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A STUDY OF CRITICALITY AND THERMAL LOADING IN A CONCEPTUAL MICRONUCLEAR HEAT PIPE REACTOR FOR SPACE APPLICATIONS

by

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Neutronic analysis of a conceptual heat pipe-cooled micronuclear reactor with 70 % enriched uranium nitride fuel is carried out by modeling the core and peripheral control drum movement to estimate the power distribution. The core configuration results in non-uniformities and hotspots. For the heat removal, empirical formulae have been used in the case of sodium, lithium, and potassium working fluids. The neutronic simulation was carried out by the OpenMC code. It has been found that the radial flux peaking as high as ~20 % can occur at various stages of the drum movement. The novelty of this research is the investigation of the effect of variable enrichment on the overall system multiplication, which can form the basis for optimal fuel distribution. It has been found that non-uniform fuel distribution can mitigate peaking factors, and thus reduce the hotspots. This analysis is useful for the design optimization of compact micro nuclear reactors for underwater, portable and space propulsion systems.

Key words: micronuclear reactor heat pipe, core neutronics, Monte Carlo simulation

INTRODUCTION

The revival of interest in space exploration missions to the Moon and Mars has led to highly enriched uranium (HEU) based micro nuclear reactor (MNR) designs with minimal moving parts [1-3]. Such non-commercial systems form the basis on which these micronuclear reactors could provide power in decentralized micro-grids [4]. Examples of commercially viable systems which are factory manufactured and easily transportable are Evinci [5] and NuScale [6] which could gain market acceptance over the next decade. For very small power production, the Los Alamos group has demonstrated a prototype 5-kW thermal (1-kW electric) Kilopower Reactor Using Stirling Technology (KRUSTY) fueled by a solid core HEU. For 5 kW thermal and 50 kW thermal with 20 % thermal-to-electrical efficiency and both HEU (93 %) and low enriched uranium (LEU) (19.75 %) fuels, the HEU reactor, Fuel and beryllium oxide (BeO) reflector, weight is reported as 161 kg and 268 kg respectively [1] out of which ^{235}U and fuel are 28 kg and 33 kg; and 38 kg and 44 kg, respectively. This compares with a larger 2400 kW thermal, 120 kW electric 70 % enriched uranium nitride (UN) fueled reactor with a 310 kg core and a thermo-electric generator (TEG) [3]. These larger designs appear to be more favorable for space missions. An advantage of using high-density UN fuel is a reduction in the core size. In another conceptual design by Wang *et al*. [7], a 500 kW thermal, 25 kW electric 65 % enriched UN fueled heat pipe-cooled reactor (HPR) is given with a core weight also of 310 kg. The *passive* heat removal system is implemented by vertically placed *heat pipes* with liquid metals as the working fluid.

Such systems have been extensively studied (see *e.g*. El-Genk and Tournier [8]) with sodium, lithium, and potassium in optimized configurations for a number of systems such as the 110 kW electric sodium-cooled scalable amtec integrated reactor space power system (SAIRS). For power conversion from thermal to electrical energy, at lower power levels for space applications, the stirling power conversion unit (PCU) would provide high thermal efficiency for alloy fuels. Moving up on the ladder towards high power systems, fuels will most likely be metal-based in high temperature systems permitting acceptable thermal-to-electrical conversion efficiency higher than the present 5 % TEG efficiency.

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This work carries out a neutronic analysis of a proposed MNR with the Monte Carlo code OpenMC [9]. For the heat pipe analysis [4, 10] empirical formulae have been used to estimate the heat removal capacities of the various liquids as a function of porosity and wick grain size. This research also considers the effects of lowering the enrichment in the innermost and outermost zones and the effects of such modification on the overall multiplication factor of the system.

MODELING AND SIMULATION

The MNR core is modeled as shown in fig. 1 for the top view and fig. 2 for the front view.

