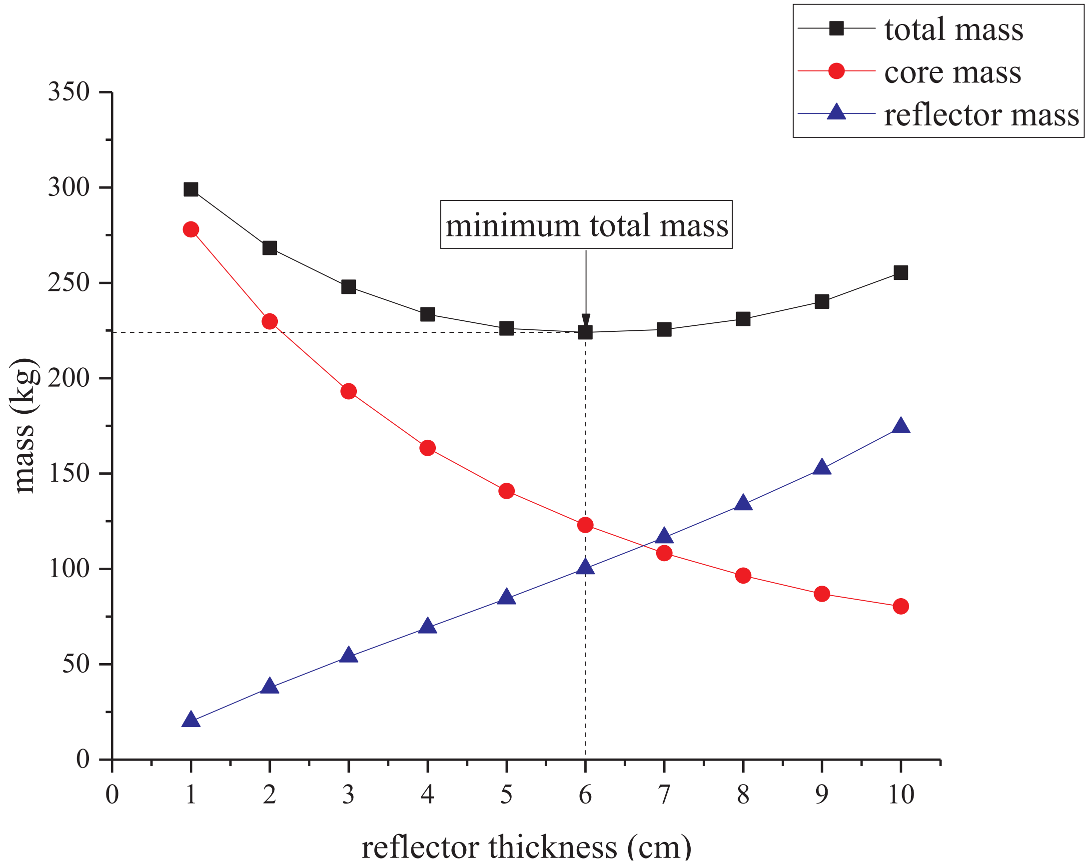

Fig. 11. Fuel and reflector mass as a function of reflector thickness for a LEU-fueled, 60 wt% heterogeneously moderated reactor, with disc fuel geometry and a multiplication factor of 1.035.

Table 7
Dimensions and masses of the minimum mass heterogeneously moderated reactors with disc geometry.

Moderator Ratio (wt%)	Core diameter (cm)	Core mass (kg)	Fuel disc thickness (cm)	Reflector thickness (cm)	Reflector mass (kg)	Control rod mass (kg)	Total mass (kg)
30	23.40	188.7	1.0	8	159.4	0.8	348.9
60	22.58	123.0	0.3	6	100.2	0.8	224.0
80	23.50	117.6	0.1	5	83.9	0.8	202.3
90	28.70	200.5	0.1	5	118.3	0.8	319.6

Table 8
Dimensions and masses of the minimum mass heterogeneously moderated reactors with helical geometry.

Moderator Ratio (wt%)	Core diameter (cm)	Core mass (kg)	Element disc thickness (cm)	Reflector thickness (cm)	Reflector mass (kg)	Control rod mass (kg)	Total mass (kg)
30	22.66	171.0	1.0	9	180.9	0.8	352.8
60	22.56	122.7	0.3	6	100.1	0.8	223.6
80	23.44	116.7	0.1	5	83.5	0.8	201.0
90	28.50	196.3	0.1	5	116.9	0.8	314.0

equal to 348.9 kg, which is 17.3 kg (4.72%) less than the best result obtained with 30 wt% moderator spherical geometry (366.2 kg).

