

Fast Modular Reactor Nuclear Design Parameters of Fuel Cycle and Power Distributions

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ABSTRACT

This paper describes conceptual design of a 112 MW thermal (50 MW electric) Fast Modular Reactor (FMR) system operating at 7 MPa with inlet/outlet temperatures of 509/800 °C. The reactor system includes the reactor core, fuel assemblies, fuel rods, reactor internals, reflector, neutron control system, flow control, and structural components. The nuclear design and analysis were conducted to search for a baseline core with a cycle length greater than 8-year and the power peaking factor less than 1.5 by adjusting the fuel assembly, reactor core, and reflector configurations. The neutronics calculations of the baseline core showed that a refueling interval of 9-year is achieved with a total peaking factor of 1.47 and a fuel rod average linear power of 3.6 kW/m.

KEYWORDS: Fast Modular Reactor, Cycle Length, Power Distribution

1. INTRODUCTION

General Atomics Electromagnetic Systems (GA-EMS) is currently developing a new 50-megawatt electric (MWe) fast modular reactor (FMR), under the Department of Energy's (DOE's) Advanced Reactor Demonstration Program (ARDP) Advanced Reactor Concepts 2020 (ARC-20) development pathway, that provides safe, carbon free electricity, capable of incremental capacity additions [1]. The FMR plant is to be designed and developed to meet the objectives of the ARC-20 program. Specifically, the FMR plant conceptual design is based on the following objectives:

- Develop an FMR conceptual design with verifications of key metrics in fuel, safety, and operational performance.
- Designed to be economically competitive and site-flexible by implementing modularity for factory-fabrication and on-site assembling and dry cooling facilitates for siting away from large bodies of water.

The FMR is a High-Temperature Reactor (HTR) that uses a non-hazardous helium coolant, i.e., a chemically inert gas that is non-explosive, non-corrosive, and does not become activated. The passive safety is achieved by implementing conduction, radiative, and gravity-driven natural convection cooling mechanism. The power conversion uses a closed Brayton cycle that does not require a complex steam generation process. The fast neutron spectrum of the FMR allows for 9 years of operation without refueling, significantly reducing high-level waste generation by a factor of 2 when compared to conventional light water reactors (LWR) and physically small

compared to a gas-cooled thermal reactor. Use of conventional rod-type fuel eliminates the large amount of graphite waste and the used fuel can go directly into dry storage. The GA-EMS FMR concept development is driven by end-user needs and the conceptual design studies are conducted to confirm the technical and economic feasibility of the system.

To achieve a high-temperature and high-efficiency operation capability of the FMR, GA-EMS selected a combination of existing and advanced technologies for the key constituting materials and safety design. These choices of technologies of mixed maturity will help optimize the cost and schedule for the successful demonstration of the FMR targeted in 2030. The following is a brief description of the selected technologies:

- The major core material is uranium dioxide (UO_2) which the most widely used and well-known fuel material.
- The silicon carbide (SiC) composite is used for both the cladding and other internal structures. This SiC is chemically inert in the helium environment. This material is exceptionally radiation tolerant, especially in the temperature range of interest for HTRs where annealing effects mitigate damage. GA EMS has pioneered and leads the industry in developing nuclear-grade SiC composite cladding under Accident Tolerant Fuel (ATF) program [2].
- Zirconium silicide (Zr_3Si_2) is used for the primary reflector. It is a heavy reflector specifically developed for the Gas-cooled Fast Reactor (GFR) [3]. GA-EMS has fabricated samples and tested then in a research reactor under low temperature and low irradiation condition to confirm the fabrication process and characteristics [4].

2. FMR DESIGN REQUIREMENTS

The requirements of design bases and nuclear performance of the reactor system including the fuel and reactivity control system are described in NUREG-0800 [5] for the light water reactor (LWR). The FMR design in general adopts that standard review plan (SRP) to develop the design bases and conceptual design report. The design bases are the fundamental criteria that must be met using approved analytical techniques.

