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Phenomena Identification and Ranking Tables (PIRT) Report for Fluoride High-Temperature Reactor (FHR) Neutronics

Computational Reactor and Medical Physics Laboratory
Nuclear and Radiological Engineering Programs
Georgia Institute of Technology
Atlanta, GA 30332

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Phenomena Identification and Ranking Tables (PIRT) Report for Fluoride High-Temperature Reactor (FHR) Neutronics

Panel Members
David Diamond (Facilitator), Brookhaven National Laboratory
Christopher Edgar, Georgia Institute of Technology
Max Fratoni, University of California – Berkeley
Hans Gougar, Idaho National Laboratory
Ayman Hawari, North Carolina State University
Jianwei Hu, Oak Ridge National Laboratory
Nathanael Hudson, Nuclear Regulatory Commission
Dan Ilas, Oak Ridge National Laboratory
Ivan Maldonado, University of Tennessee – Knoxville
Bojan Petrovic, Georgia Institute of Technology
Farzad Rahnema, Georgia Institute of Technology
Dumitru Serghiuta, Canadian Nuclear Safety Commission
Dingkang Zhang, Georgia Institute of Technology

Prepared by
Farzad Rahnema, Chris Edgar, Dingkang Zhang, and Bojan Petrovic

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FHR Fluoride Salt Cooled High Temperature Reactor

NEUP Nuclear Energy University Programs
U.S. Department of Energy

Executive Summary

A team of researchers, led by the Georgia Institute of Technology (GT), and including collaborators from The Ohio State University (OSU), Texas A&M University (TAMU), Texas A&M University Kingsville (TAMU-K), Oak Ridge National Laboratory (ORNL), and AREVA, as well as international partners at University of Zagreb, Politecnico di Milano, and Shanghai Institute of Applied Physics (SINAP) were selected by the U.S. Department of Energy to form an Integrated Research Project (IRP) exploring Fluoride High-Temperature Reactor (FHR) technology and licensing challenges. The GT-led IRP chose the ORNL preconceptual design for the Advanced High Temperature Reactor (AHTR) as its candidate design for analysis and technology development. An additional IRP, led by the Massachusetts Institute of Technology (MIT) was also funded and focuses on a different FHR reactor design.

One area of major concern is the verification and validation (V&V) of neutronics tools, codes, and methodologies for core and system design in support of licensing of FHRs. In order to begin addressing this task, the GT led IRP convened a Phenomena Identification and Ranking Table (PIRT) panel with internal and invited external experts to address issues related to the V&V of neutronics tools, codes, and methodologies. The PIRT panel for the FHR-IRP on neutronics took place on December 8-10, 2015 at Georgia Tech. The panel was led by a facilitator, and consisted of both internal and external experts on neutronics, modeling and simulation, salt and graphite properties, and other areas of relevance for FHR technologies. Student observers with an interest in neutronics or neutronics-related activities attended the PIRT exercise from both the GT- and MIT-led IRPs.

As a preliminary step to the PIRT panel, a white paper was commissioned to provide a starting point of reference for the panel as they prepare for the PIRT exercise. This document presented the most recent revision of the AHTR preconceptual design, with an emphasis on reactor components relevant to neutronics simulations. Parameters and quantities of interest based on previous neutronics analysis of the AHTR and systems sharing similar physics were discussed and an initial list of gaps in areas of concern was compiled to provide a starting point for discussions by the PIRT panel.

This publication documents the overall PIRT process, ranking methods, voting procedures, rationale for all rankings, discussion of the next steps for phenomena that require further consideration, and a record of the comments and suggested path forward from the panelists. The resulting PIRTs are presented in Appendices A-D covering fundamental cross section data, material composition, computational methodologies, and general depletion. The report is concluded by a summary of the path forward recommended for each phenomenon which requires further work and/or research and development in support of licensing of the modeling and simulation tool(s) for neutronics analysis of FHR.

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List of Abbreviations

AHTR	Advanced High Temperature Reactor
C-C	Carbon-Carbon composite
CHM	Carbon to Heavy Metal
DOE	U.S. Department of Energy
DRACS	Direct Reactor Auxiliary Cooling System
FHR	Fluoride High-Temperature Reactor
GT	Georgia Institute of Technology
FoM	Figure-of-Merit
IRP	Integrated Research Project
MIT	Massachusetts Institute of Technology
NEUP	Nuclear Energy University Programs
OD	Outer Diameter
ORNL	Oak Ridge National Laboratory
OSU	The Ohio State University
PB-FHR	Pebble Bed Fluoride High-Temperature Reactor
PIRT	Phenomena Identification and Ranking Table
SINAP	Shanghai Institute of Applied Physics
TAMU	Texas A&M University
TAMU-K	Texas A&M University, Kingston
TRISO	Tristructural-Isotropic
V&V	Verification and Validation

1. Introduction

1.1. Background

The widespread deployment of FHR technology promises many benefits: improved safety, through passive safety systems and proliferation-resistant waste forms; improved economics, through higher operating temperatures and thus higher operating efficiency; and a diversification of the nation's energy portfolio, through expanding the role of nuclear power beyond baseload electricity to meeting peaking electricity demand and supplying industrial process heat. However, significant challenges remain before this class of reactors can be deployed, mostly related to its technology readiness. A panel of experts was commissioned to identify and rank the phenomena presented by FHRs relating to the verification and validation (V&V) of neutronics tools, codes, and methodologies for core and system design in support of licensure of FHRs. Since FHRs vary greatly in reactor design, the phenomenon identification and ranking table (PIRT) was developed using the Advanced High-Temperature Reactor (AHTR) design as the basis.

1.2. PIRT Panel Membership

The PIRT panel consisted of thirteen voting members, covering a wide range of expertise in areas relevant to FHR neutronics validation and verification, including reactor physics, cross section development, national and international regulators, industry, and code and method developers. Table 1-1 provides a list of voting panelists and their organizations. In addition to the voting members of the panel, observers included several graduate students from both the Georgia Tech and MIT led IRPs, as well as Kim Stein, of AREVA Federal Services, LLC. David Diamond led the PIRT Panel and acted as the facilitator for the process.

Table 1-1: Neutronics PIRT panelists and organization.

Name	Organization
David Diamond (Facilitator)	Brookhaven National Laboratory
Christopher Edgar	Georgia Institute of Technology
Max Fratoni	University of California – Berkeley
Hans Gougar	Idaho National Laboratory
Ayman Hawari	North Carolina State University
Jianwei Hu	Oak Ridge National Laboratory
Nathanael Hudson	Nuclear Regulatory Commission
Dan Ilas	Oak Ridge National Laboratory
Ivan Maldonado	University of Tennessee – Knoxville
Bojan Petrovic	Georgia Institute of Technology
Farzad Rahnema	Georgia Institute of Technology
Dumitru Serghiuta	Canadian Nuclear Safety Commission
Dingkang Zhang	Georgia Institute of Technology

1.3. PIRT Overview

The PIRT process consisted of nine major steps:

1. Define the issue
2. Define objectives of the PIRT
3. Define hardware, scenario, methodology, etc.
4. Define evaluation criteria (figures-of- merit)
5. Identify, obtain, review database
6. Identify phenomena (processes, parameters, etc.)
7. Rank importance and provide rationale
8. Assess uncertainty/knowledge level
9. Document results and conclusions

1.3.1. Step 1: Define the Issue

Research on and eventual licensing of FHR technologies requires the availability of verified and validated neutronics tools, codes, and methodologies to provide modeling solutions which are well representative of the actual physics in the real system. These tools, codes, and methodologies may not currently exist and/or have a low level of knowledge and/or quantifiable accuracy.

1.3.2. Step 2: Define the Objectives of the PIRT

The objective of the PIRT panel was to determine the important phenomena that impact the fidelity of neutronics analysis for the FHR and determine where new databases, modeling, and detailed analysis need to be added to validate computer codes and methods.

1.3.3. Step 3: Define Hardware, Scenario, Methodology, etc.

This step involved the preparation of a whitepaper (Rahnema, et al., 2015) by students and faculty at Georgia Tech discussing the details of the AHTR (GT's chosen FHR for evaluation) and the current status of research activities applicable to FHR technology. The whitepaper was released to the panelists ahead of the PIRT session to provide a design basis and present the current state of neutronics evaluations. Additionally, expert panelists shown in Table 1-2 gave presentations on the opening day of the PIRT Panel, covering several key areas of interest related to FHR neutronics analyses. Several members of the panel were primary authors on the major literature currently published and these presentations expanded on the details presented in their publications.

Table 1-2: List of Presentation on the PIRT Panel.

Name	Presentation
Christopher Edgar	AHTR Design Features
Jianwei Hu	SCALE Updates for FHR Applications
Dan Ilas	Use and Application of the SCALE Code System to AHTR Problems
Ivan Maldonado	Use and Application of SERPENT to AHTR Problems

1.3.4. Step 4: Define Evaluation Criteria (Figures-of-Merit)

In order to assess and rank the identified phenomena, two figures-of-merit (FoMs) were selected by the panel. These FoMs were selected such that the ability/inability of a tool, code, or method to accurately and correctly resolve the FoMs would allow for a basis to say the tool, code, or method is/is not verified. The two FoMs identified by the panel were:

- FoM_1: $k_{effective}$
- FoM_2: Plate piece wise fission density or neutron flux

These two FoMs were selected because they provide items of interest when considering licensure of a plant. The eigenvalue provides the reactivity (or change in reactivity) that can be used for design of reactivity control systems and analysis of various reactivity feedback characteristics. The plate wise fission density provides a spatial and time distribution of the fission density (and therefore reaction rates, flux, power, etc.), information necessary for fuel design, thermal hydraulics, safety systems, safety analysis, fuel management and operation.

1.3.5. Step 5: Identify, Obtain, Review Database

This step was performed by the panelists when they reviewed the whitepaper together with a list of relevant references, which identified and obtained any relevant research on FHRs. The expert presentations added additional depth and direct engagement between the panel and individuals who performed many of the previous neutronics analysis of FHR technologies.

1.3.6. Step 6: Identify Phenomena

In this step, panelists identified a list of phenomena and defined each of these for ranking and knowledge level classification. These phenomena are found in Appendices A-D. This portion of the process is effectively a brainstorming session and no consideration of whether the phenomenon would affect the chosen FoMs or the knowledge level was made at this step.

1.3.7. Step 7: Rank Importance and Provide Rationale

After phenomena identification was completed, panelists ranked the importance of each phenomenon identified, in relation to its effect on the FoMs. A vote was taken, whereby each voting member of the panel chose to assign high, medium, or low importance to the phenomenon's effect on the FoMs. Votes were then averaged to assign an overall importance. Table 1-3 depicts the ranking and associated description. The rationale for each agreed upon importance was provided by the panel and is found in Appendices A-D.

Table 1-3 Phenomena importance rankings and descriptions

Ranking	Description
High (H)	Significant or dominant influence on FoM
Medium (M)	Moderate influence on FoM
Low (L)	Small influence on FoM

1.3.7.1. Voting Process for Assigning Importance Ranking

Each of the voting members were asked to vote if they felt the phenomena had a significant or dominant influence (High), moderate influence (Medium), or small influence (Low) on the Figure-of-Merit. Votes for High, Medium, and Low importance were assigned numerical score of 8, 5, and 2, respectively. If the average of the score was 6.5 or higher, the importance was assigned as High. If the average was above 3.5 and below 6.5, the importance was assigned as Medium. Finally, if the average was below 3.5, the importance was set to Low. This process was repeated for each phenomenon as it relates to each FoM.