Considering all of the disc geometry reactor systems, the 80 wt% moderator system produces the lowest total reactor mass, with a total mass equal to 202.3 kg, corresponding to a 5 cm reflector thickness and 0.1 cm fuel disc thickness. However, compared to the spherical fuel geometry reactors in Section 4.3.3, the disc fuel geometry increased the minimum achievable total mass by 9.3 kg (4.60%), based on the 80 wt% moderator geometry mass in Table 6 (193.0 kg).

With 90 wt% moderator, the minimum total mass also results from a 5 cm reflector thickness. The fuel disc thickness in this case is equal to 0.1 cm, producing a minimum total mass of 319.6 kg for this configuration. This is 96.4 kg (30.16%) higher than the result obtained with the 90 wt% moderator with spherical geometry, and 117.3 kg (63.30%) higher than the lowest total mass result among all the disc geometry reactors (see Table 7).

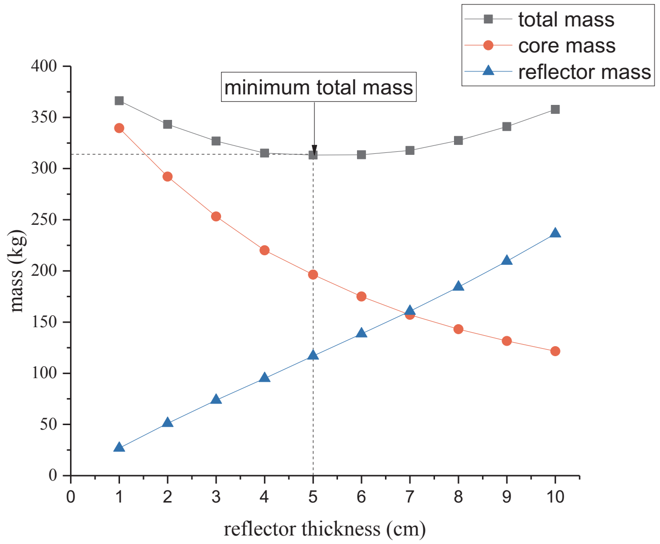

Fig. 12. Fuel and reflector mass as a function of reflector thickness for an LEU-fueled, 90 wt% heterogeneously moderated reactor, with helical fuel geometry and a multiplication factor of 1.035.

4.3.5. Mass optimization of the heterogeneously moderated reactor with helical geometry

Table 8 presents the mass optimization results for the helical geometry reactors, following the process described in Section 4.3.3. Fig. 12 represents mass optimization of the 90 wt% moderate reactor with helical fuel geometry. In this figure, the fuel elements are 0.1 cm thick. Considering the 30 wt% moderator systems, the minimum total mass point is found considering an 9 cm reflector thickness, with an element thickness of 1.0 cm. In this configuration, the minimum total mass is equal to 352.8 kg, reducing the total mass in 13.4 kg (3.66%) from the corresponding spherical fuel geometry reactor (Table 6), and an increase of 3.9 kg (1.11%) from corresponding disc fuel geometry reactor (Table 7).

Considering the 60 wt% moderator helical geometry reactor (Table 8), the minimum total mass is equal to 223.6 kg, increasing the total mass in 5.3 kg (2.37%) from the 60 wt% moderator reactor with spherical geometry. The minimum total masses for the 60 wt% moderated reactors with disc and helical fuel geometries (Tables 7 and 8) are 224.0 and 223.6 kg, respectively.

The 80 wt% moderator system has the minimum total mass amongst the helical geometry systems considered in this work. For this reactor, the minimum total mass is equal to 201.0 kg, reached with a 5 cm reflector thickness, and an element thickness of 0.1 cm. This is 22.6 kg (10.11%) less massive than the result obtained with 60 wt% moderator (Table 8). However, compared to the 80 wt% moderated spherical fuel geometry (193.0 kg, Table 6), this is an increase in total mass of 8.0 kg (4.15%). Compared to the 80 wt% moderated disc fuel geometry the helical fuel geometry decreased the minimum total reactor mass by 1.3 kg (0.64%).

The minimum total mass (314.0 kg) corresponds to a reflector thickness of 5 cm. This is considering a minimum total mass equal to 314 kg, increasing the total mass in 90.8 kg (40.68%) from the result obtained with the 90 wt% spherical fuel geometry (Table 6) reactor and decreasing the total mass 5.6 kg (1.75%) compared to the minimum mass 90 wt% moderated disc fuel geometry reactor (Table 7).

