POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Core Neutronics for Space Reactors: Analysis of HALEU Configurations

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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Academic year: 2021-2022

1. Introduction

One of the most critical technological gaps that need to be filled to support space exploration involving expeditions to other planets concerns power generation systems capable of providing for several years a power source bigger than 1 kWe to planetary settlements. Among all the possible power supply systems, nuclear fission reactors represent the most attractive solution thanks to their high specific power and the ability to produce energy regardless of their location or the external environment. This thesis work aims at analyzing - from a neutronics perspective - different possible configurations for a space reactor employing High-Assay Low Enriched Uranium (HALUE), characterized by an enrichment level between 5% and 20%. This choice allows the design to be compliant with proliferation policies that prevent the use of uranium with an enrichment level higher than 20%. Furthermore, the proposed system has to meet safety requirements for launch approval and be optimized in terms of mass, which is of most importance to reduce launch costs.
The design of the fission power system is carried out employing Kilopower reactor concept proposed by NASA as a reference, which is the only space reactor that recently has been tested with success through the experimental demonstration of the Kilopower Reactor Using Stirling TechnologY (KRUSTY) performed at the Los Alamos National Laboratory (LANL).
Serpent particle transport Monte Carlo code has been employed for the neutronic analysis. As first step, a model of KRUSTY is developed in Serpent to demonstrate the capability of the code to simulate nuclear reactors for space applications. The results are compared against both numerical simulations performed by LANL with MCNP code and with the experimental data collected from KRUSTY. Afterward, three possible design paths for HALEU reactor concept are investigated: a fast reactor just like KRUSTY, with the exception of using HALEU instead of Highly Enriched Uranium (HEU); a homogeneously moderated thermal reactor, whose fuel is a homogeneous mixture of moderator and metallic fuel; a heterogeneously moderated thermal reactor, whose fuel is composed of separate layers of metallic fuel and moderator. Each reactor concept is accompanied by a mass optimization analysis and safety analysis. In addition, the HALEU reactor is provided with a study on how the system approaches criticality

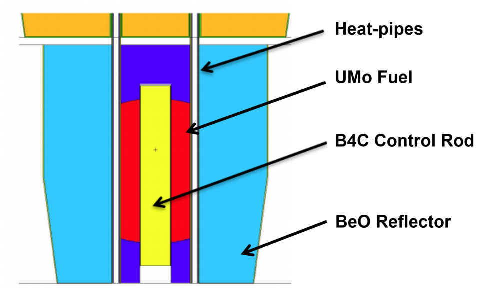

Figure 1: Schematic representation of Kilopower space reactor.

and power density distribution estimations. The analysis on the homogeneously moderated reactors is treated as an intermediate step to demonstrate the beneficial effect of adding moderator inside fuel. Finally, the effect of heterogeneity is investigated to prove the existence of an optimal fuel cell pitch that permits to maximize the reactor performance in terms of neutron economy.

2. Kilopower

Kilopower is a solid-state fast reactor intended to provide a power source to a wide range of space missions for 15 years. Its basic components are fuel, heat pipes, control rod, reflector and shielding. Fuel is in the form of a cylinder made of UMo alloy, provided with a central hole to allow the boron carbide control rod insertion. The control rod contains the required reactivity worth to ensure that the reactor can be started from a cold subcritical condition and progress to full-temperature critical operation. A cylindrical shell of BeO reflector surrounds the core, having the function of reducing neutron leakage. The thermal energy that is produced inside fuel through fission is transported to the power conversion system via sodium heat pipes. Heat pipes are designed to best accommodate the operating power level to guarantee a steady state average fuel temperature of 1100 K. Gamma shielding is provided by Lithium hydride, while neutron shielding is provided by tungsten [2]. In Figure 1 is shown a schematic representation of Kilopower reactor geometry. Four different designs of Kilopower have been proposed by NASA, given by the combination of different power levels (5 kWth and 50 kWth) and fuel enrichments (93% and 19.75%).

3. KRUSTY Modeling

Serpent model of KRUSTY is created with the goal of being as similar as possible to the MNCP model directly performed by LANL. Such similarity is attainable thanks to the availability of most design parameters that were used to create the MNCP input file, referring in particular to materials, temperature, and dimensions of all the various KRUSTY components [3]. Serpent model is used to simulate some specific aspects of KRUSTY neutronics, and the results are employed to perform code verification and validation.