The materials used, their physical and atomic densities and their operating temperatures are listed in tab. 1. The UN fuel consists of 90 rods each with a 1.065 cm diameter surrounded by a gap and cladding. Each rod has a mass of 1.9384 kg adding to a total uranium inventory of 164.6838 kg. The heat pipes are modeled as an inner cylinder with a radius 0.90 cm radius with vapor followed by a 0.2 cm thick Mo-14Re wick, a 0.8 cm thick Li liquid (99 % 7Li) region surrounded by a 0.02 cm thick Mo-14Re. The rods and heat pipes are placed in a hexagonal Nb-1Zr with sides 24.7 cm. Surrounding the hexagonal matrix is the BeO reflector of an outer radius 35 cm with six control drums each tipped with boron carbide (B_4C) absorbers. The core is surrounded, as shown in fig. 1 and fig. 2, with radial and axial reflector and shielding. On the sides the shielding is a 35 cm thick layer of water surrounded by a 40 cm thick tungsten shield. The reflector mass is 272.5122 kg, so that the total core weighs 459.4505 kg. Figure 1 shows the evaporator parts of the heat pipes inside the core. In the full reactor design, the adiabatic and condenser parts of the heat pipes extend to the power conversion unit, which is not considered in this analysis.

The evaporator, adiabatic and condenser lengths as well as the porosity and grain size in the wick are given in tab. 2.

The parameters that limit the capability of the heat pipe to transport heat are capillary limitation, boiling limitation or heat flux, entrainment limitation, sonic limitation, and viscous limitation.

It has been observed that the operating range of a heat pipe falls within the capillary limit. For the purpose of this work, capillary limits of the sodium, potassium and lithium heat pipe were calculated using eqs. (1)-(3).

$$Q_c \quad \frac{\sigma_l \ \rho_l \ l_v}{\mu_l} \ \frac{K . A_w}{l_{\text{eff}}} \ \frac{2}{r_{\text{eff}}} \ \frac{\rho_l \ \text{g} \ l_t \ \cos\Psi}{\sigma_l} \tag{1}$$