4.3.6. Mass optimization results for the heterogeneously moderated reactors

Table 9 summarizes the mass optimization results for the three fuel geometries discussed in subsections 4.3.3–4.3.5. The best results (lowest minimum masses) come from the 80 wt% moderated systems, but small differences between the 60 wt% and 80 wt% moderated reactors with disc and helical fuel geometry is also important. While this paper does not consider cladding, the disc and helical geometries facilitate the addition of cladding more readily than the spherical and homogeneous geometries.

A 20 wt% increase to the fuel mass, with a penalty of a few kilograms in total mass may be valuable, when the reactors' operating lifetime is considered. The reactor lifetime estimates are discussed in the next section.

4.4. Lifetime estimates

When comparing different LEU-fueled space reactor concepts, a comparison of expected reactor lifetime could be more important than comparing total mass at the same multiplication factor. At the same multiplication factor, a moderated reactor will contain less fissile material than an unmoderated reactor, and may thus have a dramatically shorter expected lifetime. This section considers the predicted lifetimes for the minimum mass homogeneously and heterogeneously moderated reactors determined in Section 4.3, based on a constant power output of 15 kW_{th} (assuming a constant electric power demand of 5 kW_{e} and a conversion efficiency of 33.3%).

The isotope depletion capability present in the MCNP6™ computational code predicted the multiplication factor (k_{eff}) for each of the minimum total mass geometry configurations in Section 4.3 as a function of operating time. The depletion routines in MCNP6™ consist of a linked process involving steady-state flux calculations to determine the system eigenvalue, 63-group fluxes, energy-integrated reaction rates, the fission multiplicity, and the recoverable energy per fission (Pelowitz, 2013). The CINDER90 module in MCNP6™ then performs depletion calculation to generate new number densities for the next time step. Following this, MCNP6™ uses these new number densities to generate another set of fluxes and reaction rates. The process repeats itself through the time steps specified by the user (Pelowitz, 2013). All of the lifetime evaluation cases discussed in this section considered a reactor temperature of 293 K. In the present study, an end-of-life multiplication factor of 1.0245 accounts for the loss of reactivity resulting from the change in temperature between shutdown and normal operation. This multiplication factor is based on the difference between the hot and cold k_{eff} estimated for KRUSTY (Poston et al., 2013).

Fig. 13 presents the lifetime estimate results obtained for the minimum mass homogeneously moderated LEU-fuel reactors containing 0, 30, 60, 80 and 90 wt% of moderator (Sections 4.3.1 and 4.3.2), which are, respectively, more than 100, 66, 20, 9 and 8 years. As expected, the greater the amount of fissile material inside the core, the greater the estimate lifetime.

Table 9
Minimum total mass results for the heterogeneously moderated reactors.

Moderator Ratio	Spherical geometry		Disc geometry		Helical geometry	
	Core diameter/reflector thickness (cm)	Mass (kg)	Core diameter/reflector thickness (cm)	Mass (kg)	Core diameter/reflector thickness (cm)	Mass (kg)
30	23.04/9	366.2	23.40/8	348.9	22.66/9	352.8
60	22.34/6	218.3	22.58/6	224.0	22.56/6	223.6
80	23.06/5	193.0	23.50/5	202.3	23.44/5	201.0
90	24.88/5	223.2	28.70/5	319.6	28.50/5	314.0

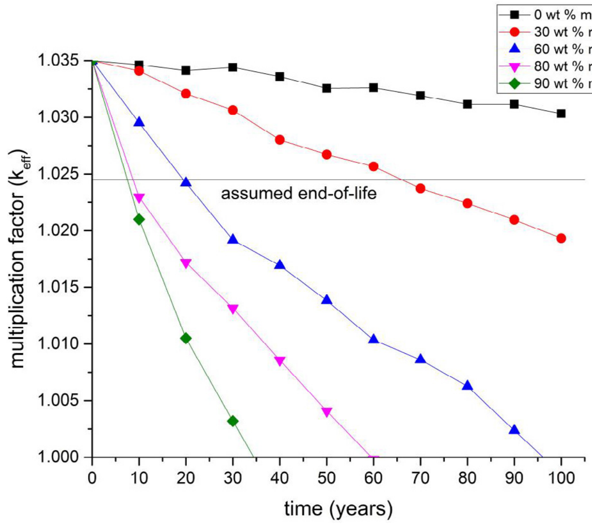

Fig. 13. Multiplication factor as a function of operating time and moderator fraction for the minimum mass homogeneously moderated LEU-fueled reactors operating at 15 kW_t.