The plant-level requirements define the functional and operational requirements for the nuclear plant. The development of these requirements traces to the project objectives. These requirements along with the institutional requirements define the overall plant-level requirements for the FMR plant. Each requirement could be designated to be critical for safety and/or a key performance parameter (KPP). KPPs are considered the most essential for successful mission accomplishment. They represent those capabilities or characteristics so significant that failure to meet the threshold value of performance can be cause for the concept or system selected to be reevaluated.

2.1. Design Characteristics

Drawing on extensive experience with the designs and deployments of the Gas-Turbine Modular Helium Reactor (GT-MHR) [6], Next Generation Nuclear Plant (NGNP) [7], and more recent GFR technology development efforts, i.e., Energy Multiplier Module (EM^2) [8], GA-EMS focuses on maturing the technology advances to push forward Brayton cycle for thermal efficiency and SiC composite for high-temperature operation. The three main distinguishing design characteristics are:

- Low core power density and use of high-temperature SiC composite cladding secure the safety margin in the highly unlikely event of an accident. Under such an accident condition, the reactor can be cooled over the long-term by a gravity-driven reactor vessel cooling system (RVCS).
- The direct helium Brayton cycle enables fast grid response for load following and high overall efficiency of ~44% during normal operation. The automatic control of the reactor power and turbomachinery keep the reactor at a constant temperature that mitigates thermal cycle fatigue associated with most load-following reactors.

- The average discharge burnup is 100 gigawatt days per ton of uranium (GWd/tU) for high assay low enriched uranium (HALEU). The high burnup UO_2 fuel is enabled by using the recognized irradiation-resistant SiC composite cladding that is derisked in the ATF program. The UO_2 fuel has been proved to be reliable in fast neutron spectrum up to 11.8 at% burnup [9].

2.2. Key Performance Parameters

The primary function of the reactor system is to produce heat from fission energy and transfer this heat to the helium coolant. While conducting this function, it should provide the first barrier to the release of radionuclides, prevents neutron leakage from the active reactor core, provides neutron shielding of the reactor pressure vessel (RPV) from core radiation and provides capability to passively transfer residual heat to the RPV. In the reactor system, the fuel rod and control rod mechanism are designed so the performance and safety requirements are met. The mechanical design and physical arrangement of the reactor components, together with the corrective actions of the reactor control, protection, and emergency cooling systems are designed to achieve these requirements, referred to as KPPs:

- The reactor system shall have a nominal thermal power output of 112 MW.
- The reactor system average core inlet temperature shall be 509°C.
- The reactor system average core outlet temperature shall be 800°C.
- The reactor system average core outlet pressure shall be 7 MPa.
- The reactor system fueling interval shall be greater than 8 years.
- The reactor system shall use UO_2 fuel with an enrichment limited to 20% in weight percent.
- The fuel temperature during normal operation shall be less than 1,500°C.
- The cladding temperature during normal operation shall be less than 1,100°C.
- The fuel temperature during emergency conditions shall be less than 2,006°C.
- The cladding temperature during emergency conditions shall be less than 1,800°C.
- The cladding maximum hoop strain shall be less than 0.6%.
- The reactor core shall have a total peaking factor of no more than 1.5.
- The reactivity control system shall provide a cold shutdown margin greater than 1%.

3. DESIGN DESCRIPTION

3.1. Analytic Method

The nuclear design and analysis have been conducted by a Monte Carlo code MCNP6 [10] with ENDF/B-VII.1 to obtain eigenvalue and neutron flux distribution. The MCNP6 calculations also generate fission energy deposition averaged over a cell (F7 tally) which are used to obtain the fuel rod and assembly power. Neutron flux averaged over a cell is obtained by F4 tally. For the physics calculations, 50 million active source histories (50,000×1,000) are used, which gives a standard deviation (1σ) of eigenvalue less than 0.01%. For the depletion analysis within MCNP6, the fuel region was divided into 10 axial layers or tally cells. The material compositions of burned fuels were obtained from the MCNP6 burnup calculations of a single fuel assembly. The fuel compositions of the once- and twice-burned fuels were taken to the full core model for the depletion. The fuel composition obtained from the assembly model may not be the same as those from the core model as the neutron leakage effect is not fully considered in the assembly model. This will be further investigated through the fuel management analysis. The KCODE option and tallies provide the effective multiplication factor and the power distribution in a reactor core.