$$r_{\text{eff}} \quad 0.1 \ d \tag{2}$$

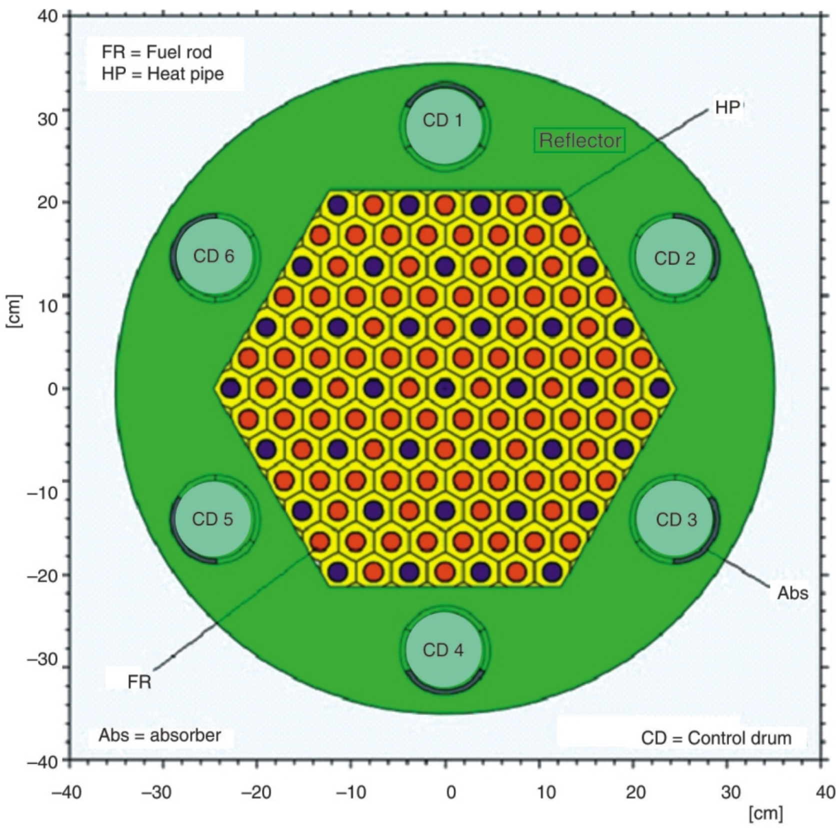

Figure 1. Top view model of the reactor core and shielding

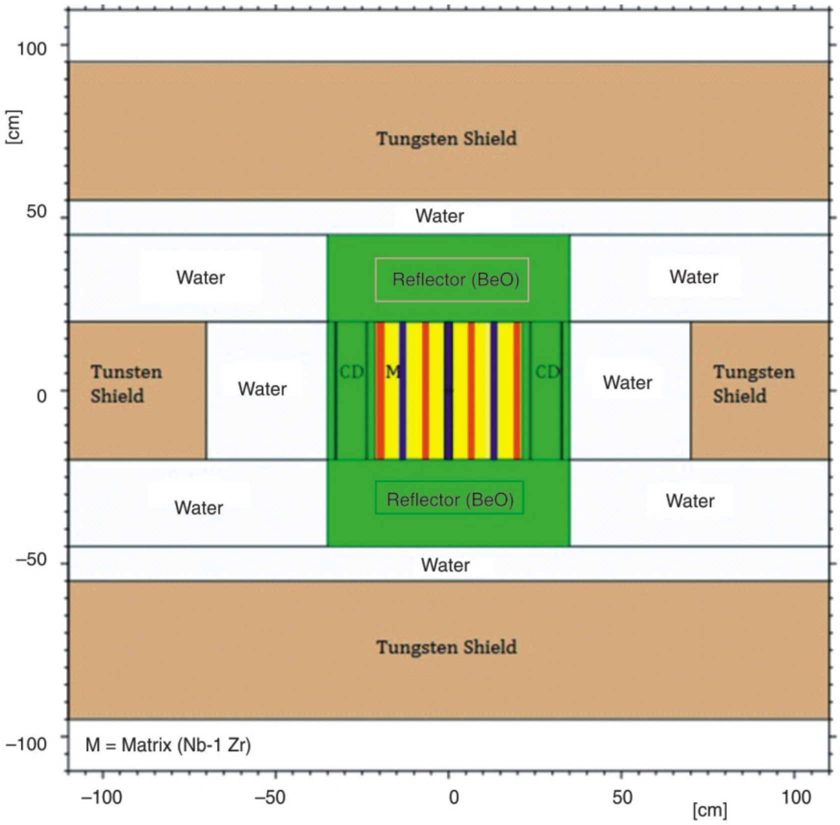

Figure 2. Side view model of the reactor core and shielding

Table 1. Material data

Material	Temperature [K]	Density [gcm^{-3}]	Atomic density/atomic fraction (atoms cm^{-3}/atom fraction*)
Fuel: UN (70 %)	2000	13.6	^{235}U 0.023025, ^{238}U 0.009743, ^{14}N 0.032768
Helium	293.6	3.7 10^{-5}	^{1}He
Lithium	1200	0.4	^{6}Li 0.01, ^{7}Li 0.99
Lithium vapor	293.6	0.001	^{6}Li 0.01, ^{7}Li 0.99
Mo-14Re	293.6	12	Mo 0.064777, Re 0.0054332
Reflector BeO	900	3.01	^{9}Be –0.360320, ^{16}O –0.639680
Absorber B_4C	293.6	2.52	^{10}B –0.782610, ^{12}C –0.217390
Matrix Nb-1Zr	1200 K	6.55	^{93}Nb 4.2031 10^{-2} Zr 4.3239 10^{-4}
Water	293.6	1.00	^{1}H 2, ^{16}O 1
Tungsten	293.6	19.3	^{74}W 1
*negative fractions indicate weight fractions			

Table 2. Heat pipe data

Parameter	Value
Evaporator length, l_e	0.40 m
Condenser length, l_c	0.80 m
Adiabatic region length, l_a	0.65 m
Total length, l_t	1.85 m
Tilt angle from vertical axis, Ψ	180^0
Acceleration due to gravity, g	9.81 ms^{-2}
Inner container radius, r_i	0.0090 m
Wick thickness, h	1.00 mm
Grain size/sphere diameter, d	40-100 m
Porosity, ε	0.55-0.70

$$K \quad \frac{(d^2 \ \varepsilon^3)}{150 \ (1 \ \ \varepsilon)^2} \qquad (3)$$

where d is the sphere diameter of the grain of porous wick material and ε – the porosity.

