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Preliminary Core Analysis of a Micro Modular Reactor

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1. Introduction

USNC (Ultra Safe Nuclear Corp.) has conceived a very compact reactor concept that integrates the power production, power conversion and electricity generation within a single unit – the **Micro Modular Reactor** (MMR). The MMR will be “melt-down proof”(MDP) under all circumstances, including the complete loss of coolant, and will be easily transportable and retrievable, and suitable for use with very little site preparation and Balance of Plant (BOP) requirements for a variety of applications, from power generation and process heat applications in remote areas to grid-unattached locations, including ship propulsion.

2. Basic Design of the MMR

The MMR is an inert gas cooled and FCM [1] fueled reactor. Its power is envisioned to be in the range of 10-40 MWth. The MMR is divided in three sub-modules that include the power reactor module or “cartridge” (PRM), the power conversion module (PCM) and the power generation module (PGM), which can be transported separately (Fig. 1). The FCM fuel and gas cooling enable horizontal operation of the assembled system. The MMR design attributes support rapid deployment and retrieval.

The PRM houses: 1) the Reactor Core, fueled with enriched fissile material (Uranium or Plutonium); 2) the Neutron Reflectors; 3) Multiple Reactivity Control Systems; 4) the flow channels for the cooling gas to properly circulate into the PRM, through the core and out of the PRM; Connection system to the Power Conversion Module (PCM). The PRM vessel is preferentially made of C-C composite material or suitable metallic material. The Core is completely ceramic, with FCM fuel embedded into blocks of graphite or silicon carbide to form the fuel elements.

- **Monolithic TRISO Fueled (MTF) block**s. The core is made of fuel blocks, manufactured with TRISO fuel in SiC pellets (FCM fuel) sealed into the graphite or SiC block, or with TRISO particles distributed in the MTF block itself. The fissile fuel employed in the TRISO particles can be an oxide, carbide, oxy-carbide or a nitride of Uranium, Plutonium, Thorium or other fissile isotope. A burnable poison rare earth oxide such as Erbia or Gadolinia may be incorporated in the SiC ceramic compact. The high-density non-porous SiC coating of the TRISO particles, the dense SiC matrix of the FCM fuel pellet and the SiC in the blocks provide multiple strong barriers to fission product migration

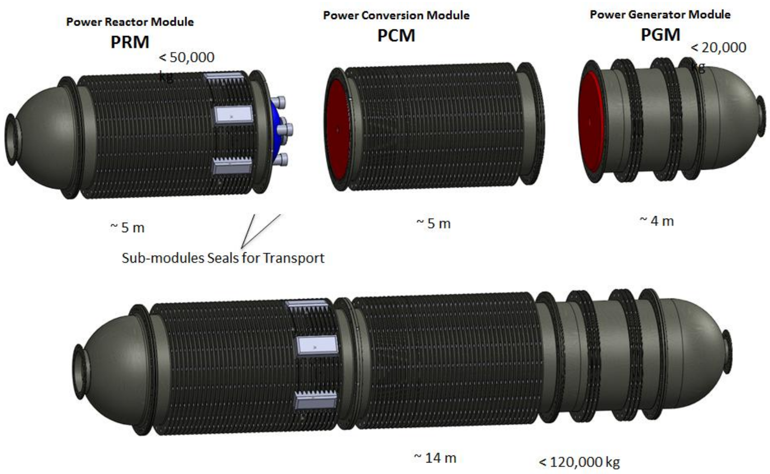

Figure 1. The modular construction of the MMR showing the three main modules (PRM, PCM and PGM) from left to right.

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- **Conductive Ceramic Core (CCC).** The CCC is composed of the MTF blocks and similarly configured reflector blocks (made of C- or SiC-composite material). The MTF blocks are designed and dimensioned to avoid excessive thermal stresses during operation. Fuel and reflector blocks contain holes for the coolant to flow in appropriate amounts. The good conductivity of the matrix and elimination of gaps between fuel and coolant increase the overall thermal conductivity, reduce fuel temperature and improve the core passive heat transfer capability during loss of coolant accidents. The base-case CCC has power of 10 MWt and it is very conservatively rated. Power can be upgraded up to 40 MWt by lengthening the core and increasing the power density.

- **Reactivity control through in-core rods.** Reactivity control will be performed by: 1) control rods in the reflector, containing absorbing and reflecting material arranged in a way to be passively engaged in absorbing mode for safety; 2) an array of in-core control rods; 3) an emergency shutdown system that injects neutron poison in the core through a passive system if the other systems fail. In System 1, the reactor is controlled by absorbing neutrons in the reflector and preventing them form re-entering the core. In System 2, the reactor is controlled by absorbing core neutrons. Control rod material is likely to be a SiC-based or C-based ceramic with boron or a rare earth absorbing material or beryllium (reflector) material. Systems 1 and 2 are independently capable of full control of the core reactivity and reactor shutdown.

