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Assessment of Local Temperature Reactivity Response in Multi-Module HTGR Special Purpose Reactor

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EXECUTIVE SUMMARY

HolosGen, LLC (HolosGen) is proposing a highly innovative microreactor concept targeting both civilian and military applications. It consists of an advanced helium-cooled gas reactor using a decoupled and electronically controlled turbojet-type turbine and compressor to achieve a highly condensed reactor that fits into commercial ISO container.

The broader scope of this project is to pursue one path to enabling autonomous or semi-autonomous operations through passive systems. To wit, we wish to characterize the local reactivity response to temperature to facilitate the design of passive variable flow controllers that would respond to local temperatures and adjust coolant flow rates that induce a desired reactivity response.

The purpose of this milestone is to perform a quantitative assessment of the local temperature reactivity response for the Holos-Quad core reactor concept. Full core Monte Carlo models of the Holos-Quad capturing local temperature distributions, and corresponding SAM models using the local power distributions were developed. A methodology to determine the local fuel and moderator temperature coefficients of reactivity was developed and applied to quantify the local reactivity responses.

The results of the analysis indicate that the fuel temperature reactivity is approximately a factor of two greater than the moderator temperature coefficient. This effect is also approximately spatially uniform. The highest worth regions are neither at the periphery or center of the core, but in the regions farthest from the subcritical module boundaries. Collectively this area accounts for about 1/3 of the doppler feedback.

Preliminary studies on the control via the conventional mechanical shim suggest that ~50 pcm is needed to perform maneuvers that encompass a range of 20% rated power. To cover 90% rated power would require closer to 300 pcm changes in reactivity. This suggests global temperature changes of ~20K or local temperature variations up to 50K. Therefore, for small power maneuvers in the range of 5% to 10% rated power, the local reactivity control via passive flow controls would be possible if temperature changes of 20K to 50K could be achieved.

This initial study along with associated preliminary results for the controllability of the reactor seem to indicate at this point that the development and use of local passive variable flow controllers is feasible from a control standpoint to support small power maneuvers.

Future work will include refining the temperature response to smaller regions in the highest worth regions, examining the coefficients at different burnups, and a closer examination of the effect on heat transfer of adjusting the coolant flow rate to produce a change in fuel temperature and moderator temperature.

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ACRONYMS

ANL	Argonne National Laboratory
HTGR	High Temperature Gas Reactor
ISO	International Standards Organization
MWt	Mega Watts thermal
SAM	Systems Analysis Module
SPM	Subcritical Power Module
TRISO	TRI-structural ISOtropic fuel
UM	University of Michigan

1. INTRODUCTION

HolosGen, LLC (HolosGen) is proposing a highly innovative micro-reactor concept targeting both civilian and military applications. It consists of an advanced helium-cooled gas reactor using a decoupled and electronically controlled turbojet-type turbine and compressor to achieve a highly condensed reactor that fits into commercial ISO container. The Holos-Quad concept being considered for civilian applications will generate 22MWt, using four Subcritical Power Modules (SPMs) that fit into one 40-foot ISO container. It is a high-temperature gas-cooled reactor concept using TRISO fuel distributed in graphite hexagonal blocks, cooled with helium gas at 7MPa and a high outlet temperature 850^{o}C.

Microreactors are an emerging strategic technology for accessing remote markets and power grids, where fuel supplies of conventional power generating systems come with a premium. In these markets, nuclear energy from microreactors is competitive. One aspect to this competitiveness is minimizing operational costs. Traditional nuclear plants require highly skilled operators to be available locally. In remote markets, maintaining the additional infrastructure and personnel for operations can be cost prohibitive. Therefore, microreactors with autonomous operation capabilities are highly desirable. The broader scope of this project is to pursue one path to enabling autonomous or semi-autonomous operations through passive systems. To wit, we wish to characterize the local reactivity response to temperature to facilitate the design of passive variable flow controllers that would respond to local temperatures and adjust coolant flow rates that induce a desired reactivity response.

The purpose of this milestone is to perform a quantitative assessment of the local temperature reactivity response for the Holos-Quad core reactor concept. The results of this assessment will inform the feasibility and design of passive variable flow controllers that can potentially drive local temperature responses in the reactor to support semi-autonomous control for flexible power operations. The remainder of this report is as follows: section 2 gives a summary of the methodology used, section 3 presents the results and gives some discussion. Section 4 provides the conclusions of this work.

2. METHODOLOGY

In order to predict the local temperature reactivity response of Holos-Quad core, Monte Carlo calculations with Serpent [1] were performed with temperature distribution obtained from the thermo-fluids code SAM [2]. Both base SAM and Serpent models were provided by ANL. The power distribution obtained from the Serpent full core calculation is applied to the single assembly SAM models to predict the individual steady-state temperature distribution. The resulting SAM temperature distribution is then used to define the input to the Serpent model to obtain the base calculation with the nominal temperature distribution. Local fuel and graphite temperature distributions were then applied to the Serpent model to calculate the corresponding reactivity response.

