2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Micro Reactors for Electricity Generation in the 20 kW to 2 MW range

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1. Introduction

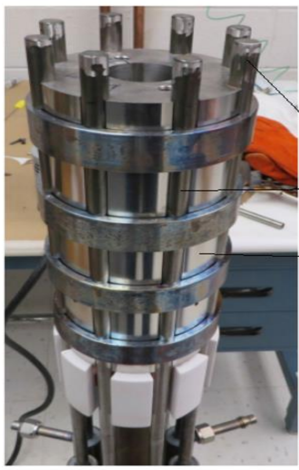
The nuclear industry, seeking to participate in the electricity micro-generation market, is studying alternative designs for micro reactors. Among the proposals, a very interesting group is that based on the technology initially developed by NASA and Los Alamos National Laboratory (LANL) for space purposes, the 4 kWt Kilopower project, which utilizes the heat pipe technology for transferring the nuclear heat from the reactor core directly to the power generation system [1,2]. This project, when transposed by LANL and the Idaho National Laboratory (INL) for terrestrial applications, begun to be identified as micro nuclear reactors based on heat pipe technology for electrical power generation between a few kW up to 20 MW [3,4]. This new reactor technology based on heat pipes opens to the nuclear industry the market of electricity micro-generation [5,6]. The INL document [4] adopted as a reference reactor, the 5 MW SPR reactor proposed by LANL. It is a fast made of a solid block of stainless steel with holes to receive nuclear fuel rods and heat pipes for heat removal. The market would include factories, military bases, electric vehicle charging stations, desalination plants, data centers, airports and seaports and, eventually, in shopping malls, skyscrapers and communities as local energy sources [5,6]. The United States, China, South Korea and other countries are studying micro reactors [7-10]. In US 2 micro reactor projects are being carried out including the eVinci project developed by Westinghouse with technical support from LANL and INL [7].

In Sect. 2 the Kilopower space reactor and the SPR micro reactor conceptual design are briefly presented in order to clarify the main characteristics of their designs. In Sect. 3 we present the study to verify the possibility of using the homogenous core of the Kilopower design to generate thermal power between 50 and 100 kWt with HALEU fuel (High Assay Low-Enriched Uranium) that is, enrichment of less than 20 w% in ^{235}U.

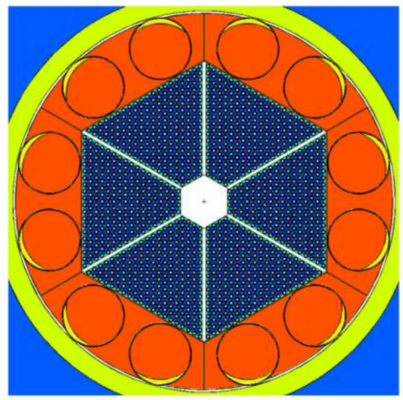
2. The Kilopower Space Reactor and the SPR Conceptual Design for Micro Reactors

The Kilopower reactor is a homogeneous fast-spectrum reactor to supply electricity in space installations on the Moon or Mars for research and data collection that require small power, fully autonomous operation from any supervision and capable of generating energy for decades [1,2]. Figure 1a shows the core of the Kilopower reactor and the heat pipes used for cooling the core. It generates a thermal power of 4 kWt and electrical power of 1 kWe from a small core of highly enriched uranium cooled by a system of 8 heat pipes that supply thermal energy to Stirling engines to produce electricity.

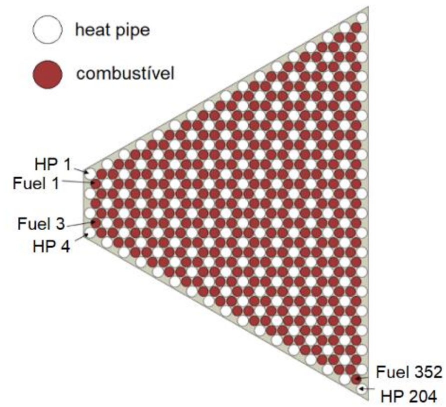
Heat pipe technology allows passive heat transfer without moving parts eliminating pumps and motors and greatly reduces the number of systems in the plant. As it is a space application, the cold source is the outer space where there is no matter to use conduction or convection heat transfer processes. The heat is exhausted to the empty space through the thermal radiation process. This technology seeks to meet space application requirements such as lightweight, resiliency, autonomous operation and service during decade [1].