3.1. KRUSTY Design

The 1 kWe HEU Kilopower reactor was taken as the baseline design for KRUSTY. Nevertheless, some changes in the design had to be made with respect to Kilopower reactor concept to allow the reactor testing inside a vacuum chamber and to exploit COMET criticality machine. One of the biggest differences was the split of the radial reflector into two portions: the platen and the shim radial reflector. The first was placed on the COMET lifting platen and was supposed to be gradually lifted to reduce neutron leakage and bring the reactor into a critical state. The latter was permanently fixed and had the only function of adding enough excess reactivity to allow KRUSTY to reach the desired operational conditions. Either of them were composed of discrete BeO disks, to perform the reflector reactivity worth measurement during KRUSTY experimental demonstration.

3.2. Code Verification

For the code verification, Serpent is employed to: i) study how KRUSTY approaches to criticality; ii) assess the radial reflector reactivity worth; iii) assess neutron spectra and power density distributions; iv) perform safety analysis.
KRUSTY reactor was designed to have a total operating reactivity defect of 1.70$, most of it (92%) being due the increase in fuel temperature up to 1100 K. This allows to perform an estimation of the reactivity defect by only considering fuel contribution, neglecting all the other components'. The effect of fuel thermal expansion is predicted assuming a 1.36% extension in all directions and a 96% reduction in fuel density. The effect of doppler broadening is taken

into account by simply imposing an average fuel temperature of 1100 K. A correct modeling of KRUSTY neutronics at operational conditions is fundamental for the study of how the reactor approaches to criticality and for the estimation of the radial reflector reactivity worth.

3.2.1 Approach to Criticality

The study on how the reactor approaches to criticality consists in defining the precise configuration that allows the reactor to become critical at environmental conditions (namely, cold conditions) and remain so until it reaches operational conditions (namely, warm conditions). KRUSTY is loaded with enough BeO disks in the platen and in the shim radial reflector to have a total excess reactivity of 2.20$ when the reflector is fully closed, 0.50$ more with respect to the predicted operating reactivity defect. Thus, in cold conditions, the reactor remains in a critical state if the reflector slightly opened, allowing neutrons to leak out of the core. As the reactor approaches warm conditions, the reactivity is reduced due to the temperature defect, and the reflector must be gradually lifted to maintain criticality conditions. In Table 1 is reported the width of the gap left between the platen and the shim reflector in cold critical and warm critical conditions.

code	LANL	Serpent
Cold Critical gap	2.2 cm	3.4 cm
Warm Critical gap	0.5 cm	2.2 cm
Gap Reduction	1.7 cm	1.2 cm

Table 1: Comparison between LANL and Serpent results.

Serpent results in terms of multiplication factor always presented a constant positive systematic error of 1200 pcm, which is why the resulting gaps are bigger than LANL results. The gap reduction to pass from cold to warm critical conditions is smaller due to the smaller reactivity defect with respect to LANL results (1100 vs. 1200 pcm).

3.2.2 Radial Reflector Reactivity Worth

The assessment of the radial reflector reactivity worth consisted in evaluating the multiplication factor as a function of the radial reflector height in cold conditions, warm conditions, and in shut down conditions. The latter conditions refer to the case in which COMET platen is dropped of 3.8 cm, and the reactor remains subcritical at any radial reflector height. The resulting curves' trend is in excellent agreement with LANL simulations, only characterized by the aforementioned systematic positive error (Figure 2).

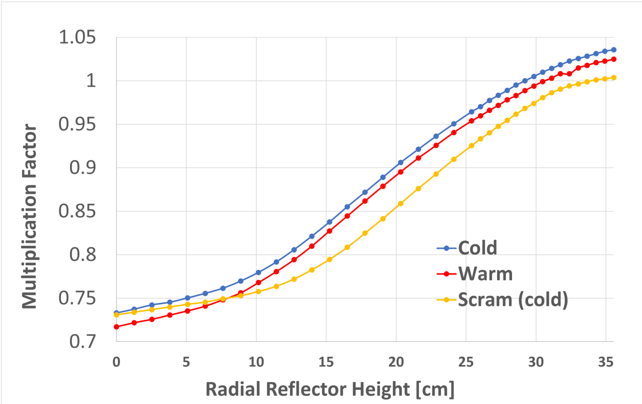

Figure 2: Radial reflector reactivity worth.

3.2.3 Neutron Spectrum and Power Density Distributions

Power density distributions and neutron spectra inside fuel have been assessed assuming a power level of 3 kWth. The results are in good agreement with those of LANL. The radial power density is flat in the central region and slightly tilted outwards because of thermal neutrons that have been scattered back into fuel from the surrounding radial reflector (Figure 3).