2.1 Thermo-fluids calculation with SAM

The SAM model consists of a detailed geometric model where the inner, edge and corner fluid channels are separately defined and connected to the solid structure for a full axial assembly. Figure 1 illustrates the representative assembly design. Table 1 provides some of design specifications and SAM model predictions for an average assembly.

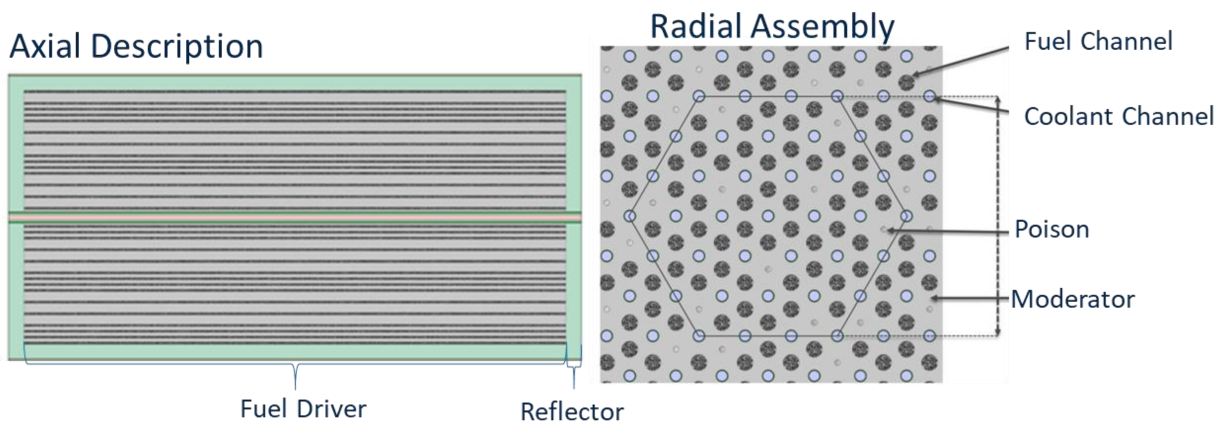

Figure 1. Illustration of Holos assembly model

Table 1. Holos assembly parameters

Power, kW	400
Maximum fuel temperature, C	955.6
Average fuel temperature, C	832.4
Inlet velocity, m/s	29.9
Pressure drop, kPa	7.2
Coolant inlet temperature, C	590.0
Coolant outlet temperature, C	849.1

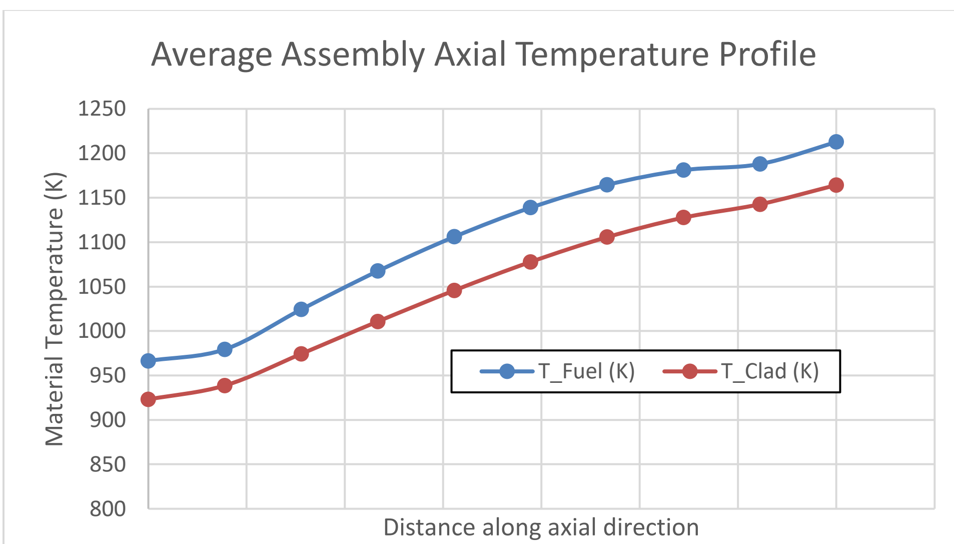

Figure 2. Average assembly axial fuel and clad temperature

2.2 Monte Carlo calculation with Serpent

A full core Serpent model was used to first obtain the radial power distribution and then to predict the local temperature reactivity response of the Holos reactor. The core radial and axial view of the Serpent model is shown in Figure 3.