1.3.8. Step 8: Assess Knowledge Level

In a similar manner to the importance ranking, the knowledge level of each phenomenon was voted on by the panel. During this process, each of the phenomena was classified as known, partially known, or unknown via a voting process. Table 1-4 provides the definition of each knowledge level ranking. The knowledge level ranking was assigned based on the majority vote of the panelists, after the discussion period. Once this step was completed, phenomena were identified for further consideration based on their combination of importance and knowledge level rankings (see section 3.3 for description on how phenomena were identified for further consideration).

Table 1-4 Knowledge level ranking and descriptions

Ranking	Description
Known (K)	Phenomenon is well understood and can be accurately modeled
Partially Known (P)	Phenomenon is understood, however, can only be modeled with moderate accuracy
Unknown (U)	Phenomenon is not well understood. Modeling is currently either not possible or is possible only with large uncertainty

1.3.9. Step 9: Document Results and Conclusions

This publication represents the primary objective and fully covers the overall PIRT process, ranking methods, voting procedures, rationale for all rankings, discussion of the next steps for phenomena that require further consideration, and a record of the comments and suggested path forward from the panelists.

2. PIRT Preliminaries

Several important preliminary steps were taken before the identification and ranking efforts undertaken by the panel. The PIRT organizers (Farzad Rahnema, Christopher Edgar, David Diamond, and Bojan Petrovic) discussed the overall objective of the PIRT, based on the needs of the FHR-IRP. Once the objective was settled (see section 1.3.2), a whitepaper was commissioned describing the geometry of the AHTR, as well as providing panelists with a literature review of applicable published works relating to the AHTR or FHRs in general. A description of the AHTR geometry can be found in Appendix E.

3. FHR Neutronics Core Physics PIRTs

The PIRT tables representing core physics of neutronics calculations were broken down into four main categories and are presented in Appendices A-D. The subsequent sections of this chapter provide a description of these categories, the format of the PIRT tables, and the criteria for deciding if a phenomenon requires further consideration. A path forward recommended by the panel for each phenomenon identified as requiring further consideration is summarized Table 3-2. This table in effect identifies the phenomena (issues) that require further work and/or research and development in support of licensing of the modeling and simulation tool(s) for neutronics analysis of FHR.

3.1. Category Descriptions

The PIRT panel identified and ranked phenomena for importance relative to the Figures-of-Merit in the following four categories, each of which is discussed in its corresponding subsection below.

3.1.1. Fundamental Cross-Section Data

Phenomena in this category include cross-sections, uncertainty in nuclear data, moderation and thermalization by isotopes and compounds, absorption rates, and reaction rates.

3.1.2. Material Composition

Phenomena in this category relate to fuel particle distributions in fuel plates, impurities present in materials, dimensional changes, and changes in conductivity.

3.1.3. Computational Methodology

Phenomena in this category were classified further into subcategories based on classes of computational methods, as follows:

- Stochastic continuous energy methods
- Stochastic multi-group methods

- Deterministic transport methods
- Two step stochastic transport-diffusion

Phenomena presented in each subcategory relate to issues faced by that computational methodology in relation to the FHR of interest. There are phenomena which cross over multiple computational methods and tables are provided in each subcategory for all phenomena discussed. Therefore, the reader may observe the same phenomena appearing in multiple subcategories.

3.1.4. General Depletion

Phenomena in this category represent effects presented in general for depletion calculations and relate to control depletion, spectral history effects, and isotope tracking.

3.2. Structure of the PIRT Tables

The structure of the PIRT tables found in Appendices A-D is as follows:

- Column 1 – Subcategory of the phenomena being addressed in that table
- Column 2 – Phenomenon that is being ranked
- Column 3 – The definition, rationale, importance, knowledge level, comments, and path forward for the phenomenon (if it meets the further consideration requirements presented in the next section)

3.3. Phenomena Identified for Further Consideration

After the identification and ranking process for each phenomenon was performed, the panel selected the phenomena requiring further consideration. This selection was based on the knowledge level ranking and importance ranking pertaining to each Figure-of-Merit. Table 3-1 depicts the combinations of knowledge level and importance ranking requiring further action.

Table 3-1: Knowledge level and importance ranking combinations for further consideration.

		Importance Ranking (IR)		
		H (high)	**M** (medium)	**L** (low)
Knowledge Level (KL)	**K** (known)			
	P (partially known)	YES		
	U (unknown)	YES	YES	

If a phenomenon met the knowledge level and importance ranking requirements to be considered further, a path forward was provided by the panel and is presented in the Path Forward section of Column 3 of the PIRT and summarized below.

Table 3-2: Phenomena Requiring Further Consideration.

Phenomena	Importance		Knowledge Level	Path forward
	FoM_1	FoM_2		
	Fundamental Cross Section Data			
Moderation by FLiBe	H	L	P	Do a formal review of existing libraries; Compare ENDF to other cross-sections; Do a critical review of covariances for this design.
Thermalization by FLiBe	H	M	U	There is currently S(α,β) data under development for FLiBe and scheduled to be released in the Fall of 2016.
Thermalization in Carbon	H	H	U	Development of S(α,β) data of ENDF quality is recommended for C-C composite
Absorption in FLiBe	M	L	U	The uncertain impact on the temperature reactivity coefficient needs to be determined
Absorption in Carbon	H	M	P	Transmission measurements of typical samples for total cross-section, correlated for impurities, and over several thermal energies representative of graphite temperatures are recommended.
	Material Composition			
Fuel Particle Distribution	M	L	U	Interact with fuel fabricators to determine realistic particle distributions in the plate. If unusual non-uniformity is a possibility, then study the effect on $k_{effective}$ and local peaking factor
Computational Methodology				
Solution Convergence	L	H	P	Study the underestimate of statistical uncertainty and the magnitude of the fission density tilt. Develop methods to improve fidelity.
Granularity of Depletion Regions	H	H	U	The analysis needs to be performed to determine what the effects on the FoMs are.
Multiple Heterogeneity Treatment for Generating MG Cross-Sections	H	H	U	Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.

Selection of Multi-group Structure	H	H	U	Perform a sensitivity study at the assembly level with control rods and burnable absorbers to determine the minimum number of energy groups and structure. Consider generalized condensation theory as a candidate.
Boundary Conditions for MG x-section Generation	H	H	U	Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.
Burnable Poison Cell	H	H	U	Review the burnable absorber candidates and develop models for treatment of the most probable choice.
Scattering Kernel	H	H	P	Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.
Spatial Mesh	M	H	U	Explore various subdivisions of the fuel assembly.
Diffusion Approximation	H	H	P	Test methods to determine level of accuracy compared to full transport. If method is not satisfactory, explore higher order diffusion.
Dehomogeniza tion	L	H	U	Develop a method to reconstruct the plate power and compare to detailed results.
	General Depletion			
Spectral History Effects	H	H	U	Adapt methods currently employed in Light Water Reactors to FHR and test.

It can be seen from Table 3-2 that each of the four categories has at least one phenomenon that requires further consideration. In the fundamental cross section data category, five phenomena were identified, three of which are related to the FLiBe and two are related to the carbon. In the material composition category, fuel particle distribution in the fuel plate requires further investigation. In the computational methodology, 10 phenomena were identified. These can be summarized as issues related to solution convergence, multigroup treatment, and approximations made in the solution methods. Finally, spectral history effect was the only phenomenon identified in the general depletion category.

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Varma, V. K., Holcomb, D. E., Peretz, F. J., Bradley, E. C., Ilas, D. Q., & Zaharia, N. M. (2012). *AHTR Mechanical, Structural, and Neutronic Preconceptual Design (ORNL/TM-2012/320).* Oak Ridge, TN: Oak Ridge National Laboratory.

APPENDIX A. Core Physics PIRTs for Fundamental Cross Section Data

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>^{6}Li Balance</td><td>Definition:
Cross sections for the production and destruction of ^{6}Li

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM_1
$k_{effective}$</th><th>FoM_2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>8
5
0</td><td>0
0
13</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:

^{6}Li has a huge absorption cross-section, distributed uniformly, this has a low impact on FoM_2
^{6}Li absorption cross-section is well known
^{9}Be (n,α) ^{6}Li production reaction is well known

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Moderation by FLiBe</td><td>Definition:
Free atom scattering cross sections for F, Li, and Be.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>7</td><td>0</td></tr>
<tr><td>Medium (M)</td><td>5</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>13</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:
• Inelastic scattering cross-sections for F and ^{7}Li have a high uncertainty
• Reactor core contains a volume fraction of around 20% FLiBe in the AHTR
• $k_{effective}$ is sensitive to F scatter

Path Forward:
• Do a formal review of what exists now in ENDF7 and beyond ENDF7 for the elastic and inelastic scatter of fluorine, based on this make a determination on seeking a new evaluation or measurement
• Compare ENDF to other cross-section libraries
• Do a critical review of covariances for this design, TNDL provides covariance for all isotopes in its library</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Thermalization by FLiBe</td><td>Definition:
S(α,β) for F, Li, and Be.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>8
4
0</td><td>3
10
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>Medium (M)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
Instruments do not measure this with enough precision to build a cross-section library experimentally; this could be calculated (standard practice).
Path Forward:
There is currently S(α,β) data under development for FLiBe and scheduled to be released by the North Carolina State University in the Fall of 2016.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Moderation by Carbon</td><td>Definition:
Free atom scattering cross-sections for Carbon.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
Thermalization and absorption in graphite will have major effects on the FoMs
There is a significant amount of graphite in the AHTR
These effects are well known fundamentally
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Thermalization in Carbon</td><td>Definition:
S(α,β) in Carbon/Graphite.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
k_{effective}</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Unknown (U)

Comments:
The Graphite S(α,β) in ENDF is for single crystal graphite, C-C composite (present in the reactor) is a different material and it is not known how the S(α,β) data will look in comparison.
Path Forward:
Development of S(α,β) data of ENDF quality is recommended for C-C composite, this material is common to the FHR and the VHTR reactors.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Absorption in Europium</td><td>
Definition:
Cross-sections for Eu, used in the burnable poisons in the reactor.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>11
0
0</td><td>7
5
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Known (K)

Comments:

Europium is an epithermal resonance absorber
Major fission product
Cross-section was updated in ENDF6+

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.
</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Absorption in FLiBe</td><td>Definition:
Absorption cross-sections for the constituents of FLiBe (with the exception of ^{6}Li which was addressed separately).

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>0</td><td>0</td></tr>
<tr><td>Medium (M)</td><td>13</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>13</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:

The absorption on Li, F, and Be are unknown but the effect of $k_{effective}$ is important for feedback coefficients
The data exists, but the potential of improvement needs to be examined
The existing data has relatively large uncertainty

Path Forward:
The absorption cross-section is low compared to scattering, however the uncertain impact on the reactivity coefficient needs to be determined. This may be more concerning in FHRs with a higher volume fraction of FLiBe, such as the PB-FHR.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Absorption in Carbon</td><td>
Definition:
Absorption cross-section information for Carbon.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM₁ k_{effective}</th><th>FoM₂ Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>6
2
1</td><td>4
9
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>Medium (M)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:

The absorption cross-section was changed between ENDF7 and ENDF7.1 and can cause differences in excess of 1% in $k_{effective}$
There is uncertainty in the accuracy of the absorption cross-section
With the amount of Carbon present in the system, this becomes relevant.