Core and assembly geometries were defined via surfaces, cells, material composition, densities, temperatures, lattices, and universes. Assemblies were modelled with heterogeneity, explicitly modeling individual fuel rods, cladding, air gap, etc., populating a repeating structured lattice rather than modeling a smeared homogenous assembly. The assembly level analysis consisted of a single assembly with reflective radial boundaries. Material cards for each zone and axial layer were generated from the single assembly burnup calculation. The core fuel

assembly layout was created via populating another lattice with the assembly geometries and material cards for each fuel zone.

Power distribution can be effectively explained via power peaking factor. The total power peaking factor $F_Q(z)$ is defined as the maximum local linear power density in the core divided by the core average fuel rod linear power density, or:

$$F_Q(z) = p(z)_{max}/\bar{p}_{core} \quad (1)$$

$F_Q(z)$ can be broken in axial and radial components f_Z and f_R :

$$f_Z = p(z)_{max}/\bar{p}_z \quad (2)$$

$$f_R = p(r)_{max}/\bar{p}_r \quad (3)$$

where \bar{p}_z and \bar{p}_r are the average axial and radial power density, respectively. In addition, the hot rod power peaking factor is determined by:

$$f_{HR} = p_{rod_{max}}/\bar{p}_{rod} \quad (4)$$

where \bar{p}_{rod} is the average rod power density.

3.2. Fuel and Fuel Assembly

The FMR fuel element is loaded with UO_2 in the form of a sintered pellet that has a packing density of 95 volume percent. The fissile, i.e., ^{235}U , content of the fuel is 19.75 weight percent, categorized as low-enriched uranium (LEU). The fuel element is designed to have a large fuel gap of 100-200 μm and a large gas plenum to accommodate fuel swelling and fission gas accumulation, respectively, from the high-burnup operation. Fuel assembly contains 120 fuel rods as a triangular array with central seven rod position used for the control rod guide tube. Figure 1 shows a cross-sectional view of a fuel assembly and the related control rod guide tube. The fuel assemblies are arranged in a hexagonal array, forming an annular core.

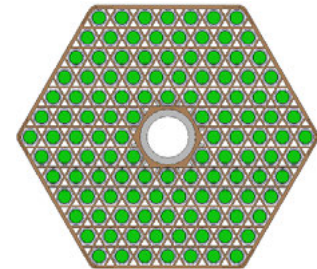


Figure 1. Plan View of a Fuel Assembly

3.3. Reactor Core Configuration

The fuel rods within a given assembly have the same initial uranium enrichment in both the radial and axial planes. Fuel assemblies of three different enrichments are used in the initial core loading to establish a favorable radial power distribution. The 112 MWt reactor core consists of 144 fuel elements, with 120 fuel rods per assembly within a SiC composite cladding. The fuel region is arranged in an annular configuration with an active height of 180 cm, surrounded by a Zr_3Si_2 /Graphite reflector and B_4C neutron absorber, with an overall core outer diameter (OD) ~ 358 cm.