1a – Kilopower reactor core with 8 heat pipes for core cooling [7]



1b – SPR reactor top view. Monolithic core with 6 stainless steel blocks surrounded by the reflector and 12 control drums. In the center are placed 2 safety control rods [3]



1c – Details of the stainless steel block showing the hexagonal lattice with a heat pipe surrounded by 6 fuel rods. Three heat pipes directly cool each fuel rod [3]

Figure 1 – The Kilopower reactor and the SPR conceptual design for Micro Reactors. 1a) The Kilopower space reactor core showing the U-Mo) monolithic block of high-enriched uranium and the system of 8 heat pipes to remove heat from the core directly to the Stirling engines. 1b) Top view of the LANL/INL SPR reactor showing the stainless steel monolithic core with a plurality of fuel rods and heat pipes, and the Alumina reflector with 12 control drums. 1c) details of the one of the stainless steel blocks showing the hexagonal lattice of heat pipes and fuel rods. Source: Ref. 8 (fig. 1a) and Ref. 4 (figs. 1b and 1c).

The Kilopower is a monolithic block of U-Mo) alloy with enrichment above 90 w%, with an external diameter of 11 cm and a height of 25 cm, thermal power of 4 kWt and electrical power of 1 kW. The 8 external hollows in the block are locations for receiving heat pipes to transfer heat from the core to the power generation system based on Stirling engines. The central hollow receives a boron control rod to keep the reactor shutdown until it starts operating. To start of operation, the control rod is slowly removed until the reactor reaches criticality. The reactor operates in critical state at 4 kW, with the excess reactivity being completely absorbed by temperature and power defects. The power density is approximately 2% of that of conventional power reactors (~ 2 W/cm^3) so that the reactivity loss due to burnup is minimal; the expected cycle is 15 years with a slight decrease in thermal power over the period.

The reference project presented by the INL/LANL study [4], named Special Purpose Reactor, is a generalization of the Kilopower project to generate 5 MWt and 2 MWe, that is, a thermal power about 1000 times greater than that of the Kilopower reactor. Figures 1b and 1c show details of the reactor, which is a heterogeneous fast reactor with a solid stainless steel monolith replacing the liquid Na or Pb metal in typical fast reactors. The fuel rods and heat pipes are embedded in 6 stainless steel blocks that form the monolith, which provides structure to the core and a medium for conducting heat from the fuel rods to the heat pipes. Reactivity control is done via B_4C control drums and 2 safety rods. The core is 150 cm high and the reflector outside diameter is 77.85 cm. The total number of heat pipes is 1224 so each heat pipe removes approximately 4.1 kW [3,4].

Results and Discussions

The objective of this study is to determine whether it is possible with a homogeneous cylindrical core similar to that of the Kilopower to generate between 50 and 100 kW with HALEU fuel based on U-Mo enriched at 19.75 w% in ^{235}U. Figure 2 schematically shows the top and side views of the cylindrical reactor. The core is a homogeneous uranium-molybdenum alloy having 7% Mo. Two types of reflectors were considered: stainless steel and BeO; the core height was 60 cm and the whole reactor temperature was uniform at 1050 K.