Path Forward:
Transmission measurements of typical samples for total cross-section, correlated for impurities, and over several thermal energies representative of graphite temperatures are recommended. This phenomenon is common to FHR, High Temperature Reactor (HTR), and Transient Reactor Test Facility (TREAT).
</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Neutron Production from Be</td><td>Definition:
Cross-sections information for photoneutrons, (α,n), and (n,2n) reactions.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
12
1</td><td>0
0
12</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:

Have to know basic cross-section information for photoneutrons, (α,n), and (n,2n).
This should be accounted for in code methodology
This may be more important for transient analysis than steady-state and comes from delayed gammas.
Current codes don’t account for (α,n) reactions.

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Fluorine Reaction Rates</td><td>Definition:
Reaction rates for (α,n) reaction on Fluorine.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM_1 $k_{effective}$</th><th>FoM_2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
4
8</td><td>0
0
13</td></tr>
<tr><td>Assigned Importance</td><td>Low (L)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
None
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Fuel Absorption and Fission Rates</td><td>Definition:
Rates of fission and absorption reactions in FHR fuel.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
• This is known for uranium and plutonium, but there is no validation for this system.
• Fission products and minor actinide cross-sections may carry larger uncertainties

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Absorption Rate in Control Rod Materials</td><td>Definition:
Absorption rates in Mo, Hf, and C

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
None
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Fundamental Cross Section Data</td><td>Moderation and Thermalization in SiC</td><td>Definition:
Free atom scattering cross-sections and S (α,β) for SiC

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
0
13</td><td>0
0
13</td></tr>
<tr><td>Assigned Importance</td><td>Low (L)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
• S (α,β) for SiC is well known on all levels

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

APPENDIX B. Core Physics PIRTs for Material Composition

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Material Composition</td><td>Fuel Particle Distribution</td><td>Definition:
The spatial distribution of the TRISO particles in the fueled portion of the plates.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
6
5</td><td>0
5
8</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:

Modeling the randomness of TRISO particles presents challenges
Particles have to be explicitly modeled – this has a huge effect on $k_{effective}$, once explicitly modeled the effect is small
This may impact the peaking factor within the plate itself

Path Forward:
Interact with fuel fabricators to determine realistic particle distributions in the plate. If unusual non-uniformity is a possibility, then study the effect of $k_{effective}$ and local peaking factor</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Material Composition</td><td>Impurities in FLiBe</td><td>Definition:
Impurities and their associated concentrations present in FLiBe

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
0
13</td><td>0
0
13</td></tr>
<tr><td>Assigned Importance</td><td>Low (L)</td><td>Low (L)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
The issues presented in this phenomena are important for activation and not relevant to neutronics models
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Material Composition</td><td>Impurities in Carbon</td><td>Definition:
Impurities and their associated concentrations present in Carbon.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Known (K)

Comments:
Impurities are both important for neutronics and activation, these are batch dependent for Carbon
Impurities can be quantified – nuclear grade graphite has a specification that must be met
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Material Composition</td><td>Carbon Density Due to Dimensional Change</td><td>Definition:
Changes in the density of Carbon components due to swelling.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
2
11</td><td>0
0
13</td></tr>
<tr><td>Assigned Importance</td><td>Low (L)</td><td>Low (L)</td></tr>
</table>
Knowledge Level:
Known (K)

Comments:

Dimensional change effectively diverts coolant to reflector region – similar to voiding
Actual behavior of the material is outside the neutronics scope of the PIRT – the dimensional change should be accounted for in the neutronics model, but isn't currently quantified.
This is a partial knowledge area for a PIRT exploring Thermal Hydraulics

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>Material Composition</td><td>Graphite Conductivity</td><td>Definition:
The change conductivity of Graphite components due to temperature and/or irradiation in the AHTR.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>6
7
0</td><td>6
5
1</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>Medium (M)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:

The change observed is approximately and order of magnitude and would affect the temperature distribution
Better knowledge of the change in conductivity due to temperature than due to irradiation
For C-C composites, irradiation affects need to be explored

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

APPENDIX C. Core Physics PIRTs for Computational Methodology

C.1. Stochastic Continuous Energy Methods

Subcategory	**Phenomena**	**Definition and Rationale (Importance, Applicability, and Uncertainty)**
C1: Stochastic Continuous Energy [e.g. MCNP, Serpent, etc.]	Solution Convergence	Definition: Convergence of the solution (eigenvalue and fission source distribution). Importance to FoMs: Knowledge Level: Partially Known (P) Comments: • Common issue to the computational method and graphite reactors • False convergence of the fission source can occur • Estimated uncertainty is significantly underestimated in the source distribution Path Forward: Study the underestimate of statistical uncertainty and the magnitude of the fission density tilt. Develop methods to improve fidelity.

Importance to FoMs:

Panelist Votes	FoM1 $k_{effective}$	FoM2 Plate Wise Fission Density
High (H)	0	13
Medium (M)	0	0
Low (L)	13	0
Assigned Importance	Low (L)	High (H)

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C1: Stochastic Continuous Energy [e.g. MCNP, Serpent, etc.]</td><td>Granularity of Depletion Regions</td><td>Definition:
Granularity of the regions used to track depletion in the reactor core.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM$_1$
$k_{effective}$</th><th>FoM$_2$
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• None

Path Forward:
The analysis needs to be performed to determine what the effects on the FoMs are.</td></tr>
</table>

C.2. Stochastic Multi-group Methods

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Multiple Heterogeneity Treatment for Generating Multi-group Cross-Sections</td><td>
Definition:
Convergence of the solution (eigenvalue and fission source distribution).

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Unknown (U)

Comments:
This is a necessary step for multi-group techniques and must be addressed for developing multi-group whole core methods.
Path Forward:
Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.
</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Selection of Multi-group Structure</td><td>Definition:
The number of and energy bounds of the multi-group cross-sections set.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM$_1$
$k_{effective}$</th><th>FoM$_2$
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
This phenomena has not been explored for the AHTR
Optimization of the few-group structure is important
Path Forward:
Perform a sensitivity study at the assembly level with control rods and burnable absorbers to determine the minimum number of energy groups and structure. Consider generalized condensation theory as a candidate.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Granularity of Depletion Regions</td><td>Definition:
Granularity of the regions used to track depletion in the reactor core.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
None
Path Forward:
The analysis needs to be performed to determine the effects on the FoMs.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Resonance Treatment</td><td>Definition:
How resonances are treated when creating multi-group cross-sections.

Importance to FoMs:
<table><tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr><tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr><tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr></table>
Knowledge Level:
Known (K)

Comments:
Although generic, one needs to study because of the spectrum of the reactor.
Current methods are applicable.
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Boundary Conditions</td><td>Definition:
How to define the boundary conditions for unit cells.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Unknown (U)

Comments:
Boundary conditions will be inaccurate, neighboring assemblies and/or reflector will have a huge impact
Cell configuration is not well defined in this reactor, not much study has been performed in this regard
Path Forward:
Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Burnable Poison Cell</td><td>Definition:
How to define the boundary of the cell representing the burnable poisons.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
Cell configuration is not well defined in this reactor, not much study has been done in this regard.
Path Forward:
Review the burnable absorber candidates and develop models for treatment of the most probable choice.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C2: Stochastic Multi-group [e.g. SCALE/TRITON, etc.]</td><td>Scattering Kernel</td><td>Definition:
The number of cosine bins and associated probabilities needed to capture the physics in the scattering kernel.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:

Probability tables are required, including the number of cosine bins need to be determined
Effect of boundary conditions is not well known

Path Forward:
Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.</td></tr>
</table>

C.3. Deterministic Transport Methods

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr>
<td>C3: Deterministic Transport</td>
<td>Multiple Heterogeneity Treatment for Generating Multi-group Cross-Sections Homogenized over the Spatial Mesh (e.g. Fuel Assembly or Sub-Assembly)</td>
<td>Definition:
How to treat the multi-heterogeneity presented by this reactor when homogenizing cross sections over the spatial mesh

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM$_1$
$k_{effective}$</th><th>FoM$_2$
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:

Effect of surrounding regions on the assembly boundary conditions are important
Proper boundary condition treatment is essential

Path Forward:
Develop methods for generating homogenized and energy condensed cross sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.</td>
</tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3:
Deterministic Transport</td><td>Selection of Multi-group Structure</td><td>Definition:
The number of and energy bounds of the multi-group cross-sections set.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:

This phenomenon has not been explored for the AHTR
Optimization of the few-group structure is important

Path Forward:
Perform a sensitivity study at the assembly level with control rods and burnable absorbers to determine the minimum number of energy groups and structure. Consider generalized condensation theory as a candidate.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3:
Deterministic Transport</td><td>Granularity of Depletion Regions</td><td>Definition:
Granularity of the regions used to track depletion in the reactor core.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• None

Path Forward:
The analysis needs to be performed to determine the effects on the FoMs.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3:
Deterministic Transport</td><td>Core Boundary Condition</td><td>Definition:
Boundary conditions representing the reactor core boundaries.

Importance to FoMs:
<table><tr><th>Panelist Votes</th><th>FoM1
keffective</th><th>FoM2
Plate Wise Fission Density</th></tr><tr><td>High (H)
Medium (M)
Low (L)</td><td>0
13
0</td><td>0
13
0</td></tr><tr><td>Assigned Importance</td><td>Medium (M)</td><td>Medium (M)</td></tr></table>
Knowledge Level:
Partially Known (P)

Comments:
None
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
C3: Deterministic Transport	Spatial Mesh	Definition: The number of mesh points per fuel assembly. Importance to FoMs: <table><tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr><tr><td>High (H) Medium (M) Low (L)</td><td>0 13 0</td><td>13 0 0</td></tr><tr><td>Assigned Importance</td><td>Medium (M)</td><td>High (H)</td></tr></table> Knowledge Level: Unknown (U) Comments: • None Path Forward: Explore various subdivisions of the fuel assembly.

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3: Deterministic Transport</td><td>Resonance Treatment</td><td>Definition:
How resonances are treated when creating multi-group cross-sections.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:

Although generic, one needs to study because of the spectrum of the reactor.
Current methods are applicable.

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3: Deterministic Transport</td><td>Boundary Conditions for Unit Cells</td><td>Definition:
How to define the boundary conditions for unit cells.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• Boundary conditions will be inaccurate, neighboring assemblies and/or reflector will have a huge impact
• Cell configuration is not well defined in this reactor, not much study has been performed in this regard

Path Forward:
Develop methods for generating multi-group cross-sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C3: Deterministic Transport</td><td>Burnable Poison Cell</td><td>Definition:
How to define the boundary of the cell representing the burnable poisons.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• Cell configuration is not well defined in this reactor, not much study has been done in this regard.

Path Forward:
Review the burnable absorber candidates and develop models for treatment of the most probable choice.</td></tr>
</table>

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
C3: Deterministic Transport	Scattering Kernel	Definition: The number of Legendre moments needed to capture the physics in the scattering kernel. Importance to FoMs: <table><tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr><tr><td>High (H) Medium (M) Low (L)</td><td>13 0 0</td><td>13 0 0</td></tr><tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr></table> Knowledge Level: Partially Known (P) Comments: • Number of Legendre moments needed to capture the scatter physics in this reactor is not known, but process is defined • Effect of boundary conditions is not well known Path Forward: Develop methods for generating multi-group cross-sections. Explore the number of Legendre moments required to obtain a stable, converged solution.