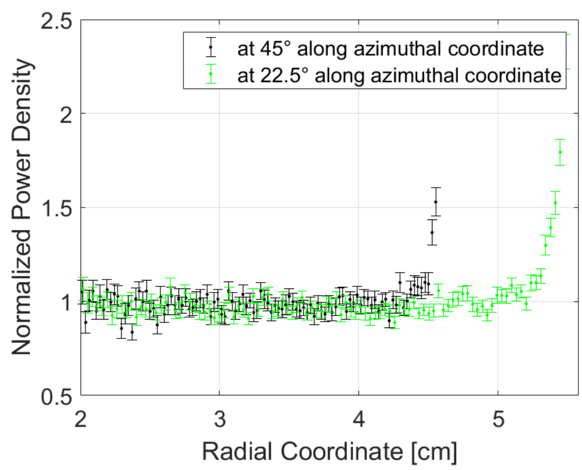

Figure 3: Normalized radial power density.

The axial power density distribution is asymmetrical due to the slightly opened radial reflector, and characterized by relatively small peaking factor. Such peaking factor reduces from 1.17 in cold critical conditions to 1.15 in warm critical conditions, due to the smaller gap left between the shim and the platen radial reflectors (Figure 4).

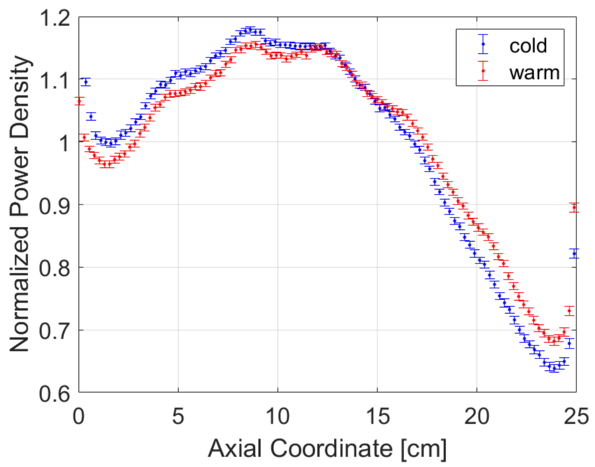

Figure 4: Normalized axial power density.

The neutron spectrum is clearly fast. The average neutron flux is of $8.4 \times 10^{11} n/cm^{-2}s^{-1}$ (same order of magnitude with respect to what LANL obtained). The resulting average power density inside fuel is of 1.55 W/cm^3 vs. 1.61 W/cm^3 of LANL simulation.

3.2.4 Safety Analysis

Safety analysis is required to gain launch approvals and consists in checking if the reactor remains largely subcritical in any possible worst accidental scenarios. Such scenarios refer to the case where KRUSTY fuel lands on the earth's surface and ends up completely surrounded by air, water, sand or wet sand (without control rod and reflector). Since KRUSTY fuel was composed of three blocks of equal length and diameter, the analysis was performed on all possible spatial arrangements of such blocks. According to LANL simulation results, there is no material that fuel could be accidentally surrounded by that would make it critical. The results of Serpent simulations in terms of multiplication factor are always characterized by positive error of 1000 pcm with respect to LANL'. The only exception refers those cases in which wet sand is the surrounding material (+3000 pcm of positive error). Despite this, in all possible accidental scenarios the system remains largely subcritical.

3.3. Code Validation

The only available experimental results of KRUSTY test that could be potentially exploited for Serpent code validation regard the calibration of the control rod [1]. The calibration curve obtained with serpent shows important deviations from the experimental curve, due to the high source of statistical uncertainty (approximately 50 cents, quite high if compared to $\Delta\rho$ increments) and the presence of systematic uncertainties in the model. The total reactivity worth of the control rod resulted of 397 cents vs. 354 cents obtained in the experimental demonstration.

4. Reactor Design

The second part of the thesis focuses on the neutronics analysis of possible reactor configurations for a space reactor that employs HALEU. Starting from a simplified reactor geometry whose dimensions and materials are exactly equal to those of KRUSTY (only composed by fuel and reflector), the resulting multiplication factor would be of 1.044 and the total system mass of 170 kg. The aim of the analysis is to investigate the variation in the total mass of such a simplified reactor concept in order to maintain a multiplication factor of 1.044 and to satisfy the non-proliferation requirement (i.e., not employing when HEU fuel). The following design changes are considered: i) fuel enrichment is reduced from 93% to 19.75%; ii) fuel height-to-diameter ratio ($\frac{H}{D}$) is reduced from 2.27 to 1.81; iii) moderator is integrated inside the core, converting the reactor into thermal.