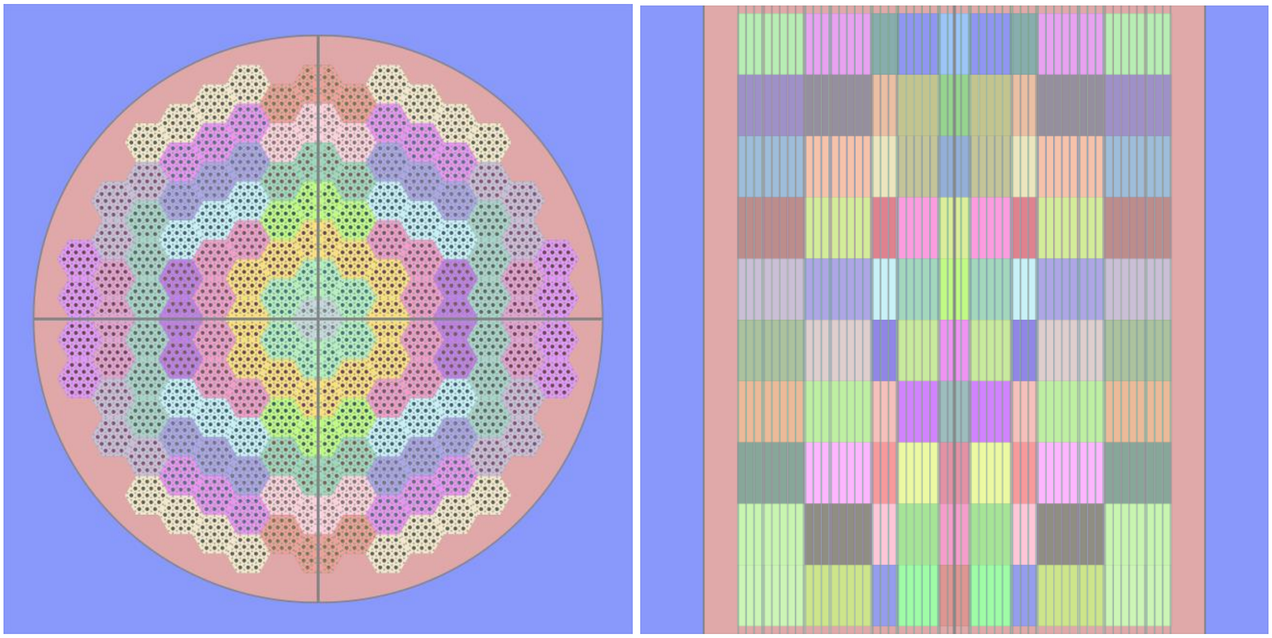

Figure 3. Holos Reactor radial (left) and axial Serpent model

The Serpent model contains 43 assemblies (33 fuel, 9 half and 1 quarter) in one of the quadrants of the core. Ideally temperature distributions can be set up for each of these 43 assemblies however preprocessing and storing all the cross sections with that many different temperatures (10 axial regions are considered) requires a significant amount of memory. In order to reduce the memory demand 10 axial and 17 radial regions were defined to set a temperature distribution in the Serpent model. The radial region numbering is shown in Figure 4.

The Serpent model is generated with TRISO particles that are explicitly defined and randomly positioned in each of the 10 axial and 17 radial sections of core. The fuel temperature in the reactivity calculation is considered as the average temperature of the uranium kernel inside the TRISO particle for one of the 17x10 regions defined in the model. The graphite temperature is defined as the temperature of the graphite in the TRISO coatings, matrix, and assembly graphite.

All temperature treatments for the material are done on the fly by setting temperature in the “tmp” card of Serpent. Temperature treatment of the $S(\alpha,\beta)$ thermal scattering kernel was done by using the interpolation functionality of Serpent between two predefined $S(\alpha,\beta)$ data at temperatures bounding the required temperatures.