3. Neutronic Analysis Model

Conductive ceramic core of MMR is a cylindrical structure. FCM fuel compact is made of typical TRISO fuel particles with SiC matrix. Graphite pan-cake like block has 14 mm fuel compact hole and 8 mm coolant holes with 17 mm center to center distance hexagonal lattice. Fuel disks of 200 cm diameter and 200 cm length in total are surrounded by 50 cm thick beryllium oxide reflectors. Total core assembly size is 300 cm diameter and 300 cm length as shown in Fig.2. The control drums are located at outer reflector region for normal operation and control rods are located in fuel disk. Central hole of fuel disk is used for shutdown control rod. The control drums are rotatable 20 cm diameter cylinders of BeO with B_4C absorber at one section as displayed in Figure 2. Scattering mean freepath of thermal neutron in BeO is 4.2 cm. So separation between outward and inward location of rotation the control drum will give significant change in the effective core reactivity. There are 8 shutdown control rods, 4 at the core center and 4 in the fuel region of the fuel disk. Shutdown control rods are used to shut down the reactor and to maintain subcriticality when the reactor is not in service.

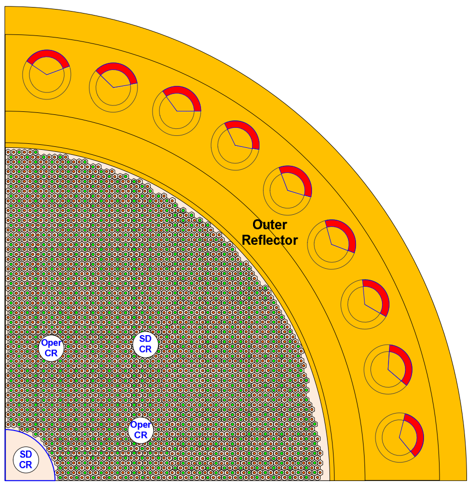

Figure 2. Plane view of 1/4 MMR core.

4. Results of the Performance Analysis

The Monte Carlo simulation code McCARD [2] with ENDF-B VII.1 [3] based library is used for the reactor physics analysis in this study. We assumed the thermal condition similar to other helium cooled reactor design [4]. The core temperature is fixed to 800 K which is the typical core average temperature of a gas cooled reactor. The core power density for 40 MW design is $6.37 MW/m^3$, and the average heat transfer rate at coolant channel surface is 19 W/cm^2. Considering typical heat transfer coefficient of helium, 1,800

W/m^2/K, the graphite to coolant temperature drop is 106 K which is quite acceptable value for a high temperature reactor. With 20 w/o LEU kernel of 800μm diameter and 40% TRISO packing fraction, the 40 MWt design achieves 3,669 effective full power days (or 10 years) of core life time. To consider the difficulty in fuel manufacturing, we have studied variations of the TRISO packing fraction, the kernel diameter, and the uranium enrichment and the compact diameter.

It was found that the enrichment is the most sensitive factor for the reactor criticality. We cannot use enrichment below 10 w/o in the 200 cm long core to achieve a reasonably long life. With 15 w/o LEU, it is possible to achieve 4.5 years. TRISO packing fraction is also important factor to have enough fissile material for long core life. At 30 % packing fraction, it is possible to achieve 7.5 years life.

Table 1. Reference TRISO and Compact parameters

TRISO particle	
Kernel (enrichment)	UN (20 w/o)
Kernel (diameter)	800 μm
Buffer layer (thickness, density)	70 μm, 1.0 g/cm^3
IPyC layer (thickness, density)	35 μm, 1.9 g/cm^3
SiC layer (thickness, density)	35 μm, 3.2 g/cm^3
OPyC layer (thickness, density)	20 μm, 1.9 g/cm^3
Fully Ceramic Compact	
Radius	0.699 cm
SiC matrix (density)	3.2 g/cm^3
TRISO Packing fraction	40 %

Figure 3 displays the change of effective multiplication factor during depletion. Initial excess reactivity in a gas reactor is controlled only by solid burnable poison. The burnable poison is introduced as a homogeneous mixture in the SiC matrix of the FCM fuel compact. Erbia (Er_2O_3) is suitable for the long term poison. We tried to reduce initial excess further by mixing gadolinia(Gd_2O_3). The reduction in core life time due to the poison is about 20 ~ 30 % for erbia and the mixture respectively. The mixed poison gives less loss in the core life time.

Usage of erbia poison keeps the temperature feedback coefficient negative over the lifetime of core. However, mixed poison with gadolinia makes positive moderator temperature coefficient at the beginning of life. Due to strong Doppler effects, total temperature coefficient remains negative even at the beginning of life time.

The reactivity of control drum and 8 control rods in the core are used during normal operation to compensate excess reactivity. Table 2 displays the effective multiplication for control rod insertion at the beginning of core life. Reflector side control drum and the incore control rods have sufficient worth for normal operation and burnup compensation. At early life, the incore control rods are required to maintain criticality, but after middle of life, control drum is sufficient to control the criticality. Worth of all rods are sufficient to keep subcriticality at room temperature.