C.4. Two Step Stochastic Transport-Diffusion

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C4: Two Step Stochastic Transport-Diffusion</td><td>Multiple Heterogeneity Treatment for Generating Multi-group Cross-Sections Homogenized over the Spatial Mesh (e.g. Fuel Assembly or Sub-Assembly)</td><td>Definition:
How to treat the multi-heterogeneity presented by this reactor when homogenizing cross sections over the spatial mesh

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• Effect of surrounding regions on the assembly boundary conditions are important
• Proper boundary condition treatment is essential

Path Forward:
Develop methods for generating homogenized and energy condensed cross sections. Stochastic continuous energy response methods may prove to be a good candidate for this purpose.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C4: Two Step Stochastic Transport-Diffusion</td><td>Selection of Multi-group Structure</td><td>Definition:
The number of and energy bounds of the multi-group cross-sections set.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM_1
$k_{effective}$</th><th>FoM_2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
This phenomenon has not been explored for the AHTR
Optimization of the few-group structure is important
Path Forward:
Perform a sensitivity study at the assembly level with control rods and burnable absorbers to determine the minimum number of energy groups and structure. Consider generalized condensation theory as a candidate.</td></tr>
</table>

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
C4: Two Step Stochastic Transport-Diffusion	Granularity of Depletion Regions	Definition: Granularity of the regions used to track depletion in the reactor core. Importance to FoMs: <table><tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr><tr><td>High (H) Medium (M) Low (L)</td><td>13 0 0</td><td>13 0 0</td></tr><tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr></table> Knowledge Level: Unknown (U) Comments: • None Path Forward: The analysis needs to be performed to determine the effects on the FoMs.

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C4: Two Step Stochastic Transport-Diffusion</td><td>Core Boundary Condition</td><td>Definition:
Boundary conditions representing the reactor core boundaries.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>0
13
0</td><td>0
13
0</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>Medium (M)</td></tr>
</table>
Knowledge Level:
Partially Known (P)

Comments:
None
Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C4: Two Step Stochastic Transport-Diffusion</td><td>Diffusion Approximation</td><td>Definition:
Use of diffusion theory as a solution method for neutronics calculations.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)
Medium (M)
Low (L)</td><td>13
0
0</td><td>13
0
0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Partially Known (P)

Comments:
• Burnable poisons and control rods are a problem for diffusion calculations
• Method is known but application to this reactor type is new

Path Forward:
Test methods to determine level of accuracy compared to full transport. If method is not satisfactory, explore higher order diffusion.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>C4: Two Step Stochastic Transport-Diffusion</td><td>Spatial Mesh</td><td>Definition:
The number of mesh points per fuel assembly.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>0</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>13</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
• None

Path Forward:
Explore various subdivisions of the fuel assembly.</td></tr>
</table>

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
C4: Two Step Stochastic Transport-Diffusion	Dehomogenization	Definition: Generation of the plate wise fission density from the assembly or sub-assembly mesh results. Importance to FoMs: <table><tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr><tr><td>High (H) Medium (M) Low (L)</td><td>0 0 13</td><td>13 0 0</td></tr><tr><td>Assigned Importance</td><td>Low (L)</td><td>High (H)</td></tr></table> Knowledge Level: Unknown (U) Comments: • Plate power reconstruction is unknown. Path Forward: Develop a method to reconstruct the plate power and compare to detailed results.

APPENDIX D. Core Physics PIRTs for General Depletion

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>General Depletion</td><td>Depletion of Control Rods</td><td>Definition:
The depletion of neutron control rod materials, including the in core residence time and depletion chains for control materials.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1 $k_{effective}$</th><th>FoM2 Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>0</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>13</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>Medium (M)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Known (K)

Comments:
• The rod insertion history is unknown for this reactor type, but should be given – with this information the knowledge level is known.

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>General Depletion</td><td>Spectral History Effects</td><td>Definition:
Accounting for control rod effects on depletion cross-sections.

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>

Knowledge Level:
Unknown (U)

Comments:
This is only relevant for two-step neutronics simulation procedures
Methods are currently available, but the way to account for this phenomena in the FHR is not known
Path Forward:
Adapt methods currently employed in Light Water Reactors to FHR and test.</td></tr>
</table>

<table>
<tr><th>Subcategory</th><th>Phenomena</th><th>Definition and Rationale (Importance, Applicability, and Uncertainty)</th></tr>
<tr><td>General Depletion</td><td>Number of Isotopes to Track</td><td>
Definition:
The number of isotopes to track in depletion simulations

Importance to FoMs:
<table>
<tr><th>Panelist Votes</th><th>FoM1
$k_{effective}$</th><th>FoM2
Plate Wise Fission Density</th></tr>
<tr><td>High (H)</td><td>13</td><td>13</td></tr>
<tr><td>Medium (M)</td><td>0</td><td>0</td></tr>
<tr><td>Low (L)</td><td>0</td><td>0</td></tr>
<tr><td>Assigned Importance</td><td>High (H)</td><td>High (H)</td></tr>
</table>
Knowledge Level:
Known (K)

Comments:

This could be an issue from a computational overhead and memory standpoint.
This phenomenon is not specific to the FHR.

Path Forward:
None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration.
</td></tr>
</table>

APPENDIX E. AHTR Geometry Description

The subsequent sections of this chapter provide the description of the AHTR geometry as an excerpt from the *Whitepaper: The Current Status of the Tools for Modeling and Simulation of Advanced High Temperature Reactor Neutronic Analysis*, published by the Georgia Tech FHR-IRP team in December 2015. (Rahnema, et al., 2015) For background information on associated published works, the reader is directed to the whitepaper for further reading.

E.1. General Overview of the Plant Design

The Advanced High-Temperature Reactor (AHTR) was designed to have a thermal power of 3400 MW_{th} and an efficiency of approximately 45%, corresponding to an electrical power of 1530 MW_e. The AHTR design concept is a Fluoride High-Temperature Reactor (FHR) with a primary coolant of FLiBe (2LiF-BeF_2), coupled to an intermediary salt loop containing (58-42 mol%) KF-ZrF_4. The power cycle is based on the supercritical water cycle, with the water loop coupled to the intermediary salt loop. The AHTR exploits passive safety systems, such as Direct Reactor Auxiliary Cooling System (DRACS), in order to minimize the requirements for external support during accident scenarios. A general plant overview is presented in Figure E-1.

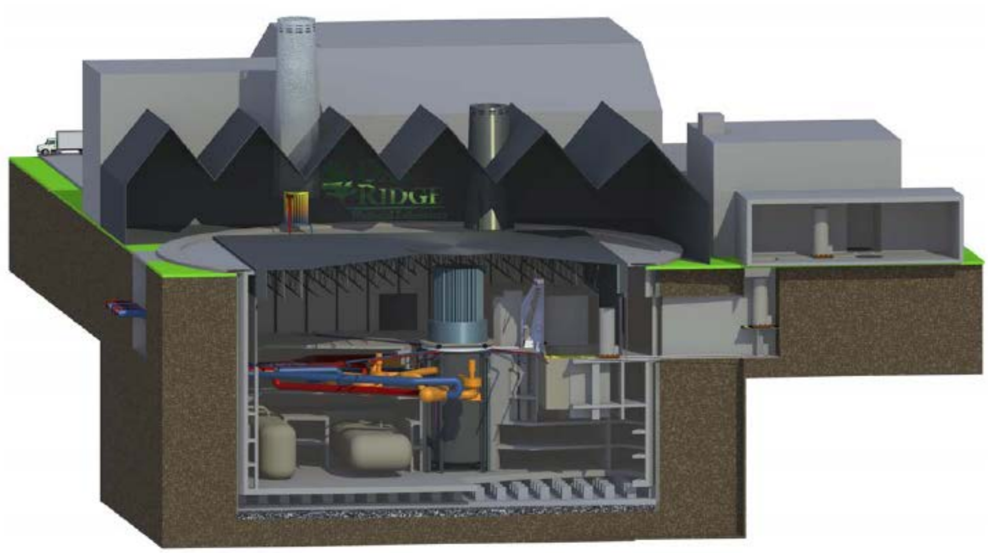

Figure E-1: Overview of the AHTR plant design. (Varma, et al., 2012)

The reactor fuel is based on the Tristructural-Isotropic (TRISO) particles and is in the form of a layered uranium oxy-carbide (UCO) material. The most recent design from ORNL calls for a fuel enrichment of 9 wt%, though an enrichment of 19.75 wt% was called for in the original preconceptual design. (Holcomb, et al., 2011) (Varma, et al., 2012) The core consists of these TRISO particles loaded into 252 active fuel assemblies containing 18 fuel plates each, arranges such that the assembly is hexagonal. The active height of the AHTR core is 5.5 m and utilizes graphite for both moderation and reflection of neutrons.

The primary reactor coolant salt is FLiBe, which undergoes a temperature increase of 50°C on average, across the core (including the bypass flow). The core inlet and outlet average temperatures are 650°C and 700°C, respectively. From the design parameters, one can calculate the mass flow rate of FLiBe (assuming the average specific heat of the coolant is 2,415 J/kg·K) to be approximately 28,150 kg/s. The reactor vessel is not pressurized.

Table E-1: General AHTR plant parameters.

Parameter	Value	Units
Core Thermal Power	3,400	MW
Overall Thermal Efficiency	45%	-
Fuel Type	TRISO	-
Uranium Composition	UCO	-
Number of Fuel Assemblies	252	-
Moderator and Reflector Material	Graphite	-
Active Core Height	5.5	m
Primary Coolant Salt	FLiBe	-
Core Inlet Temperature	650	°C
Core Outlet Temperature	700	°C

Further details on the core specifications will be provided in the subsequent sections of this document. Additionally, general information about the intermediate salt loop, power cycle, and decay heat removal system can be found in the ORNL preconceptual/conceptual design documents. (Holcomb, et al., 2011) (Varma, et al., 2012)

E.2. Reactor Vessel and Out-of-Core Structure

This section describes the AHTR reactor vessel and some components of the out-of-core structure. The reactor vessel is roughly cylindrical in nature and hung from its upper flange, to minimize the stress incurred by the thermal expansion. (Varma, et al., 2012) Figure E-2 depicts the basic overview of the AHTR vessel and core location.

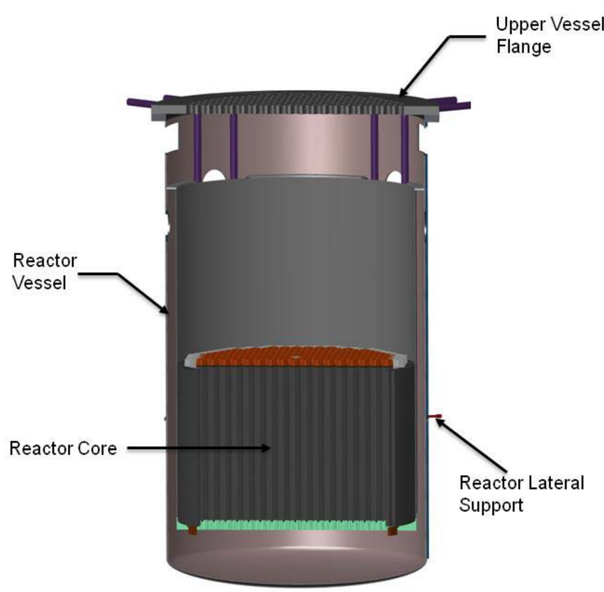

Figure E-2: AHTR reactor vessel cross section. (Varma, et al., 2012)

Table E-2 provides the global parameters of the AHTR reactor vessel, which is made from 800-H alloy and has a yield strength of 20 MPa at 700°C. There is a possibility of corrosion with the FLiBe coolant and the 800-H alloy, thus a thin (1 cm thick) liner of Alloy-N is included on surfaces contacting the FLiBe. The vessel thickness is not defined in the ORNL reference reports. However, it is assumed to be 5 cm.

Table E-2: Global parameters of the AHTR reactor vessel.