RESULTS

The Monte Carlo simulations for 1000 histories simulated and 5000 cycles are shown in tab. 3. The source was sampled uniformly in each of the 90 fuel rods with a Watt fission spectrum

Table 3. Monte Carlo results

Absorber position	Number of particles sampled (particles batches)	k_{eff} (Relative standard error) MCNP5	k_{eff} (Relative standard error) OpenMC
Front	1000 5000	0.955739 (0.0003)	0.96215 (0.0004)
Back	1000 5000	1.026546 (0.0003)	1.02615 (0.00038)

$$f(E) \quad Ce^{E/a} \sinh(\sqrt{bE}) \tag{4}$$

with $a = 0.965$, $b = 2.29$, and $C = 0.4527$ giving a mean energy of 1.9806 MeV.

The system multiplication k_{eff} was estimated as 0.96215 and 1.02615 with rods facing and away from the core, respectively.

The estimates were compared with MCNP5 [11] and the delayed fraction β from two simulations (with and without delayed neutrons)

$$\beta \quad 1 \quad \frac{k_p}{k_{eff}} \tag{5}$$

was found to be 0.006951. The maximum excess reactivity is thus 2548.360 pcm, and the shutdown margin is 3933.898 pcm.

The fluxes in the core are shown in fig. 3. The fluxes can be seen to be dominated by the higher energy range in the fuel and matrix in contrast to the fluxes in the water shield. Thus, power in the core is expected to have more contribution from high energies.

With the 1/6th symmetry in the core, as shown in fig. 4, the power distribution was estimated using the fission reaction tally. Figures 5 and 6 show the distri-