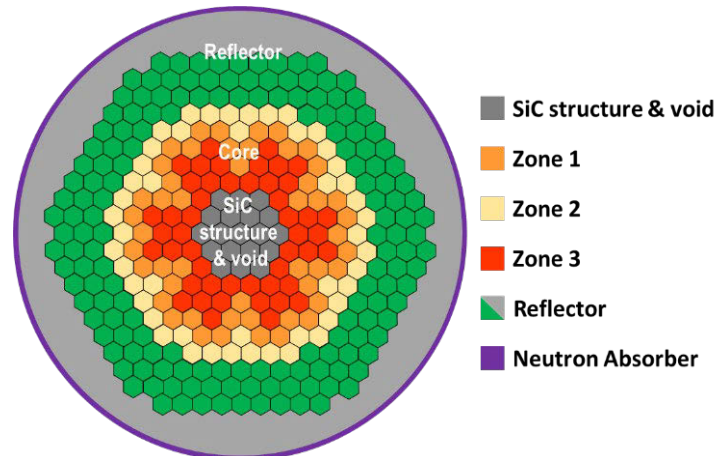


Figure 2. Fuel Loading Pattern

Figure 2 shows the fuel loading pattern of the initial and equilibrium core. The core is divided into three zones in radial direction with equal volume. For the initial core, the fresh fuels with the highest enrichment are loaded in the middle zone (Zone 1). Fuels with a lower enrichment are loaded in the outer zone (Zone 2), which mimics the loading of once-burned fuels. Fuels with the lowest enrichment are loaded in the inner zone (Zone 3), which mimics the twice-burned fuels. The exact reloading pattern, the initial and final positions of assemblies, and the number of fresh assemblies and their placement are dependent on the energy requirement for the fuel cycle and burnup, which requires further investigations.

4. BASELINE CORE NUCLEAR PERFORMANCE

4.1. Fuel Cycle

The core average enrichment is determined by the amount of fissionable material required to provide the desired energy requirements. The FMR uses the maximum allowed enrichment of LEU material. Neutron leakage from the core is minimized by surrounding the core with high efficiency reflector materials. The thickness of the reflector was adjusted to preserve the neutron economy, reduce the power peaking around the periphery, and minimize the overall core diameter. In a fast reactor, significant amount of fertile uranium is transmuted to a fissile plutonium and burned in situ that enhances a longer fuel cycle.

The equilibrium core, as well as the initial cycle, was designed to operate approximately 9 years between refueling, accumulating a cycle burnup of approximately 33 GWd/tU. The initial excess reactivity of the equilibrium core is 1.06 and linearly decrease through the cycle as shown in Figure 3. At the beginning of any cycle a reactivity reserve equal to the depletion of the fissionable fuel and the buildup of fission product poisons less the buildup of fissile fuel over the specified cycle life is built into the reactor. The estimation of the fueling cycle interval should also consider the reactivity margin associated with parasitic neutron capture in the system. During the operation, the excess reactivity is controlled by control rod insertion.

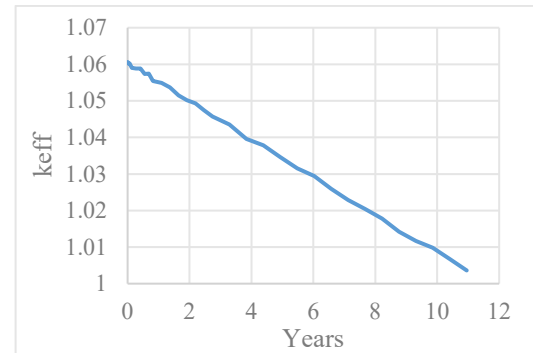


Figure 3. Effective Multiplication Factor

4.2. Radial Power Distribution

The power shape in horizontal sections of the core at full power depends on the fuel assembly loading pattern, the control rod insertion, and the fuel burnup distribution. The equilibrium core power peaking factors are summarized in Table I from beginning of cycle (BOC) to end of cycle (EOC). The effects of power level, xenon, samarium, and coolant density on the radial power shape are considered, but these are relatively small. The total peaking factor F_Q is ~ 1.47 , the hot rod power peaking factor f_{HR} is ~ 1.41 , and the axial peaking of the hot rod is ~ 1.11 . The peaking factors were estimated based on 1/6 core symmetry. The hot rod location is at the innermost hex vertex of the innermost fresh fuel assembly.

Table I. Linear power and hot channel factors

	BOC	MOC	EOC
Core average linear power, kW/m	3.6	3.6	3.6
Total power peaking factor	1.473	1.463	1.458
Hot rod power peaking factor	1.405	1.402	1.387

The normalized power distribution by fuel batch 1, 2, and 3 is 0.37, 0.30, and 0.33, respectively, meaning that the zone powers are relatively flat, with increased power in the fresh fuel and a power drop in the exterior zone. An

alternate loading scheme swapping zone 1 and 2 (placing fresh fuel in the outer zone) was also studied, resulting in a flatter power profile (0.34,0.333,0.327), however the total peaking factor was slightly higher at ~1.5 (shifting the peak to the outer annular boundary) and the effective multiplication factor (~1.058) was slightly lower. Figure 4 compares the power distributions of the baseline and alternative fuel loading cases.