Parameter	Value	Units
Exterior Vessel Diameter	10.5	m
Vessel Height	19.1	m
Primary Salt Depth Above Upper Support Plate	7.15	m
Primary Piping Interior Diameter	1.24	m
Number of DRACS	3	-
Core Barrel Material	C-C Composite	-
Vessel and Primary Piping Material	800-H Alloy w/Alloy-N Lining	-

The full reactor vessel configuration can be observed in Figure E-3, and depicts the location of the refueling lobe. The vessel size exceeds the limits for transportation by rail, thus the vessel must be transported to the site in sections and welded into the final vessel. (Varma, et al., 2012)

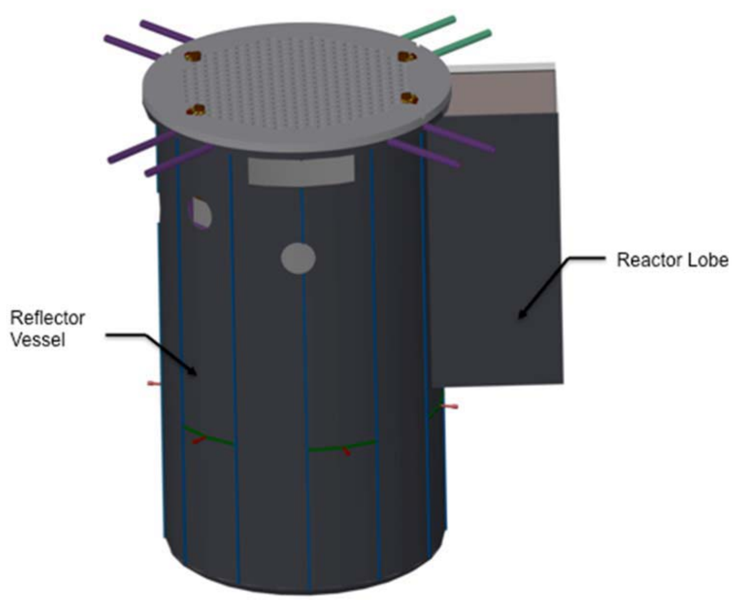

Figure E-3: AHTR reactor vessel. (Varma, et al., 2012)

E.2.1. Upper Plenum

The upper plenum is delimited by the upper support plate and the reactor vessel flange. The upper portion of the plenum is filled with Argon cover gas (not pressurized) at a temperature of 250°C. The cover gas volume has a height of 3.19 m. The lower portion of the upper plenum (Figure E-4) is filled with FLiBe coming from the core, at an average temperature of 700°C. The salt is 7.15 m deep from the upper core plate. During normal operation, guide tubes for leader rods occupy the upper plenum. These rods are retractable, in order to provide access for refueling.

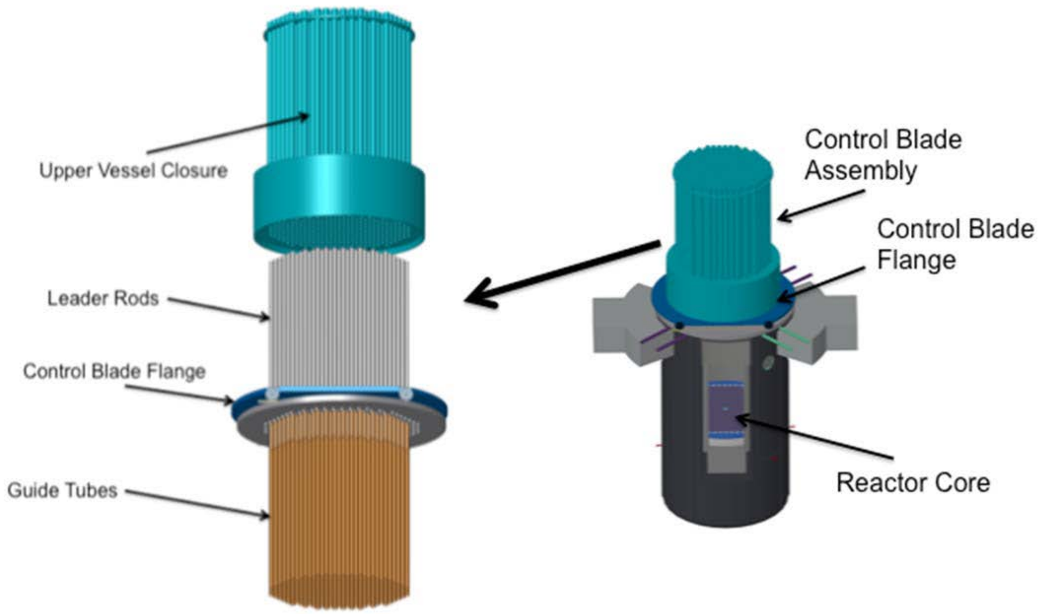

Figure E-4: AHTR upper plenum, guide tubes, and the upper vessel closure. (Varma, et al., 2012)

E.2.2. Top Flange

The top flange (Figure E-5) has a diameter of 11.6 m and a thickness of 35 cm, consisting of a truss structure fabricated by two 1.5 cm thick stainless steel top and bottom plates (to reduce weight). The volume fraction of the solid material is 13.45% of a reference cylinder that wraps the flange. The flange is maintained at a temperature of 250°C by the Argon gas in the upper portion of the upper plenum.

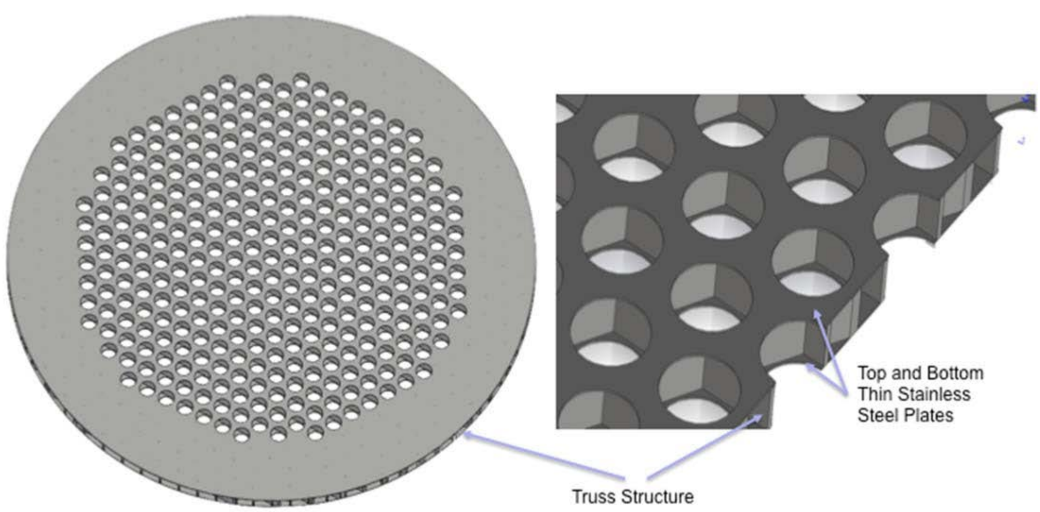

Figure E-5: AHTR top flange configuration. (Varma, et al., 2012)

E.3. Core Barrel and Downcomer

The core barrel separates the core from the downcomer/DRACS heat exchanger region and is made up of a 2 cm thick Carbon-Carbon (C-C) composite. The interior face (towards the core) of the barrel has a thin plating of boron carbide (thickness 1 cm), which attenuates neutron radiation before it impacts the reactor vessel. The internal diameter of the core barrel is 9.56 m and the outer diameter is 9.62 m. The operating temperature is 650°C (same as inlet core temperature) and flow direction is downward in the downcomer region (upward in the core). The downcomer region is subdivided azimuthally into 8 angular zones; 3 downcomer sections, 3 DRACS sections, 1 maintenance cooling system, and a 1 refueling lobe. Figure E-6 depicts the core barrel and downcomer regions of the AHTR.

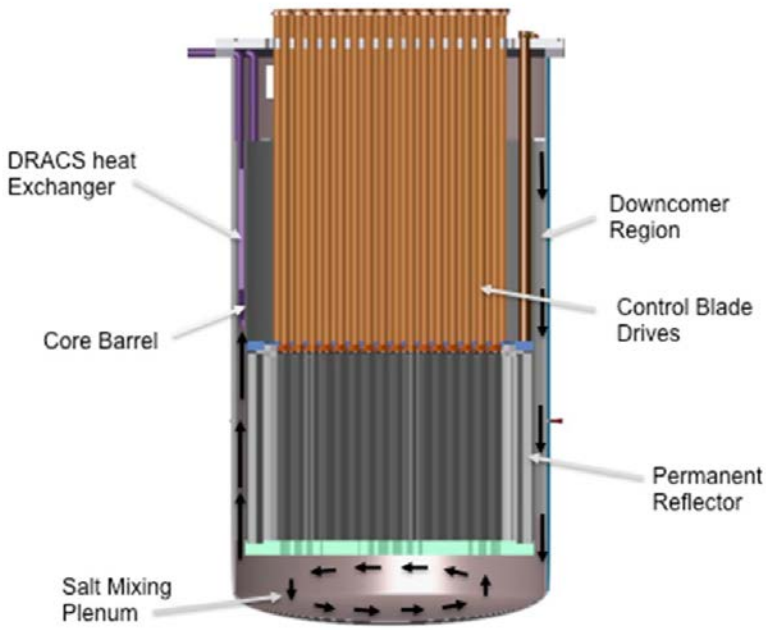

Figure E-6: Vertical cross section of the AHTR reactor vessel and core, showing the downcomer region and core barrel. (Varma, et al., 2012)

E.4. Reactor Core

The reactor core contains 252 fuel assemblies arranged hexagonally. The central assembly is not fueled, but serves as a moderator block (it has the same composition and structure as the outer removable reflector blocks). The gap between assemblies is 1.8 cm and the equivalent diameter of the reactor core is 7.81 m for the fueled part. One ring of replaceable reflector assemblies surrounds the last ring of fueled assemblies, and then a permanent reflector completes the core. The equivalent diameter of the core including the replaceable reflector is 8.69 m. The outer radius of the permanent reflector is 9.56 m. The core height is 6 m, of which 5.5 m is the active core; top and bottom nozzle/reflector regions are 25 cm each, the support plates are 35 cm thick, resulting in an overall height of 6.7 m for the core and support plates. Figure E-7 provides a view of the core reflectors, upper support plate and lower support plate. Figure E-8 depicts a horizontal cross section of the core through the fuel midplane.