Table 10 summarizes the predicted lifetimes for the minimum mass reactors with the three heterogeneous fuel geometries (spherical, disc, and helical, Sections 4.3.4 thru 4.3.6, respectively), using the same depletion methodology as the homogeneous cases. The lifetime is directly proportional to the initial amount of fissile material in the core in all of the cases.

Comparing the expected lifetime results for the homogeneous and heterogeneous models, the heterogeneously moderated cores have shorter lifetimes than the homogeneously moderated cores with the same moderator/fuel ratio. However, the heterogeneously moderated cores result in lower total reactor masses than the homogeneously moderated cores. Although the minimum total mass is a preponderant factor to the design of a space nuclear reactor, the lifetime estimate is also a key consideration. Considering a balance between these two essential factors, the 60 wt% moderated systems with disc or helical fuel geometries are preferred. Based on the results in Table 10, the mass penalty (21.7 kg for disc fuel geometry and 22.6 kg for helical fuel geometry) between the 60 wt% and 80 wt% reactors is more than made up for by the increased operating lifetime (+8 years for the disc fuel geometry and +9 years for the helical fuel geometry).

4.5. Mass comparison

Table 11 compares the HEU-KRUSTY fast reactor (Gibson et al, 2015) and the final recommended 60 wt% disc and helical geometry.

As shown in Table 11, the LEU-moderated reactors have less fissile material than the HEU-KRUSTY, but more uranium, larger reflectors, and the addition of moderator. The results LEU-fueled reactors are about 2.1 times as massive as the equivalent HEU-fueled reactor. However, when considering the overall system, the reactor is only a fraction of the total system mass. The shadow shield may represent another 148 kg in a HEU-fueled kilopower reactor system with a thermal power of 4.3 kW_t (Gibson et al, 2015). A moderated reactor system may require a less massive shield as the gamma contribution from the scattering of fast neutrons will be reduced. A future paper will consider the differences in shielding requirements for unmoderated and moderated space nuclear reactors.

5. Summary and conclusions

The low-enriched uranium fueled space nuclear reactor considered in this paper is based on the Kilowatt Reactor Using Stirling TechnologY (KRUSTY) reactor designed by the Los Alamos National Laboratory. The reactor cores are compared in terms of the minimum core diameter required to yield a cold-clean multiplication factor (k_{eff}) of 1.035. MCNP6™ calculations estimated the multiplication factor as a function of moderator weight percentage and core diameter for homogeneously and heterogeneously moderated cases, for core diameters from 11 cm to 30 cm. To reach the lowest mass reactor with a given moderator, the reflector thickness was decreased in steps of 1 cm, increasing the core diameter with a H/D ratio of 1.81 to maintain the multiplication factor equal to 1.035.

For the homogeneously moderated cases, increasing the percentage of moderator in the core decreased the core diameter required to reach a cold-clean multiplication factor at 1.035. In the heterogeneously moderated cases, adjusting both the fuel (U-10Mo) geometry and the weight percentage of the moderator ($ZrH_{1.5}$) is required to determine the minimum core diameter.

Considering the four possible moderator geometries, for the 30 wt% moderator systems analyzed, a spherical fuel geometry produces the lowest minimum total mass (366.2 kg). In the 60 wt% moderator systems analyzed, disc and helical fuel geometries yield a minimum total mass equal to 224.0 kg and 223.6 kg, respectively. However, the spherical fuel geometry still has the lower minimum total mass (218.3 kg) among all the four possible moderator geometries. Considering the 80 wt% moderator systems, a spherical fuel geometry results in the overall minimum total mass of 193.0 kg. Finally, for the 90 wt% moderator systems considered in this paper, a spherical fuel geometry produces a minimum total mass equal to 223.2 kg.

All three heterogeneous fuel geometries yield a minimum mass reactor using a moderator/fuel ratio of 80 wt%. With a spherical fuel geometry, decreasing the fuel sphere diameter while an increasing the moderator ratio leads to a minimum core diameter with a fuel sphere diameter of 0.2 cm. The disc and helical fuel geometries yield a minimum total mass (202.3 and 201.0 kg, respectively) with a fuel thickness of 0.1 cm, a 5 cm thick reflector, and core diameters at 23.50 and 23.44 cm, respectively.