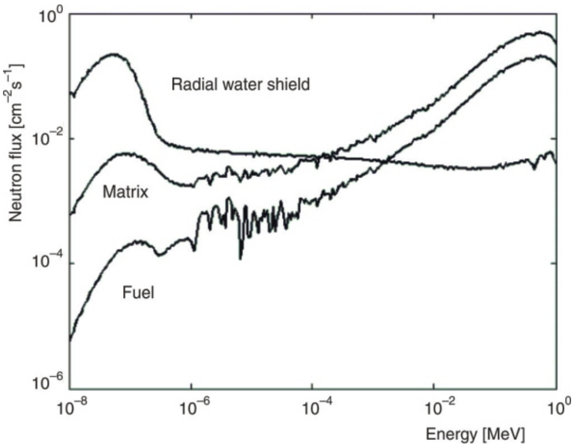

Figure 3. Core and shield fluxes

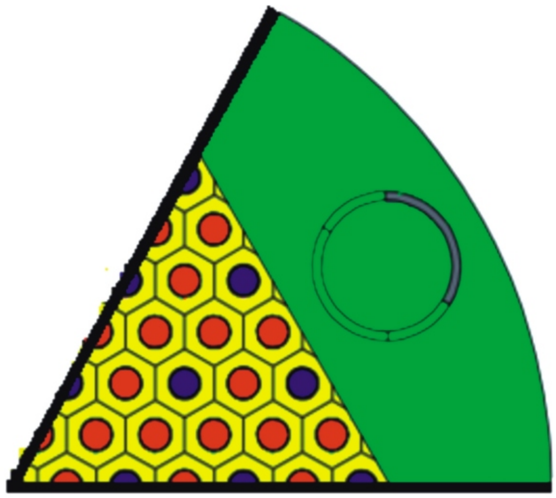

Figure 4. Model 1/6th core symmetry

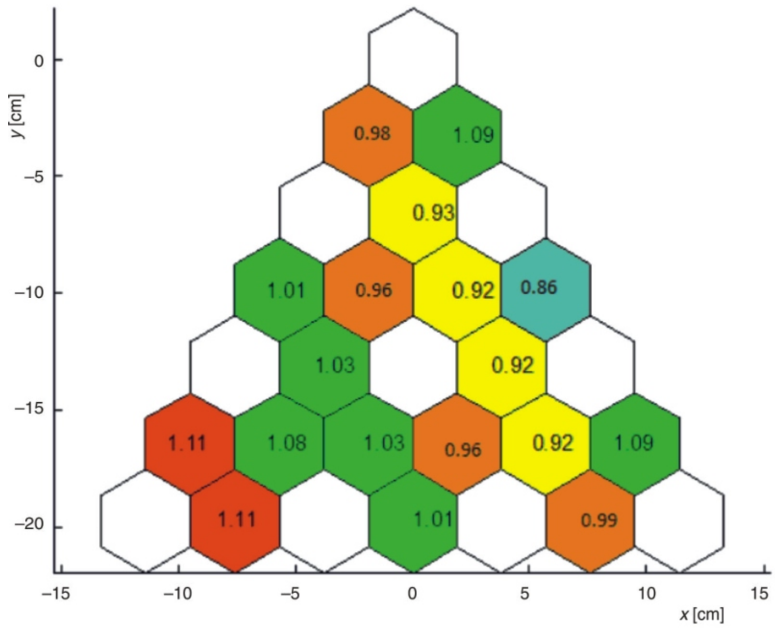

Figure 5. Absorber rods facing the core

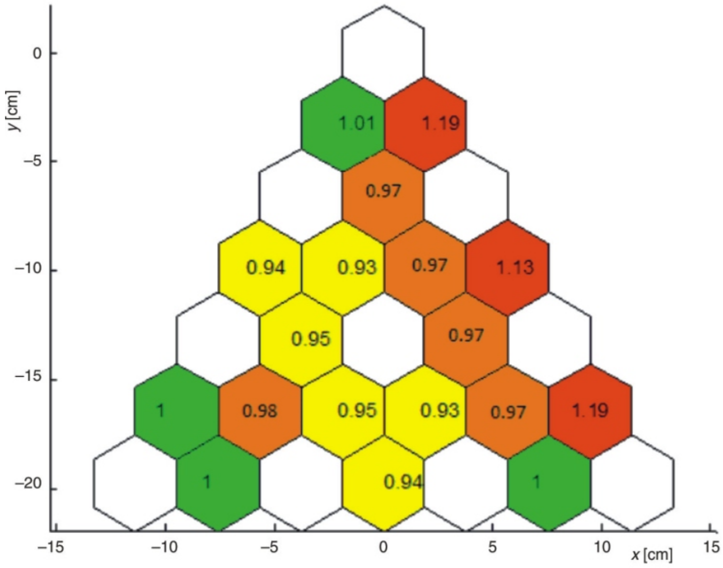

Figure 6. Absorber rods away from the core

bution with rods facing and away from the core, respectively.

In fig. 5, the radial power peaking (RPP) is predominantly in the inner fuel cells showing a maximum of 11 % with respect to the average power distribution. These decrease gradually towards the periphery and show the trend, as anticipated, of lowest RPP (0.86) in the fuel cells directly facing the absorber and 1.09 each in cells influenced by the reflector.

In fig. 6 with the absorber rods facing away from the core, the maximum RPP is ~20 % since the reflector influences the peripheral core to a greater extent than for the previously considered case.

Both previously given estimates in excess of 10% and up to ~20% variations in the heat removal requirement from the core.

To mitigate the power peaking effect, variable enrichment fuel distribution is considered. Three enrichment zones – inner, middle, and outer – are considered, similar to the consideration of fast breeder reactors from the earliest to modern fast breeder reactors. The zones have enrichment in the vicinity of 70 %, that has been proposed [3] for compact underwater and space applications. The inner and outer fuel zones have 60 % and 55 % enrichment respectively, while fuel in the middle zone has 70 % enrichment. The difference in fission rates is shown in tab. 4. When the absorber rods are away from the core, there is a decrease of ~10 % and ~11 % in fission rates in the inner and outermost fuel zones, respectively. When the absorber rods are facing the core there is a decrease of ~10 % and ~12 % in the innermost and outermost fuel zones, respectively. Results of tab. 4 show an acceptable improvement in core power distribution. These results can be further improved by finding an optimal fuel enrichment distribution.

Table 4. Fission rates

Absorbers away			
Zone	70 %	Variable enrichment	Difference
Inner	0.0046157	0.00412015	10.74 %
Outer	0.00534334	0.00472698	11.54 %
Absorbers facing			
Inner	0.00484883	0.00436976	9.88 %
Outer	0.0045104	0.00397153	11.95 %

We now consider the heat pipes in the capillary limits for sodium, potassium, and lithium at 0.70 porosity and 100 m grain size of the porous Mo-14Re wick with an 18 m average effective pore radius.