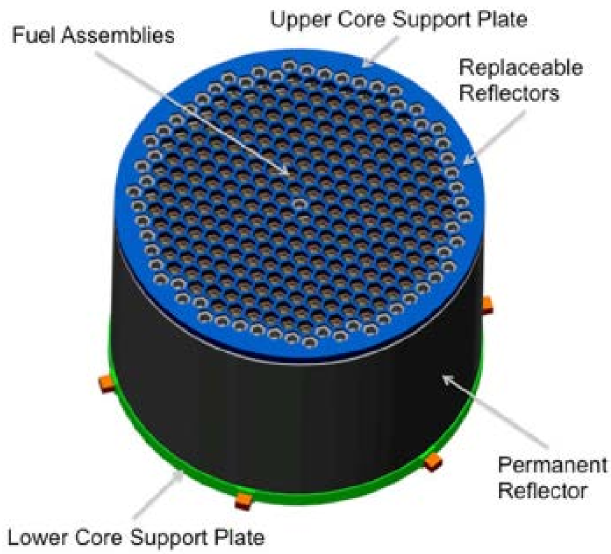

Figure E-7: Overview of the AHTR core design. (Varma, et al., 2012)

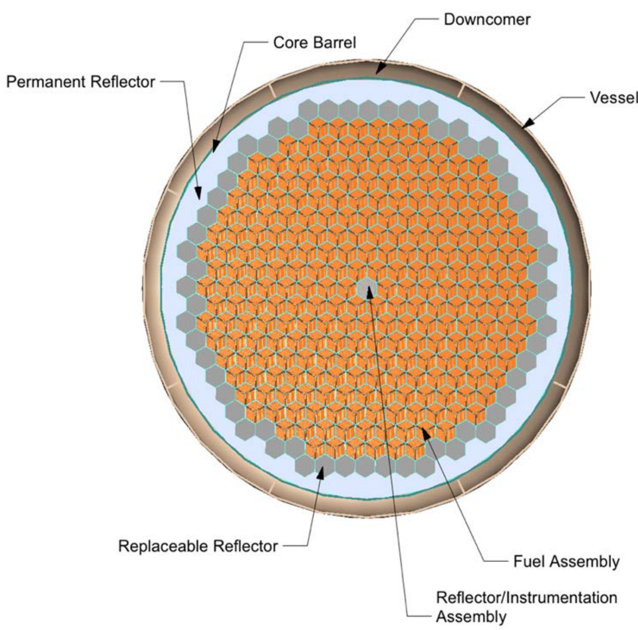

Figure E-8: AHTR core horizontal cross section through fuel midplane. (Varma, et al., 2012)

E.4.1. Replaceable Reflector

The replaceable reflector surrounds the outermost fuel assembly ring and consists of a single ring of removable reflector blocks (shown as dark gray in Figure E-8). The replaceable reflector blocks are made of graphite and have the same size and shape as the fueled assemblies. In the reference design they are not provided with control rods. However, in principle a control rod could be added to each reflector block to facilitate the control of the reactor power. No coolant channels are present in the reflector block, but they could be added if cooling is required.

E.4.2. Permanent Reflector

The permanent reflector surrounds the removable reflector ring and consists of solid graphite sections (depicted as light grey in Figure E-8). Its shape conforms to the replaceable reflector blocks on the inner side and has a cylindrical outer shape that conforms to the core barrel.

E.4.3. Lower Support Plate

The lower support plate provides support to the core and reflector. It is a honeycomb structure that is attached to the reactor vessel through lateral junctions. The lower support plate is made of SiC-SiC composite and is 35 cm thick. Channel cuts have been made in the lower plate to direct the flow of FLiBe into the fuel assemblies (Figure E-9). Additionally, indexing holes and guides provide for proper alignment of fuel assemblies during refueling operations.

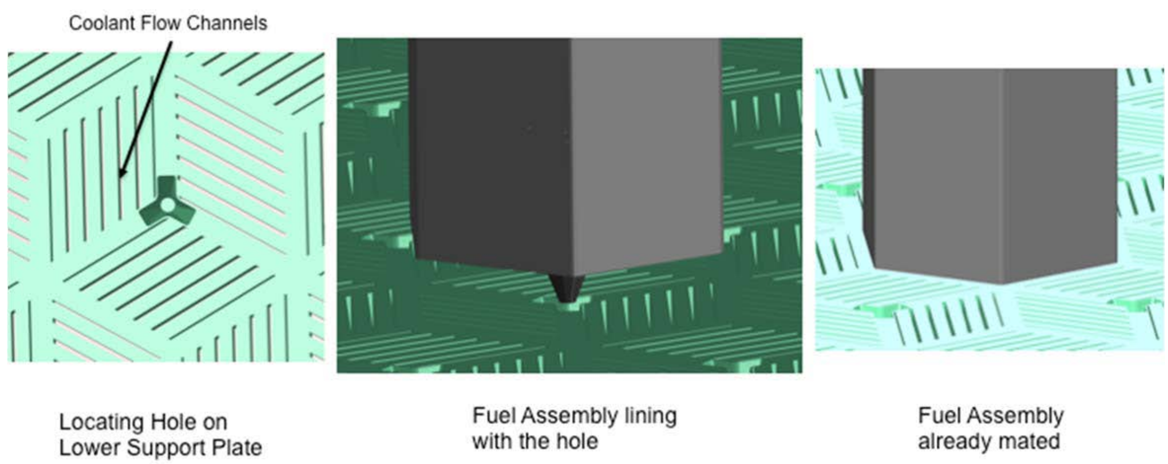

Figure E-9: Detailed representation of the AHTR lower support plate. (Varma, et al., 2012)

For neutronics modeling purposes, as simplified model of the lower support plate can be represented by a cylinder of the same dimensions made of 14.96% FLiBe and 85.04% graphite, by volume at a temperature of 650°C.

E.4.4. Upper Support Plate

The upper support plate's primary function is to hold core components in place, against the upward flowing salt. The upper support plate is 35 cm thick and made of a SiC-SiC composite (same material as the lower support plate). Four drive rods are used to raise and lower the upper support plate during refueling outages. Figure E-10 depicts the location of the upper support plate and the location of the drive rods in the salt filed portion of the upper plenum.

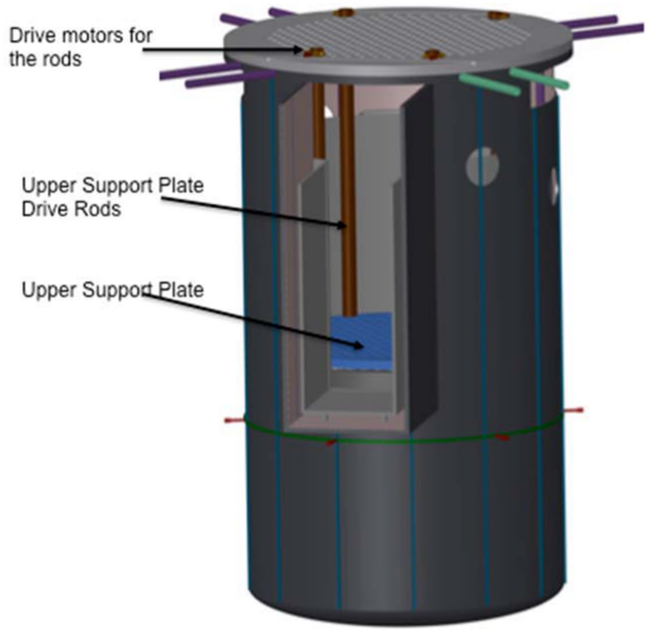

Figure E-10: View of the salt filled portion of the upper plenum and the drive rods for the upper support plate. (Varma, et al., 2012)

The upper support plate makes tangential contact with the hemispherical contacts on the grappling collar of the fuel assemblies (Figure E-11). The webbing on the upper core support plate fills the inter-assembly gap and provides a reduction in flow vibrations. For neutronics modeling purposes, as simplified model of the upper support plate can be represented by a cylinder of the same dimensions made of 78.9% FLiBe and 21.1% graphite, by volume at a temperature of 700°C.

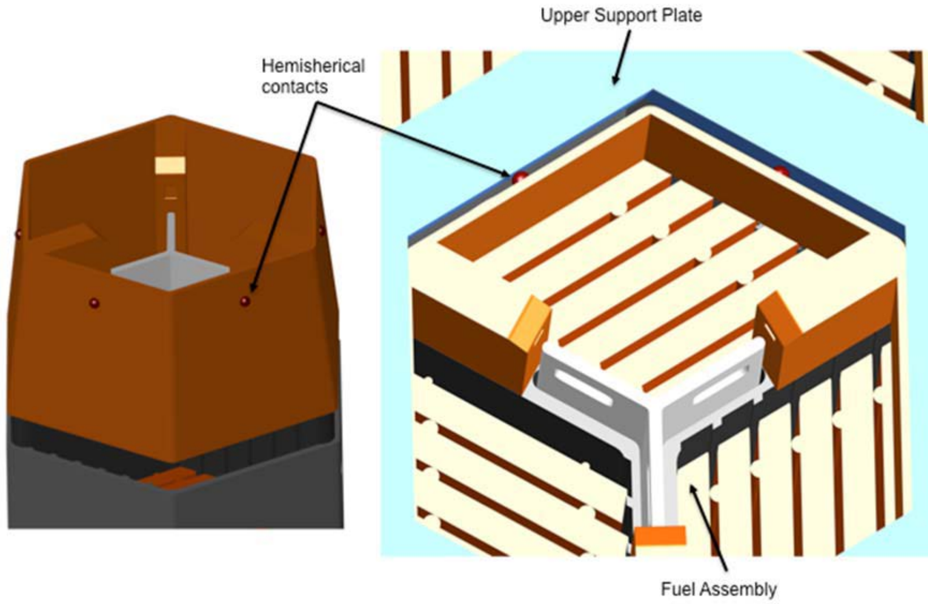

Figure E-11: Contact between the AHTR fuel assembly grappling collar and the upper support plate. (Varma, et al., 2012)

E.4.5. Consolidated AHTR Core and Vessel Dimensions

This section provides a consolidated placement of the overall dimensions of the major components in the AHTR vessel and core. Some parameters have been assumed, since they are not fully specified in the ORNL preconceptual AHTR design description. Table E-3 provides the outer diameters (OD) of the various vessel components. The following assumptions were made in preparation of these dimensions:

- The height of the lower plenum is assumed to be 2 m; this results in a cover gas volume height of 3.19 m. Increasing the lower plenum height results in a decreased cover gas volume height in the upper plenum.
- The reactor vessel thickness is 5 cm, plus a 1 cm Alloy-N liner.
- The height of the downcomer (with respect to the lower face of the lower support plate, corresponding to the top of the lower plenum) is assumed to be 13 m.

Table E-3: AHTR vessel and core component outer diameters (OD). (Varma, et al., 2012)

Parameter	Value	Units
Core OD	7.81	m
Replaceable Reflector OD	8.69	m
Permanent Reflector OD	9.56	m
Boron Layer OD	9.58	m
Barrel OD	9.62	m
Downcomer OD	10.38	m
Alloy-N Liner OD	10.40	m
Vessel OD	10.50	m

Figure E-12 presents the major vessel and core dimensions, while Figure E-13 and Figure E-14 provide an enhanced view of the top of the downcomer and top of the core, respectively.

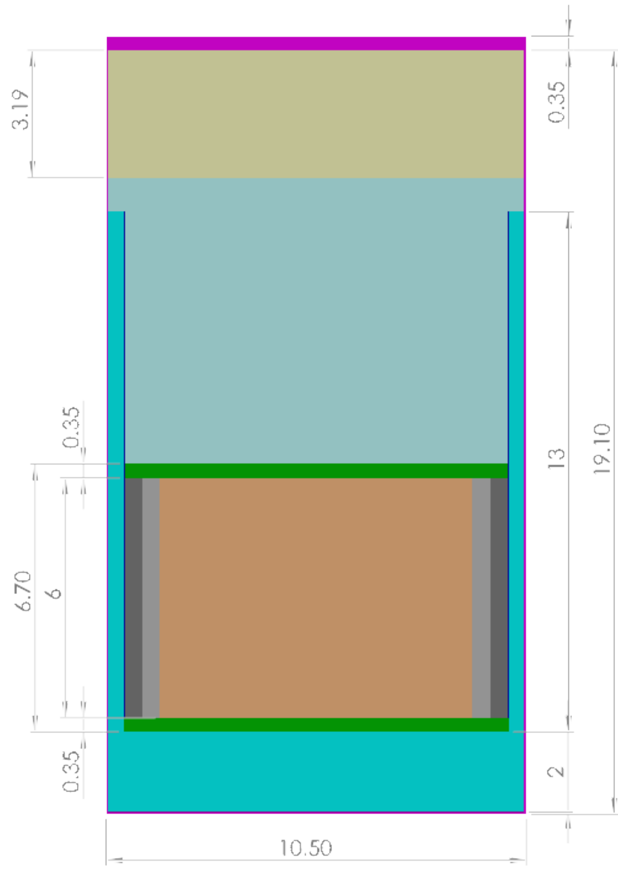

Figure E-12: AHTR vessel and core major dimensions in meters.