4.1. Effect of Passing from HEU to HALEU

A reduction of the fuel enrichment would necessarily imply an increase in reactor dimensions to obtain the desired multiplication factor of 1.044. Specifically, there are two possible paths to follow to improve neutron economy: increasing the fuel mass or increasing the reflector thickness. Nevertheless, to be compliant with the goal of minimizing the reactor mass, a mass optimization analysis has to be performed to figure out the best combination of fuel dimensions and reflector thickness. The basic idea would be to consider a range of radial reflector thicknesses from 0 to 20 cm and perform for each of them an iterative procedure in which the fuel diameter is gradually increased until a geometry that enables a multiplication factor of 1.044 is found. In such analysis, the $\frac{H}{D}$ is fixed to 2.27, as it was for KRUSTY (Figure 5). 4).

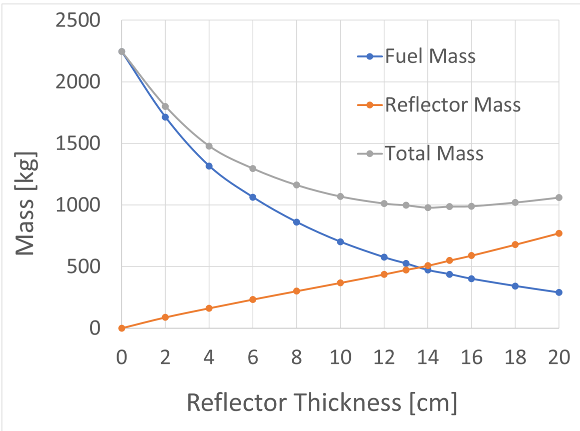

Figure 5: Mass optimization analysis.

The resulting lightest reactor is characterized by a total system mass of 986 kg, 6 times greater with respect to the HEU reactor concept. Safety analysis is also performed, to demonstrate that the satisfaction of inadverted criticality safety constraints could be guaranteed at the only cost of an increased mass (+100 kg) with respect to the mass-optimized reactor concept, due to the necessity of a thicker reflector (20 cm instead of 14 cm).

The resulting lightest HALEU reactor concept is supported by a further study on how the system approaches critical conditions, aiming to perform a comparison with the HEU reactor concept. In this analysis, the temperature defect is predicted by employing the same method that was applied for KRUSTY. From the results of the analysis (Table 2), the control rod worth is smaller for the HALEU reactor due to its bigger fuel dimensions. Therefore, the control rod withdrawn to maintain the reactor critical from cold to warm conditions is bigger.

Core Type	HEU	HALEU
Control rod worth (pcm)	7400	5600
Temperature Defect (pcm)	-1100	-1100
Rod Withdrawal (cm)	2	9

Table 2: Comparison between HEU and HALEU reactor concepts.

Finally, an evaluation of the separate effects of Doppler resonance broadening and thermal expansion is performed (Table 3). As it could be expected, due to the higher U-238 content inside HALEU fuel, doppler effect is much more important than in HEU fuel. Furthermore, thermal expansion contribution is smaller since fuel dimensions are bigger and therefore the change in the non-leakage probability is reduced.

Core Type	HEU	HALEU
Doppler Effect (pcm)	-100	-500
Th. Expansion (pcm)	-1000	-600

Table 3: Reactivity defect due to fuel thermal expansion and fuel Doppler effect.

4.2. Effect of reducing $\frac{H}{D}$ ratio

The same procedure followed in Subsection 4.1 is applied for a HALEU reactor having an $\frac{H}{D}$ ratio equal to 1.81, as KRUSTY was originally intended. The small reduction of such ratio moves the reactor towards the optimal condition of having $\frac{H}{D} = 0.9$, which would allow to obtain the best behavior in terms of neutron economy, thus the minimum fuel critical mass. From the mass optimization analysis, the lightest reactor resulted in having a 78 kg smaller total mass with respect to the one having $\frac{H}{D}$=2.27. From the safety analysis, the lightest reactor can still not satisfy inadverted criticality safety constraints. The safest reactor is characterized by a 20 cm reflector thickness and a 62 kg bigger mass with respect to the lightest reactor. No significant changes from the approach to criticality perspective is observed with respect to the HALEU reactor having $\frac{H}{D}$=2.27.