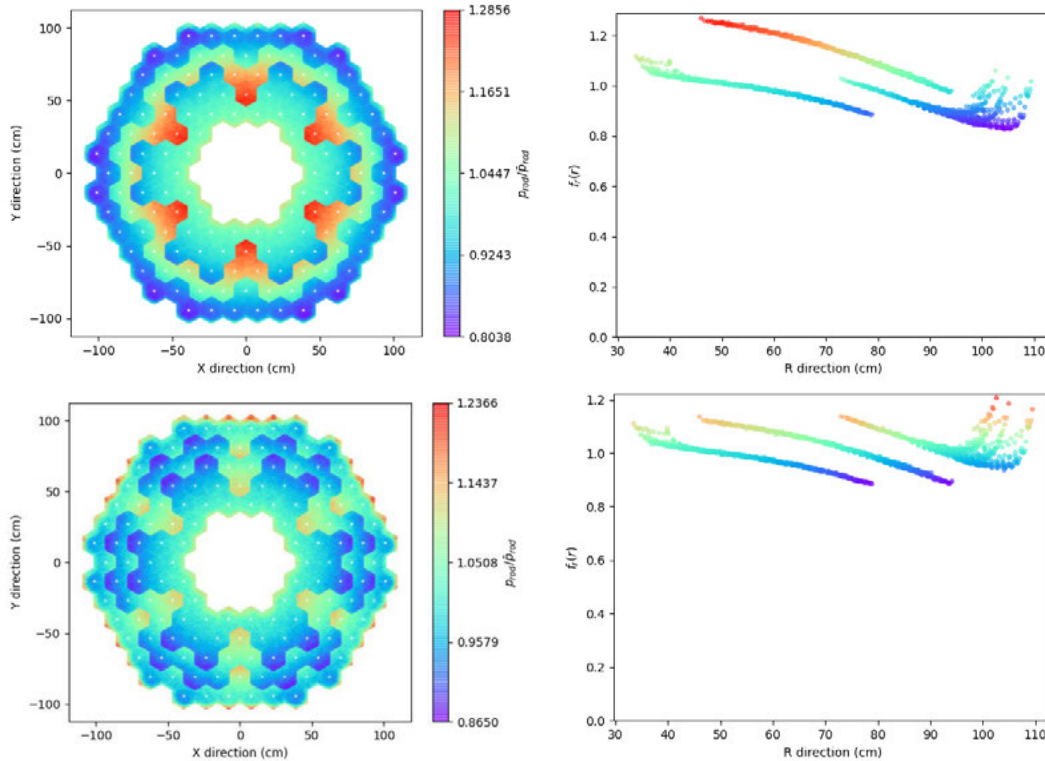


Figure 4. Radial Power Distributions, BOC (Top: Baseline Loading, Bottom: Alternate Loading)

4.3. Axial Power Distribution

As the fissile content of the fuel is uniform in the axial direction, the axial power profile in general follows the cosine shape. However, the top and bottom section of the active core are affected by the top and bottom reflector, respectively. The axial power shapes of selected rods are shown in Figure 5. During normal operation, the actual axial power distribution is affected by the control rod insertion. Other parameters that could cause variations in the axial power shape typically include Doppler effect, xenon spatial distribution, fuel burnup, and coolant density.