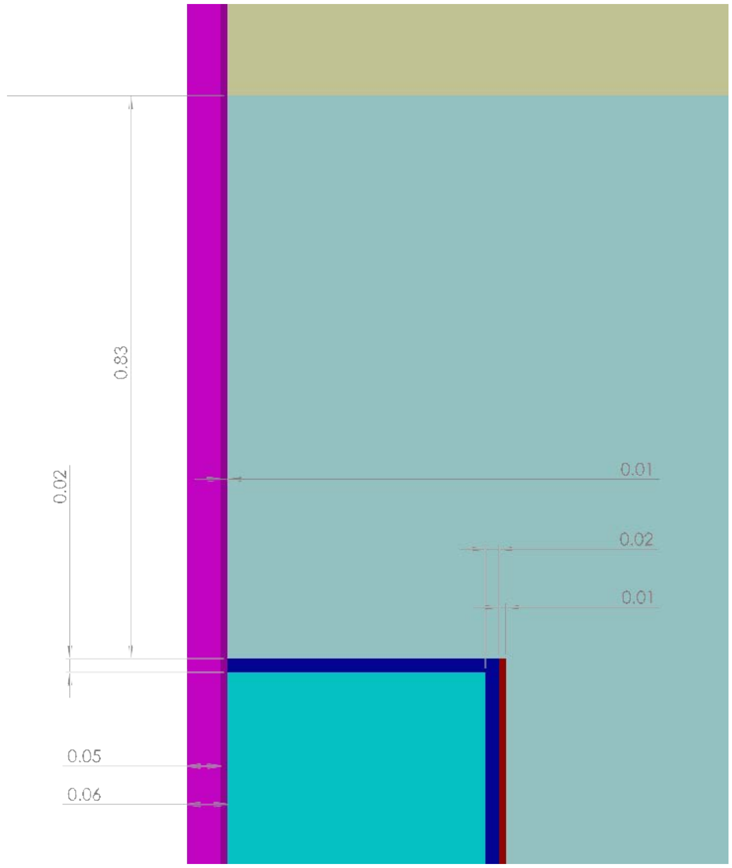

Figure E-13: Enhanced view of dimensions at the top of the AHTR downcomer

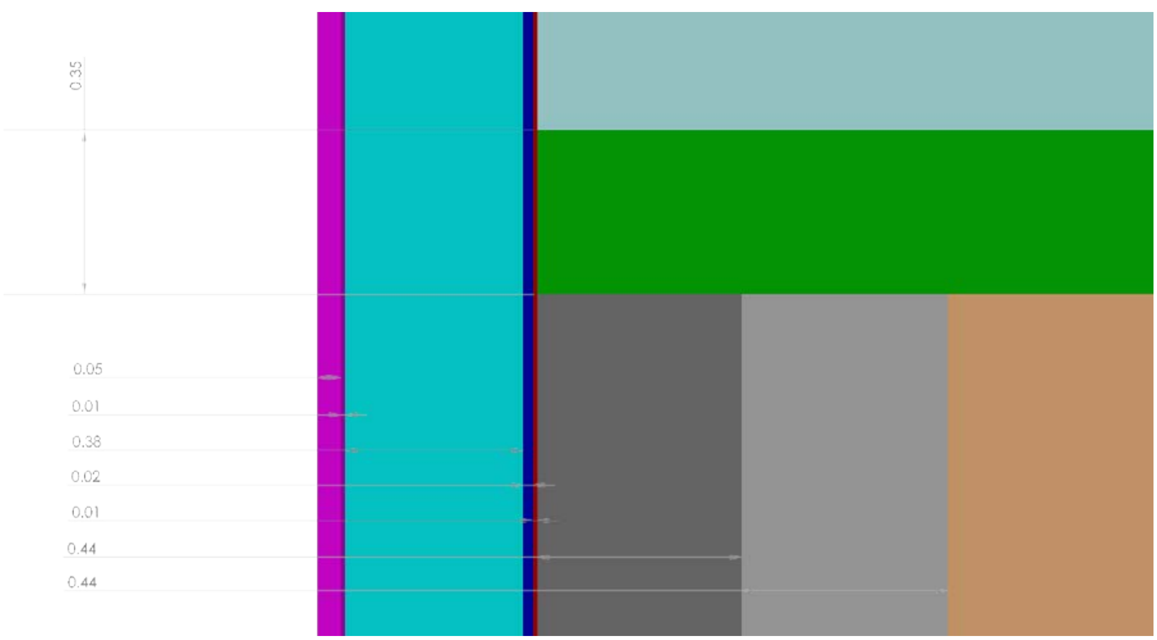

Figure E-14: Enhanced view of dimensions at the top of the AHTR core.

E.5. Fuel Assembly

Fuel assemblies are made up of 18 fuel plates, grouped in 3 clusters of 6 plates each. Each plate is 2.55 cm thick. The entire fuel assembly is fabricated with high temperature materials. The plates in the assembly are 6 m long, the active (fueled) part is 5.5 m (of the total 6 m), and the remaining part (25 cm on top and bottom) are made of reflector material. These plates are enclosed in a hexagonal C-C fuel channel box (density 1.95 g/cm^3), which is 1 cm thick. The outer apothem of the box is 22.5 cm, corresponding to 45 cm distance between two parallel outer faces of the box wall. The three symmetric regions (groups of plates) are separated by a Y shaped support structure that is 4 cm thick and made of C-C composite (density 1.95 g/cm^3). The coolant channels are 0.7 cm thick, except for the first and last channel of every region, which are half of the full thickness (0.35 cm). Figure E-15 shows the reference dimensions of the horizontal cross section of the assembly, while Figure E-16 shows some dimensions that can be derived from the reference dimensions. A three dimensional view of the fuel assembly structure is given in Figure E-17.

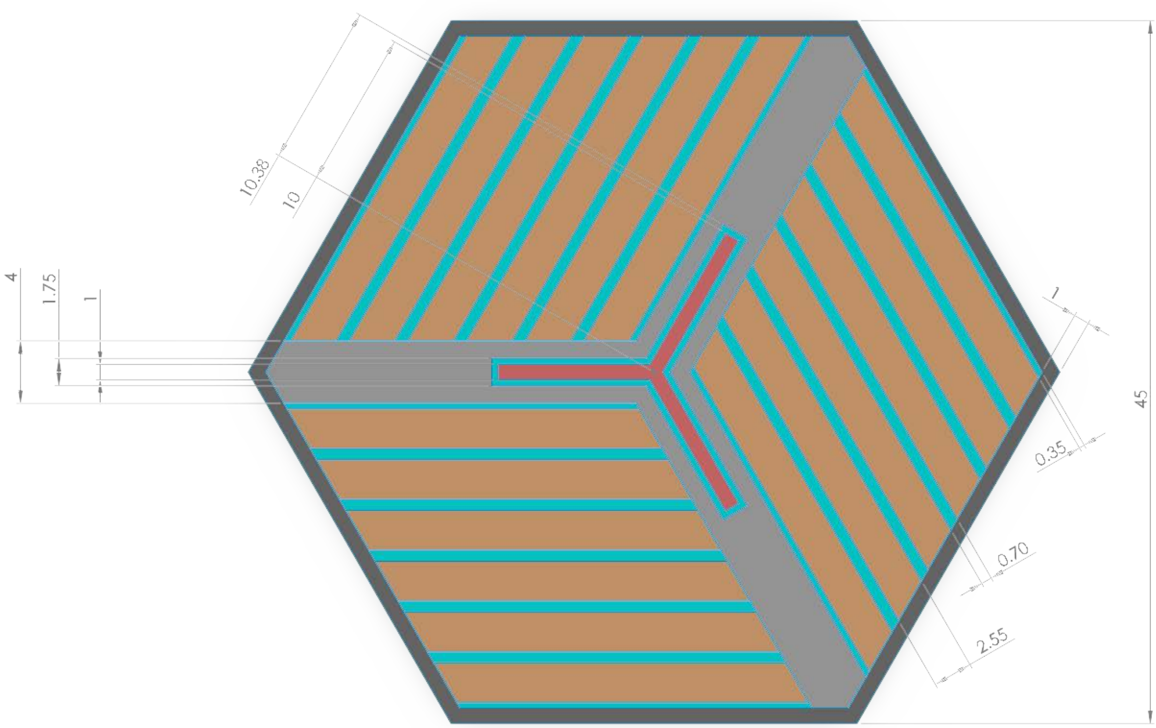

Figure E-15: AHTR fuel assembly reference dimensions. (Varma, et al., 2012)

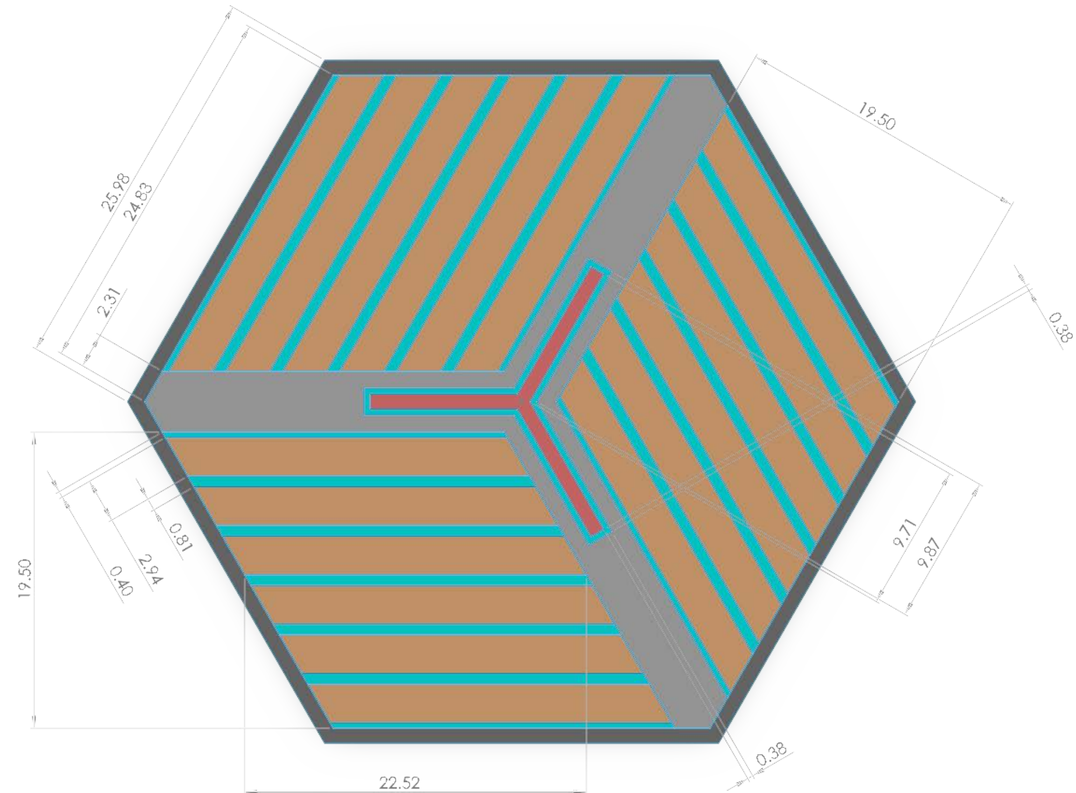

Figure E-16: AHTR fuel assembly derived dimensions. (Varma, et al., 2012)