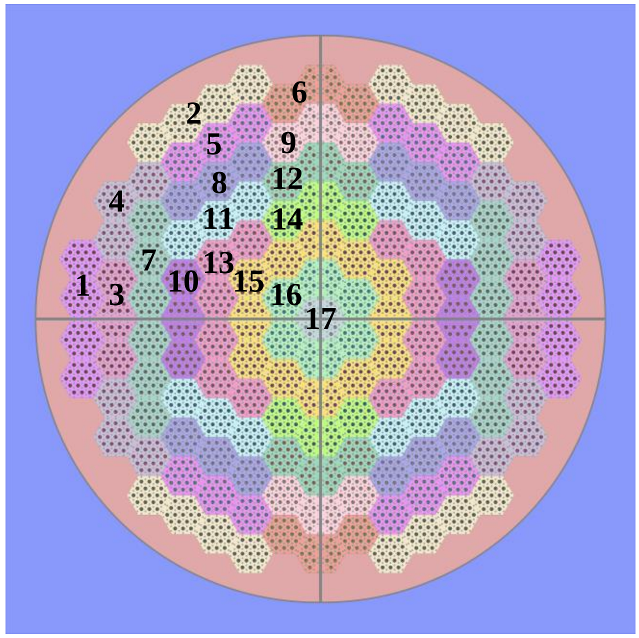

Figure 4. Radial region numbering

The power distribution for each radial region calculated by Serpent is given in Table 2. The assembly power calculated by using the power fractions in this table was then provided as input the single assembly model of SAM which used a predefined axial power profile for each radial region.

Table 2. Serpent radial power distribution

Region	Power Fraction	Region	Power Fraction
1	**0.67**	10	**1.07**
2	**0.67**	11	**1.07**
3	**0.72**	12	**1.10**
4	**0.83**	13	**1.30**
5	**0.78**	14	**1.27**
6	**0.80**	15	**1.36**
7	**0.93**	16	**1.49**
8	**0.97**	17	**1.07**
9	**0.90**		

3. RESULTS

All the Serpent calculations were performed with 200,000 neutrons per cycle, 100 inactive and 1,000 active cycles, which provided around 8 pcm statistical uncertainty for all calculations.

3.1 Fuel and Graphite Temperature Reactivity

A base calculation is performed at the predicted temperature distribution which was obtained from SAM. First a 400K temperature perturbation was applied to the whole core to obtain the overall fuel and graphite temperature reactivity coefficients. To obtain the local temperature reactivity response a 400K perturbations in the fuel and graphite temperatures were applied for each region defined in the Serpent model. While the 400K may seem unreasonable, there were initial attempts to use smaller perturbations, however, this methodology was insufficient to overcome the statistical uncertainties of the Monte Carlo transport. Since the doppler coefficient is relatively constant over a broad temperature range, and linear with respect to the square root of temperature, the larger temperature perturbation of 400K can be justified. This approach is additionally verified in the result as the sum of the local coefficients is consistent with the whole core reactivity coefficients.

Table 3. Overall Temperature Reactivity Coefficients

	Temperature Coef. (pcm/K)
Fuel	-3.17
Graphite	-1.53

Table 4. Local Fuel/Graphite Temperature Reactivity Coefficients

	Fuel Temperature Coef. (pcm/K)	**Graphite Temperature Coef. (pcm/K)**
1	-0.10	-0.05
2	-0.18	-0.09
3	-0.10	-0.02
4	-0.18	-0.12
5	-0.20	-0.08
6	-0.04	-0.07
7	-0.25	-0.14
8	-0.26	-0.11
9	-0.15	-0.09
10	-0.21	-0.09
11	-0.41	-0.18
12	-0.19	-0.11
13	-0.52	-0.32
14	-0.26	-0.16
15	-0.53	-0.25
16	-0.29	-0.18
17	-0.11	-0.02
Sum	-3.98	-2.09

From Table 4, it is observed that there is up to a factor of 5 variation in the local fuel temperature coefficient and a factor of 6 for the moderator. The fuel temperature reactivity is approximately a factor of two greater than the moderator temperature coefficient. This effect is also approximately spatially uniform. The highest worth regions are 15, 13, and 11. Collectively they account for about 1/3 of the doppler feedback. These regions are neither at the core periphery or core center. Given the high operating temperatures and thermal inertia of the graphite, it can be expected from a dynamics standpoint that the reactivity driven by the graphite moderator will drive a secondary smaller reactivity feedback effect.

Other preliminary studies [3] on the control via the conventional mechanical shim suggest that ~50 pcm is needed to perform maneuvers that encompass a range of 20% rated power. To cover 90% rated power would require closer to 300 pcm changes in reactivity. This suggests global temperature changes of ~20K or local temperature variations up to 50K. Therefore, for small power maneuvers in the range of 5% to 10% rated power, the local reactivity control via passive flow controls would be possible if temperature changes of 20K to 50K could be achieved.

4. CONCLUSIONS

Full core Monte Carlo models of the Holos-Quad capturing local temperature distributions, and corresponding SAM models using the local power distributions were developed. A methodology to determine the local fuel and moderator temperature coefficients of reactivity was developed and applied to quantify these numbers.

This initial study along with associated preliminary results for the controllability of the reactor seem to indicate at this point that the development and use of local passive variable flow controllers is feasible from a control standpoint to support small power maneuvers.

Future work will include refining the temperature response to smaller regions in the highest worth regions, examining the coefficients at different burnups, and a closer examination of the effect on heat transfer of adjusting the coolant flow rate to produce a change in fuel temperature and moderator temperature.

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