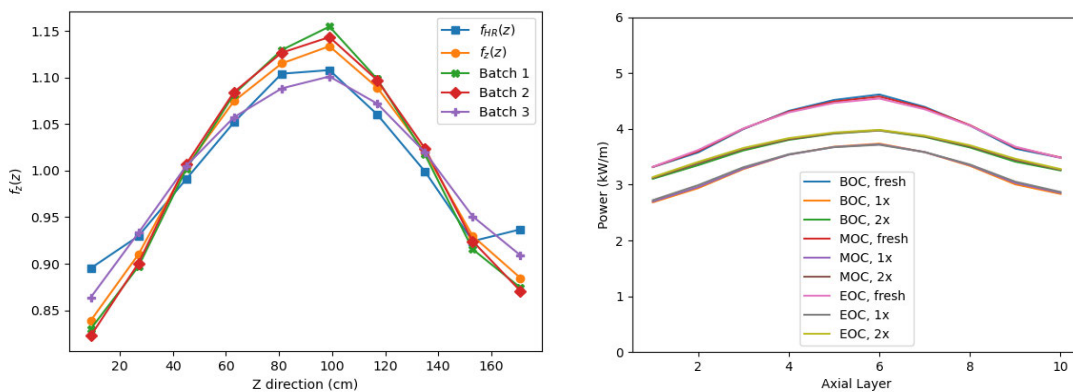


Figure 5. Axial Power Distributions, BOC

4.4. Assembly Power Distribution

Rod-wise power distribution at the BOC is shown in Figure 6 for the hot rod assembly and adjacent assemblies, showing that spatial distribution depends on assembly location. Table II represents a breakdown of linear power by fuel zone and axial layer position. In the baseline loading pattern, the hottest rod is the innermost rod of the fresh fuel, which has a linear power density $\sim 25\%$ above the average rod, and the standard deviation over the hot assembly rods is ~ 0.11 . It can be seen in Figures 4 and 6 that the power distribution within each zone is relatively uniform with a minor radial gradient. An inter-zone power discontinuity can also be seen in Figures 4 and 6; this discontinuity could possibly assist in flow mixing by generating a crossflow, however further analysis is required in that determination. During the cycle, power decreases in the higher power regions and increases in the lower power regions.

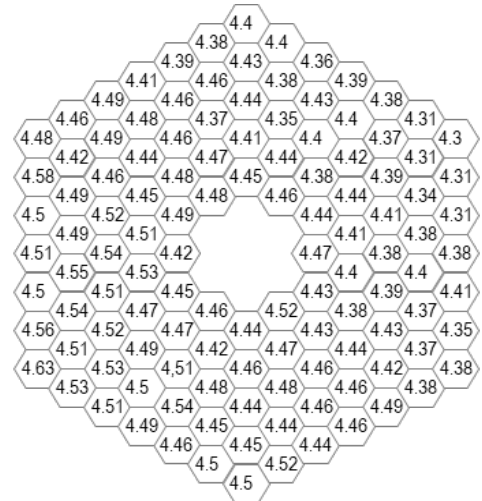


Figure 6. Hot Assembly Power Distribution, BOC

Table II. Zone linear power (kW/m), BOC

Axial section	Hot assembly	Fresh batch (excluding hot assembly)	Once-burned	Twice-burned	Hot rod	Core average
1	3.821	3.240	2.672	3.079	4.089	3.021
2	4.047	3.513	2.925	3.326	4.247	3.277
3	4.436	3.934	3.271	3.582	4.527	3.616
4	4.735	4.258	3.522	3.768	4.805	3.869
5	4.933	4.446	3.660	3.878	5.044	4.015
6	5.029	4.547	3.714	3.924	5.061	4.082
7	4.814	4.321	3.564	3.820	4.844	3.923
8	4.501	3.996	3.326	3.634	4.564	3.673
9	4.107	3.589	3.002	3.389	4.222	3.348
10	3.994	3.417	2.829	3.240	4.280	3.186

4.5. Limiting Power Envelope

The envelope drawn in Figure 7 represents an upper bound envelope on local power density versus fuel residence time in the core. This envelope is a conservative representation of the bounding values of local power density. This upper bound envelope was obtained from the peak power density at a given burnup state, not necessarily following the power density of the hot rod. For the FMR, the average linear power at full power is 3.6 kW/m. The conservative upper bound value of normalized local power density, including possible uncertainties associated with the neutronics calculations, is ~ 5.5 kW/m at 100% power.