4.3. Effect of Adding Moderator

The conversion of the reactor from fast to thermal is achieved through the integration of moderator, either by uniformly mixing it with UMo fuel, either through the design of a core in which moderator and UMo are separated in alternating disks. The effect of adding moderator is to improve neutron economy, as it shifts the neutron spectrum towards the thermal energies, where the probability of inducing fission events vs. the probability of being absorbed is maximized. In this analysis, among all possible metallic hydrides, $ZrH_{1.5}$ is employed as moderator, representing an optimal trade-off between moderating properties and maximum operating temperature [4]. However, the main drawback of using $ZrH_{1.5}$ still remains its maximum operating temperature, which cannot be higher than 1100 K (which is the fuel operating temperature) due to hydrogen's tendency to diffuse out of the fuel matrix. Starting from an homogeneously moderated reactor concept, it is evaluated the multiplication factor as the amount of HZr is increased, while fixing the amount of UMo. The analysis allowed to demonstrate that the reactor is always under-moderated, meaning that the increase in the amount of moderator will always lead to an improvement in the system neutron economy.
A mass optimization analysis is arbitrarily performed on two homogeneously moderated reactors having a volumetric moderator fraction ($f_m = \frac{V_{HZr}}{V_{HZr}+V_{UMo}}$) of 60% and 80%, and the resulting lightest reactors had a total mass of 772 kg and 515 kg, respectively. In both cases, total masses are smaller with respect to the HALEU fast reactor concept, effectively proving what it was quoted above.

4.3.1 Effect of Heterogeneity

The study of heterogeneity's effect consists of considering fuel as composed of UMo and ZrH alternating disks stacked orthogonal to the control rod axis and evaluating the multiplication factor of such systems as a function of UMo plate thickness. Indeed, for a fixed value f_m, an increase in plate thickness turns into an increase in fuel heterogeneity. The extreme case of homogeneous fuel is obtained when plates' thickness approaches zero and their number approaches to infinity. Furthermore, to each value of f_m it corresponds a specific ratio between HZr and UMo plate thickness. Such a ratio is fundamental to directly assessing moderator plate thickness as the UMo plate thickness is varied, guaranteeing that the volumetric moderator fraction is respected.
For either values of f_m, the best performance in terms of neutron economy is obtained at a specific value of fuel plate thickness, that is reported in Table 4 together with the corresponding lattice pitch and total number of "fuel cells", defined as a couple of UMo and ZrH plates.

f_m	**60 %**	**80 %**
UMo plate thickness	1.5 cm	0.5 cm
ZrH plate thickness	2.25 cm	2 cm
Lattice pitch	3.75 cm	2.5 cm
Number of fuel cells	15	20

Table 4: Optimal fuel and moderator plates thickness.

A mass optimization analysis is also performed on heterogeneously moderated reactors with a f_m of 60% and 80%, characterized by the optimal fuel and moderator plates thickness. The resulting lightest reactors had a total mass of 544 kg and 374 kg, respectively, 228 kg and 141 kg lower with respect to the corresponding homogeneously moderated reactors. This evidently demonstrates the beneficial effect of heterogeneity on the system neutron economy.

5. Conclusions

The whole thesis work demonstrated the feasibility of HALEU fast reactor concepts - from a neutronic point of view - able to satisfy launch safety approvals, but at the only cost of a 900 kg increase in the total system mass with respect to the case of using HEU as fuel. A further reduction of 100 kg in the system mass could be achieved by figuring out a solution that eliminates the risk of inadverted criticality. On the other hand, a hypothetical thermal reactor for space applications requires to be heterogeneously moderated, since the problem of hydrogen diffusion eventually could be offset through the moderator thermal insulation. As an added benefit, heterogeneity was proven to

improve the system neutron economy, turning into a further reduction of the system fuel mass with respect to the corresponding homogeneously moderated reactor concept.
The only limit in the entire analysis is related to the fact that the amount of fissile material inside fuel is not a fixed quantity, but it is determined by the reactor geometry that allows to obtain a multiplication factor of 1.044. Fortunately, all proposed reactor geometry were characterized by an amount of fissile material at least equal to the amount contained inside KRUSTY, with the exception of thermal reactors having $f_m = 60\%$. Nevertheless, KRUSTY was designed to have a very low burnup during its 15-years lifetime, suggesting that the small amount of fissile material may not represent a problem. A more detailed analysis involving the estimation of such reactors burnup would be required to prove it. However, the presence of an optimal lattice pitch at each specific f_m value would allow to design a heterogeneously thermal reactor whose lifetime can be elongated as it is desired by simply adding more fuel cells.

References

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