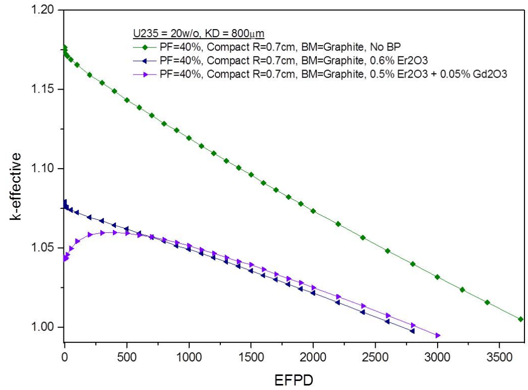

Figure 3. Change of effective multiplication factor as burnup (200 cm length with 20 w/o LEU)

Table 2. Beginning of life criticality according to control rod insertion.

Inserted control rods	k-effective	
	200 cm core	300 cm core
No control (outward drum)	1.07912	1.13316
Control drum inward	1.03697	1.09011
Drum + incore control	1.00784	0.98434
All rods in	0.91702	0.92216
Cold shutdown (at 300K)	0.93649	0.95791

For the purpose of reducing uranium enrichment, core size is extended to 300 cm without changing the core radius. This extension will not change the "factory manufactured" core feature. Neutron moderation is increased using thinner compact. A sensitivity study is performed to find suitable fuel compact radius for 300 cm effective core length. Figure 4 shows the effective multiplication factor with the compact radius at 10w/o LEU. From the figure, it indicates that the lifetime of the core is increased at the lower compact radius due to the enhanced moderation effects of the graphite fuel disk. The 0.4cm of compact radius is an optimum value for this MMR core.

Figure 5 displays depletion curve of the 300 cm effective core with 12w/o LEU which is enrichment of the 20-years lifetime core at 10MWt MMR. The core life is 2,042 days without burnable poison, the life decreases to 1,883 days (about 8%) with 0.4% erbia poison mixed in matrix region. The excess reactivity is 133mk which can be well controlled by the same configuration of control rods as displayed at Table 2.

The temperature coefficients such as fuel, moderator, and isothermal, are negative throughout the life time of core. The negative temperature coefficients are the most important factor for the safety of the reactor core during operation.

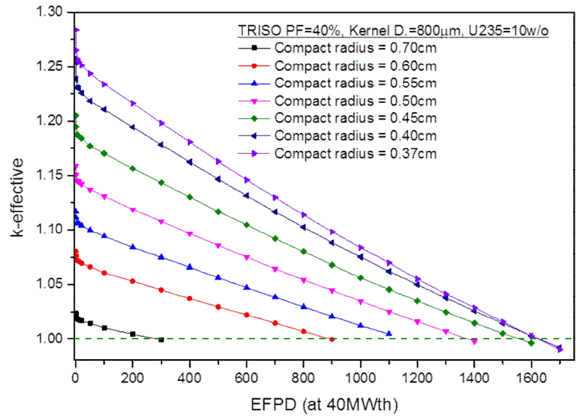

Figure 4. Change of effective multiplication factor with compact radius as burnup (300cm core, 10 w/o LEU)

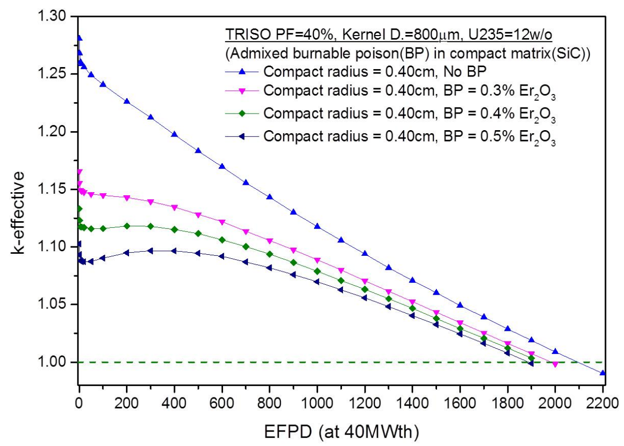

Figure 5. Change of effective multiplication factor as burnup (300cm core, 12 w/o LEU)

5. Conclusions

The Micro Modular Reactor design proposed in this paper has 3 meter diameter core (2 meter active core) which is suitable for “factory manufactured” and has few tens year of service life for remote deployment. We confirmed the feasibility of long term service life by a preliminary neutronic analysis in terms of the excess reactivity, the temperature feedback coefficient, and the control margins.

We are able to achieve a reasonably long core life time of 5 ~ 10 years under typical thermal hydraulic condition of a helium cooled reactor. However, on a situation where longer service period and safety is important, we can reduce the power density to the level of typical pebble bed reactor. In this case we can design 10 MWt MMR with core diameter for 10 ~ 40 years core life time without much loss in the economics. Several burnable poisons are studied and it is found that erbia mixed in the compact matrix seems reasonably good poison.

The temperature feedback coefficients were remaining negative during lifetime. Drum type control rods at reflector region and few control rods inside core region are sufficient to control the reactivity during operation and to achieve safe cold shutdown state.

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