It is estimated that, while sodium and potassium have a similar operating temperature range, the sodium heat pipe provides ~2.5 times more heat transfer capability. The lithium heat pipe not only provides higher heat transfer capability but also has a higher operating temperature range. One of the reasons for the difference in capabilities of sodium, potassium, and lithium is their respective latent heat of vaporization. For a lithium heat pipe having an inner container radius of 0.0090 m, Mo-14Re a porous wick of 0.001 m thickness with 0.70 porosity is adopted. Using eqs. (1)-(3), it has been found that such a heat pipe has the capacity to remove power in a 14-17 kW range. Thus, if the reactor operates at a thermal power of 2-3 MW, each fuel rod will be producing ~20-30 kW thermal which would far exceed the capabilities of sodium and potassium as shown in fig. 7.

Even lithium with a maximum envisaged of ~18 kW thermal would be at its maximum capacity. Given the low conversion efficiency of a system such as the TEG , such an MNR would at most produce ~150 kW electric. However, the RPP could cause a further reduction by ~20 % bringing the performance down.

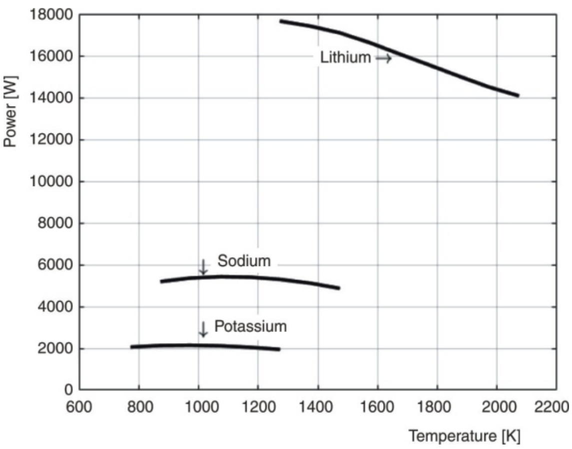

Figure 7. Capillary limits in the heat pipe

To further analyze the power generation capacity of the system, some parameters: porosity, grain size of the porous wick material, and effective pore radius of the capillary structure, affecting the heat transfer capability are investigated. The effect of porosity on the capacity of lithium heat pipes showed that capacity can be increased by up to ~4.5 times when porosity is increased from 0.55 to 0.70 but still remains below ~ 18 kW thermal as the temperature exceeds ~1500 K.

To study the effect of grain size of the porous Mo-14Re wick on heat transfer capacity, four grain sizes - 40 m, 60 m, 80 m, and 100 m, were considered. For all four calculations, porosity and effective pore radius were kept constant at 0.70 and 0.18, respectively. It was found that with an increase of the 20 m diameter (from 40-60 m, 60-80 m, 80-100 m) the improvement is ~1.5, ~1.4, and ~1.3 times respectively. It is thus hypothesized that a further increase in capacity can be achieved by varying the effective pore radius of the capillary structure, as a smaller effective pore radius will result in an increased pressure and, consequently, the performance of the capillary structure will be improved. With a reduction of the effective pore radius by about 3 % from 18 % and increased capillary pressure, the heat transfer capacity in the operating temperature range of the lithium heat pipe can thus be increased from ~18 kW thermal by ~16% in the range 1200-1500 K. This was found to be one remedy for handling the non-uniformities in the core power.

Another possible remedy could be the use of variable conductance heat pipes which alter the effective heat removal by the inclusion of a non-condensable gas at the condenser end of the heat pipe. However, this has not been investigated in detail during this study. The variable enrichment strategy can be further developed using variational methods or the Monte Carlo perturbation theory to seek an optimal distribution [12] for minimizing overall mass or reducing the non-uniformities in power distribution.