The estimated reactor lifetime is directly proportional to the initial amount of fissile material in the core in all cases. Comparing the estimated lifetime results for the homogeneous and heterogeneous models, the heterogeneously moderated cores have shorter lifetimes than the homogeneously moderated cores with the same moderator/fuel ratios; however, the heterogeneously moderated cores result in lower mass

Table 10
Lifetime estimates for the minimum mass heterogeneously moderated reactors.

ModeratorRatio (wt%)	Spherical geometry			Disc geometry			Helical geometry		
	Total/fissile mass (kg)	Fuel diameter (cm)	Lifetime estimate (years)	Total/fissile mass (kg)	Fuel disc thickness (cm)	Lifetime estimate (years)	Total/fissile mass (kg)	Element disc thickness (cm)	Lifetime estimate (years)
30	366.2/22.4	2.0	47	348.9/23.5	1.0	44	352.8/21.3	1.0	44
60	218.3/8.5	1.0	15	224.0/8.7	0.3	16	223.6/8.7	0.3	16
80	193.0/4.0	0.2	9	202.3/4.2	0.1	8	201.0/4.1	0.1	7
90	223.2/2.3	0.2	6	319.6/3.6	0.1	8	314.0/3.5	0.1	7

Table 11
Estimated masses for the HEU-KRUSTY fast reactor and the recommended 60 wt % disc and helical geometry LEU-moderated reactors.

Region	Component	KRUSTY Disc geometry Uranium enrichment		Helical geometry
		93 wt%[‡]	19.75 wt%	19.75 wt%
Core	U_{235}	22.3	8.75	8.72
	U_{238}	1.7	35.53	35.47
	Mo	2.7	4.92	4.91
Reflector	BeO	70.5	100.2	100.1
Moderator	$ZrH_{1.5}$	0.0	73.8	73.6
Control rod	B_4C	0.8	0.8	0.8
Total mass (kg)		98.0	224.0	223.6

[‡] (Poston et al., 2013).

than the homogeneously moderated cores. The difference in terms of minimum total mass (21.7 kg for disc geometry and 22.6 kg for helical geometry) between the 60 wt% and 80 wt% reactors is overweighed by the longer lifetime of the 60 wt% moderated reactors, 16 years for the disc and helical fuel geometries.

Acknowledgments

Leonardo de Holanda Mencarini thanks the Brazilian Air Force and the Brazilian agency “Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)” for educational fellowship support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nucengdes.2018.09.017.

References

Angelo, J.A., Buden, D., 1985. Space Nuclear Power. Orbit Book Company Inc, Malabar, FL.

Bodansky, D., 2004. Nuclear Energy: Principles, Practices, and Prospects. Springer-Verlag, New York, NY.

Buden, D., 2011a. Space Nuclear Propulsion and Power: Book 2. Polaris Books, Lakewood, CO.

Buden, D., 2011b. Space Nuclear Fission Electric Power Systems: Book 3. Polaris Books, Lakewood, CO.

Chan, L., Wood, G., Schreiber, J., 2007. Development of Advanced Stirling Radioisotope Generator for Space Exploration. NASA Report NASA/TM-2007-214806.

Gibson, M.A., Mason, L., Bowman, C., Poston, D. I., McClure, P.R., Creasy, J., Robinson, C., 2015. Development of NASA’s Small Fission Power System for Science and Human Exploration. NASA/TM-2015-218460.

IAEA safeguards glossary, 2001 ed., – Vienna: International Atomic Energy Agency, 2002.

Lee, H.C., Lim, H.S., Han, T.Y., Čerba, Š., 2015. A neutronic feasibility study on a small LEU fueled reactor for space applications. Ann. Nucl. Energy 77, 35–46.

Pelowitz, D., 2013. MCNP6 User's Manual version 1.0. Los Alamos National Laboratory report LA-CP-13-00634, Rev. 0.

Poston, D.I., Dixon, D.D., McClure, P.R., Gibson, M.A., February 2013. A Simple, Low-Power Fission Reactor For Space Exploration Power Systems. In: Proceedings of Nuclear and Emerging Technologies for Space 2013, Albuquerque, NM. Paper 6965. pp. 25–28.

Reay, D., Kew, P., 2006. Heat Pipes – Theory Design and Applications. Butterworth Heinemann, Oxford.

Terremoto, L.A.A., 2004. Apostila da disciplina Fundamentos de Tecnologia Nuclear – Reatores (TNR5764), Divisão de Ensino – Secretaria de Pós-Graduação (IPEN/CNEN-SP). São Paulo, SP, Brasil.