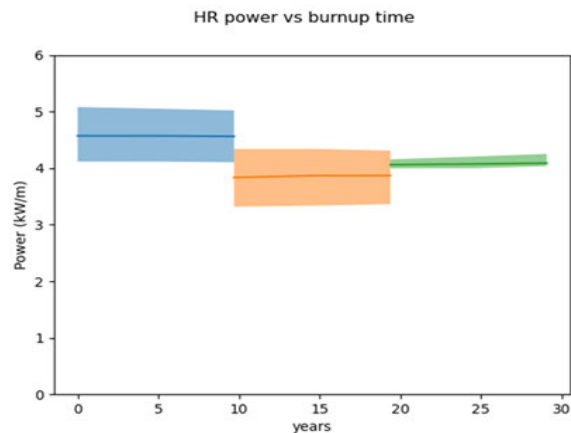


Figure 7. Limiting Power Envelope

4.5. Trade Analysis

Various trade studies were conducted, including sensitivity to reflector thickness, pin pitch, and assembly handling gap. Pin pitch was incremented between 1.3 and 1.5, and the gap between fuel assemblies was varied between 0.21 and 0.95 cm. Examples of resultant sensitivity trends in k_{eff} and F_Q are shown in Figure 8.

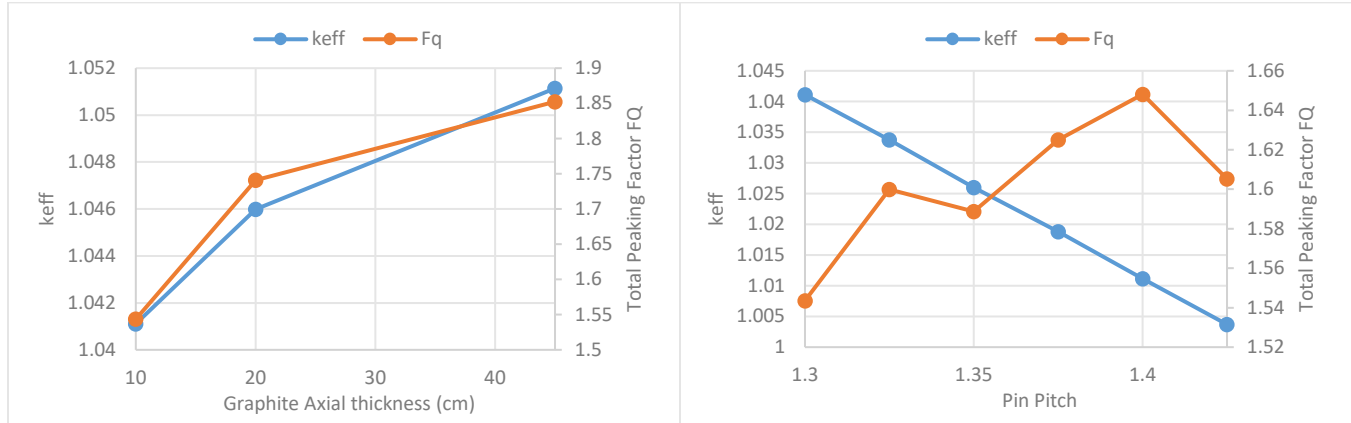


Figure 8. k_{eff} and Total Peaking Factor Trends

Decreasing the space between fuel rods/elements predictably increased excess reactivity and peaking factor. Increasing axial reflector thickness resulted in an increase in excess reactivity and total peaking factor. Further study of this case by increasing the inner reflector thickness from 2 to 3 hex layers has shown some effect of reducing total power peaking factor by minimizing peaking at the outer annular boundary.