CONCLUSIONS

A neutronic study of a conceptual 70 % highly enriched uranium based micro nuclear reactor with heat pipes was carried out to determine the core power distribution due to the core configuration and the movement of the control mechanism in the surrounding reflector. It was found that the variations in radial power peaking were up to ~20 % when the absorbers were facing away from the core. Through variable enriched fuel distribution in the inner, outer, and middle zones of the core, this peaking has been significantly reduced. By using a 10 % less enriched fuel in the inner zone and 15 % less enriched fuel in the outer zone, from the middle zone, ~10 % and ~11 % drop in fission rate is observed in the inner and outermost fuel zones when the absorber rods are away from the core. When the absorbers are facing the core, a drop of ~10% and ~12 % in the fission rate is observed in the inner and outer zones, respectively. The use of 60 %, 70 % and 55 % enriched fuel as variable enrichment is sub-optimal; power peaking can be further improved by finding an optimal enrichment level for the core through the application of Genetic Algorithms. Thus, when there is variation of power distribution in the fuel zones at any given power level, the heat pipe performance would require variations of an equivalent order. Considering the capacities of three liquids viz. lithium, sodium and potassium, only lithium was found at 18 kW thermal for the dimensions and parameters (porosity, grain size and pore radius) considered to be suitable for a 2-3 MW thermal micro nuclear reactor with ~5 % conversion efficiency from a thermoelectric generator. Thus, an additional mechanism was found to be necessary to avoid degradation in the system performance. An approximately 16 % margin for improvement in lithium heat pipe performance was estimated for the reduced pore radius while the use of a variable conductance heat pipe is recommended for further consideration.

NOMENCLATURE

A_{w} – wick cross-sectional area [m^2]
K – wick permeability [m^2]
d – grain size/sphere diameter m
Q_{c} – heat transfer rate due to capillary limit [W]
g – acceleration due to gravity [ms^{-2}]
h – wick thickness [mm]
k_{eff} – effective multiplication factor
k_p – multiplication factor with prompt neutrons
l_a – adiabatic region length [m]
l_c – condenser length [m]
l_e – evaporator length [m]
l_t – total length of heat pipe [m]
l_v – latent heat of vaporization [Jkg^{-1}]

r_{eff} – wick capillary radius [m]
r_i – inner heat pipe radius [m]

Greek letters

β – delayed fraction
Ψ – tilt angle from vertical axis
ε – porosity
ρ_l – liquid density [kgm^{-3}]
σ_l – liquid density [kgm^{-3}]
μ_l – liquid viscosity [Nsm^{-2}]

Abbreviations and Acronyms

pcm – per cent mille
BeO – Beryllium oxide
HEU – Highly enriched uranium
HPR – Heat pipe cooled reactor
KRUSTY – Kilopower reactor using stirling technology
LEU – Low enriched uranium
MNR – Micro nuclear reactor
PCU – Power conversion unit
RPP – Radial power peaking
SAIRS – Scalable amtec integrated reactor space power power systems
TEG – Thermo-electric generator
UN – Uranium nitride

AUTHORS' CONTRIBUTIONS

U. Aziz is the first author, main implementer, and one of the theoretical contributors of the research. Z. U. Koreshi is the corresponding author, who conducted the supervision and is the main thought contributor of the research. S. R. Sheikh and H. Khan are thought contributors of the research, they provided conceptualization, as well as carrying out the review and editing. All authors participated in the final analysis and discussion, and the manuscript was conceived and written by all authors.

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ИСТРАЖИВАЊЕ КРИТИЧНОСТИ И ТЕРМИЧКОГ ОПТЕРЕЋЕЊА У КОНЦЕПТУАЛНОМ МИКРОНУКЛЕАРНОМ РЕАКТОРУ СА ТОПЛОТНОМ ЦЕВИ ЗА СВЕМИРСКЕ ПРИМЕНЕ

Неутронска анализа концептуалног микронуклеарног реактора хлађеног топлотном цеви, са 70 % обогаћеним уранијум-нитридним горивом, врши се моделовањем кретања језгра и периферног контролног цилиндра ради процене расподеле снаге. Конфигурација језгра доводи до неуниформности и ужарених тачака. За уклањање топлоте, емпиријске формуле коришћене су у случајевима радних флуида натријума, литијума и калијума. Неутронска симулација изведена је помоћу OpenMC кода. Откривено је да се радијални пик флукса који досеже до 20 % може појавити у различитим фазама кретања цилиндра. Новост у овом истраживању је испитивање утицаја промењљивог обогаћења на целокупно умножавање система, што може бити основа за оптималну расподелу горива. Откривено је да неуједначена расподела горива може ублажити факторе пикова и на тај начин смањити жаришта. Ова анализа корисна је за оптимизацију дизајна компактних микро нуклеарних реактора за подводне, преносиве и свемирске погонске системе.

Кључне речи: микронуклеарни реактор, топлотна цев, неутроника језгра, Монте Карло симулација