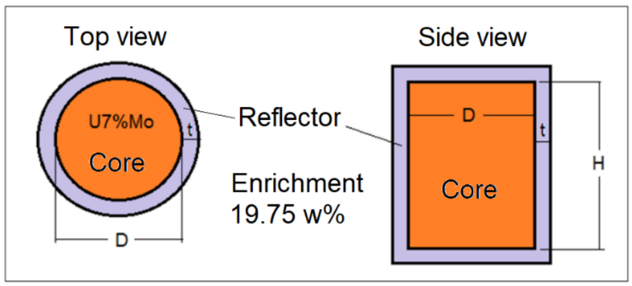


Figure 2 – Schematic of the cylindrical micro reactor showing core and reflector regions.

Figure 3 shows the results obtained using the Serpent code [11] for k_{eff} as a function of the core radius and the thickness of the reflector. Figure 3a shows the k_{eff} as a function of the core radius, keeping the thickness of the reflector fixed at 20 cm. Note that with a radius of 15 cm, the core with stainless steel reflector has k_{eff} barely greater than 1 while with the BeO reflector, $k_{eff} > 1.2$. The core with 15 cm radius was chosen to study the impact of the reflector thickness on k_{eff}. Figure 3b shows that with a 10 cm BeO reflector the core has a k_{eff}, slightly greater than 1.1, while with a stainless steel reflector, a 20 cm reflector the k_{eff} is slightly greater than 1.

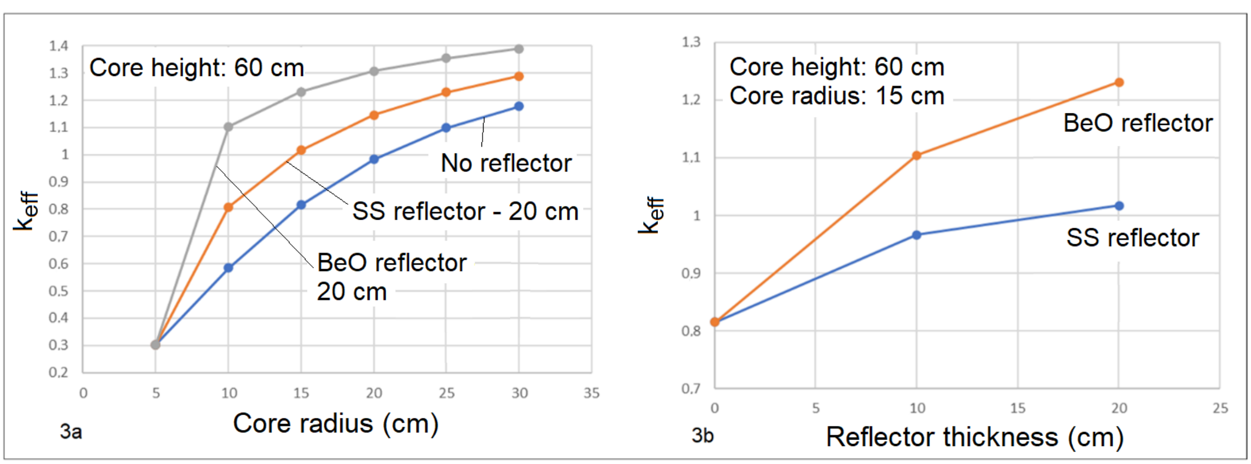


Figure 3 – k_{eff} results as a function of reflector radius and thickness for a cylindrical core of U7%Mo and enrichment of 19.75 w%. Two types of reflectors: stainless steel and beryllium oxide with 20 cm thickness and 60 cm core height. Core with 15 cm radius and 60 cm height can generate ~ 80 kW with average power density of 2 W/cm^3. The standard deviation for the keff Monte Carlo calculations with the Serpent code varied between 0.00018 and 0.00054.

The results show that a homogeneous fuel reactor of U7%Mo and 19.75 w% enrichment and 20 cm BeO reflector can generate ~80 kW with a power density of 2 W/cm^3. The excess reactivity required to operate for 15 years is very low for the micro reactor due to its low power density that proportionally reduces the level of burnup at the end of the cycle for fuels with the same technology. There is therefore room to reduce fuel enrichment for this core dimensions.

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