4.6. Comparison of Reactor Parameters

Table III present summaries of the plant thermal design parameters, reactor core physical dimensions, and structural component parameters. It also compares the design parameters of the FMR to those of the HTGR and conventional pressurized water reactor (PWR). The selected HTGR and PWR are General Atomics GT-MHR and Westinghouse AP1000 [11], respectively. The AP1000 is a water-cooled reactor working on indirect steam cycle. The core power density and linear power of the fuel rod of the AP1000 are approximately five time higher than those of the FMR. The GT-MHR is a helium-cooled direct Brayton cycle reactor like the FMR. The core power density is only 1/3 of the FMR power density. This low power density is achieved by loading large amount of graphite moderator. As such, the physical size of the GT-MHR is extremely large. The linear power of the GT-MHR fuel compact is also very low at 3.9 kW/m. The FMR core was designed to have a very low linear power of 3.6 kW/m, which is necessary to secure the safety margin during the accident conditions.

Table III. Comparison of reactor design parameters

	FMR	GT-MHR	AP1000
<i>Fuel assembly design</i>			
Fuel assembly type	Hexagonal	Hexagonal, block	Square 17×17
Number of fuel assemblies	144	102 ^{a)}	157
Fuel rods per assembly	120	210 ^{b)}	264
Rod pitch (cm)	1.3 – 1.5	1.8796 ^{b)}	1.26
Fuel assembly dimension, flat-to-flat (cm)	15.3 – 17.6	36	21.4×21.4
Fuel weight, as uranium (kg)	12,294	4,681	84,600
Cladding weight (kg)	6,170	-	19,552

Number of grids per assembly			
Top and bottom	2	-	2
Intermediate	3	-	8
Intermediate flow mixing	-	-	4
Loading technique, first cycle	3 zones	2 zones	3 zones
<i>Fuel rods</i>			
Number	17,280	20,700 ^{c)}	41,448
Outside diameter (cm)	0.95	1.245	0.95
Diametral gap (cm)	0.02 – 0.04	-	0.0165
Clad thickness (cm)	0.08 – 0.1	-	0.0572
Clad material	SiC composite	Graphite	ZIRLO
<i>Fuel pellets</i>			
Material	UO ₂	UC _{0.5} O _{1.5}	UO ₂
Density (% theoretical)	95	95.6	95.5
Diameter (cm)	0.71 – 0.77	1.245	0.8192
Length (cm)	-	4.928	0.983
Core diameter, equivalent (cm)	206 – 236	296/ 483	304.04
Core height, cold, active fuel (cm)	180	793	426.72
Fuel enrichment, equilibrium cycle (wt.%)	19.75	19.8	4.45
<i>Reactor power</i>			
Thermal power, MW	112	600	3300
Power density, MW/m ³	16 – 21	6.6	106.3
Rod linear power, kW/m	3.6	3.9	18.6

- Fuel column, i.e., hexagonal block
- Standard element, fuel compact holes
- Number of fuel compact holes

5. CONCLUSION

The FMR contains a matrix of fuel rods assembled into mechanically identical fuel assemblies along with control and structural elements. The fuel assemblies are configured into the core arrangement located and supported by the reactor internals. The reactor internals also direct the flow of the coolant to pass the core and take the heat out of fuel rods. The coolant material is helium at a normal operating pressure of 7 MPa. The fuel, internals, and coolant are contained within a heavy-walled reactor pressure vessel. The fuel assembly consists of 144 fuel rods in a triangular array. Central 7-rod position is used for a guide tube that is reserved for control rod insertion. The guide tube is joined to the top and bottom nozzles of the fuel assembly and provide the supporting structure for the fuel grids. Initial core configurations of FMR and respective power distributions have been evaluated by MCNP6. The power peaking was well-controlled by the heavy reflectors and reloading patterns. The average linear power of the fuel rod is 3.6 kW/m. The fuel management scheme is 3-batch with a refueling period of ~10 years. The average discharge burnup is 100 GWd/tU. The observations from this preliminary analysis are as follows:

- The refueling interval is ~6 times longer than that of the current commercial reactor, which reduces the spent fuel generation, refueling work, and fuel transportation requirement accordingly.
- The linear power is approximately one-fifth of the existing LWR fuel value (~20 kW/m), which enables the passive cooling of the core during loss of active shutdown cooling. The low decay heat also allows onsite dry storage of the spent fuel.

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