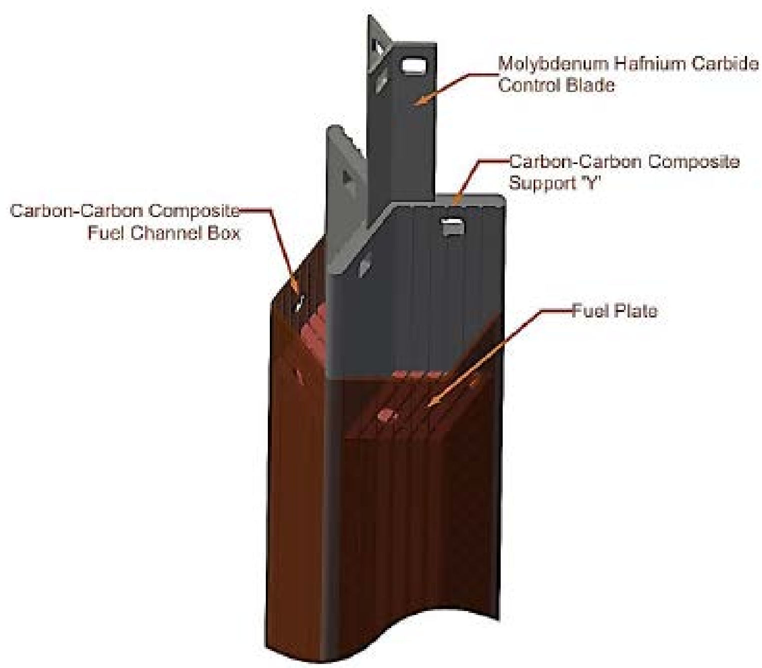

Figure E-17: AHTR fuel assembly, 3-D view. (Varma, et al., 2012)

The gap between nearby assemblies is 1.8 cm, in order to accommodate for any mechanical distortion. The triangular fuel assembly pitch is then 46.8 cm. Figure E-18 shows the horizontal cross section of 7 nearby assemblies.

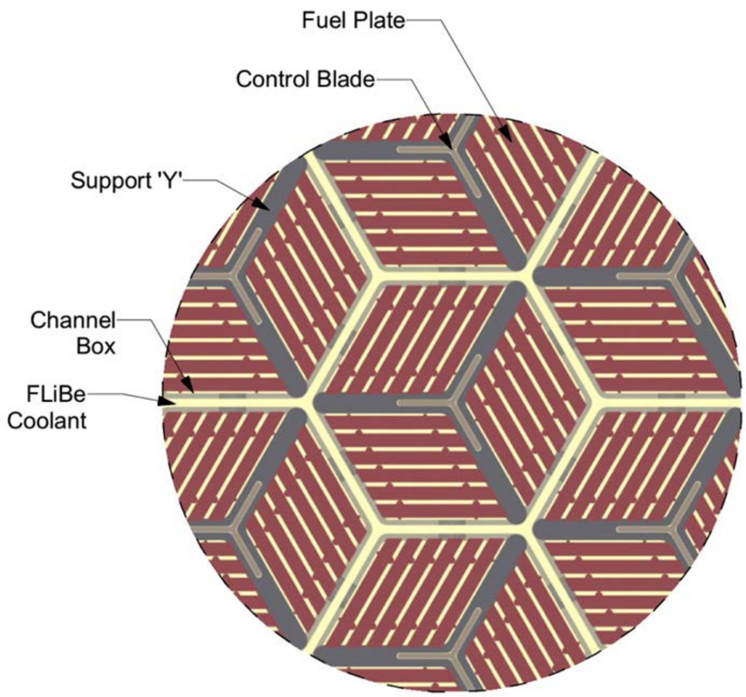

Figure E-18: Horizontal positioning of the assemblies in the core. (Varma, et al., 2012)

E.5.1. Control Blade

Each fuel assembly has its own control blade, with relatively low worth per blade. The Y-shaped control rod is made of molybdenum hafnium carbide (MHC) and is inserted into a central Y-shaped support. The MHC is a commercial, microstructurally-strengthened molybdenum-based allow with 1.2 wt% hafnium and 0.1 wt% carbon, with a density of 10.28 g/cm^3. The leader rod attaches at the top of the control blade, using the grappling holes, and serves to move the control blade up and down. The Y-shaped control blade slot dimensions are 10.38 cm long for each wing (with respect to the center of the assembly) and 1.75 cm thick. This allows for the Y-shaped control blade to be inserted, which has dimensions of 10 cm long for each wing (with respect to the center of the assembly) and 1 cm thick. Figure E-19 shows the AHTR control blade geometry.

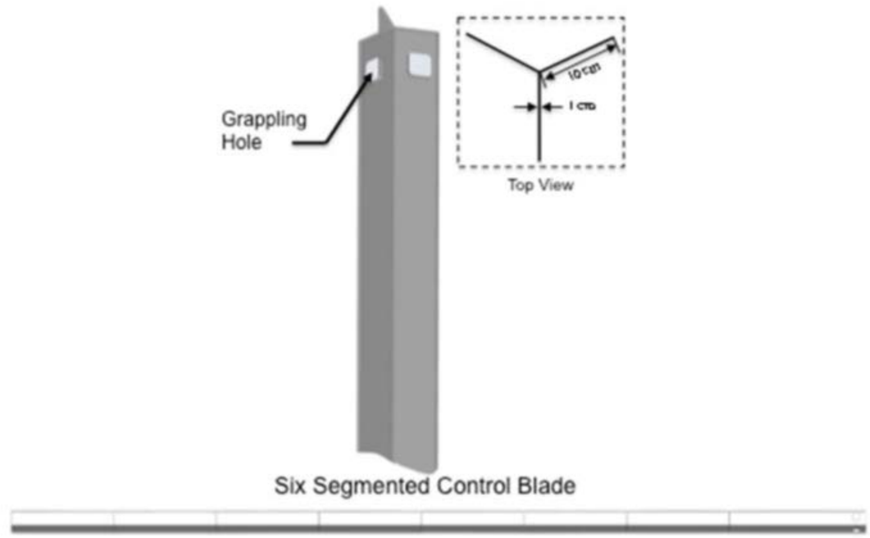

Figure E-19: AHTR control blade geometry. (Varma, et al., 2012)

E.5.2. Grappling Collar and Drive Mechanism

The grappling collar (Figure E-20) interfaces with upper plate and provides grappling interface for fuel handling.

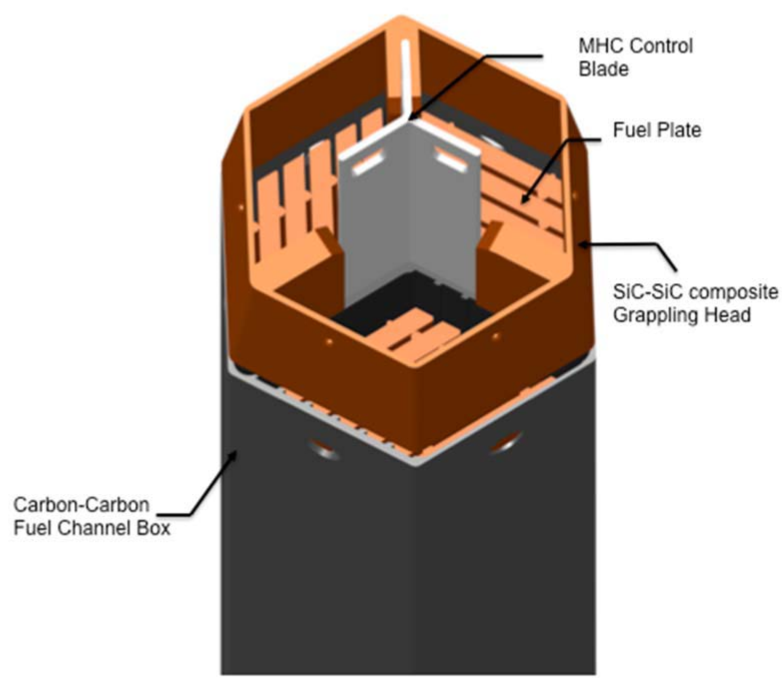

Figure E-20: AHTR grappling collar in detail. (Varma, et al., 2012)

Each control blade has a leader rod that extends from the top of the control rod to the vessel flange. Each leader rod is encased in a control blade guide tube (Figure E-21). Leader rod and guide tube are made of SiC-SiC composite.

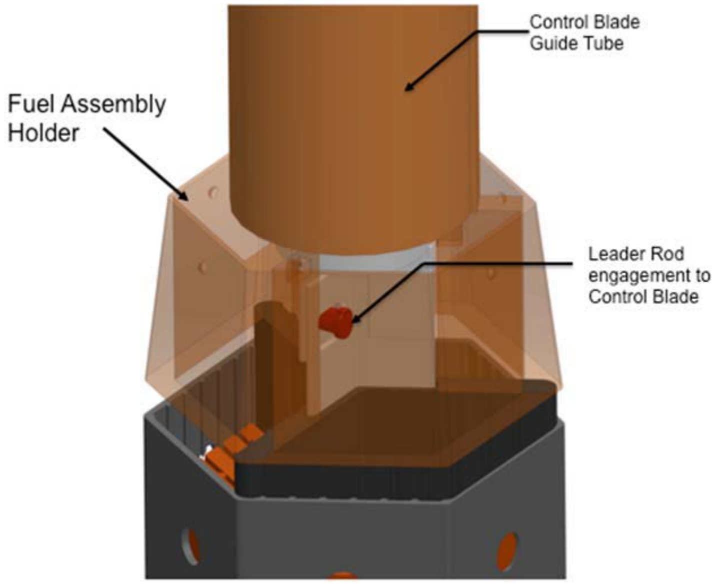

Figure E-21: Guide tube and grappling collar in detail. (Varma, et al., 2012)

E.6. Fuel Plate

The AHTR fuel plank is shaped as a parallelepiped with two fuel stripes sandwiching a central carbon slab. There is a thin 1mm pyrocarbon sleeve around the fuel stripes to prevent erosion of TRISO particles. The TRISO fuel particles are randomly dispersed within the fuel strip with a 40% packing fraction in the 2011 model. (Holcomb, et al., 2011) This can be modeled with a TRISO spherical square lattice with a pitch of 0.09265 cm. The newer 2012 reference design has a carbon to heavy metal ratio that is twice as high at 400 compared to the 2011 design. (Varma, et al., 2012) It also has 9 wt% enrichment down from 19.75 wt% enrichment in the preliminary preconceptual design. The enrichment was lowered to reduce the fuel cycle cost and initial capital investment. The fuel stripe could be made smaller or the packing fraction can be reduced to produce a higher CHM ratio. It is recommended that the fuel stripe thickness be set to contain six fuel layers and a 20% packing fraction. This gives a square pitch of 0.116736 cm. High density graphite matrix is inside the fuel stripe in between the TRISO particles. The density of the carbon matrix is 1.75 g/cm^3. Burnable poison particles included near the center of the plate. There are two semi-cylindrical spacers on each of the fuel planks. Figure E-22 gives a general idea of the configuration of the plate; Figure E-23 and Figure E-24 present the dimensions of the plate.

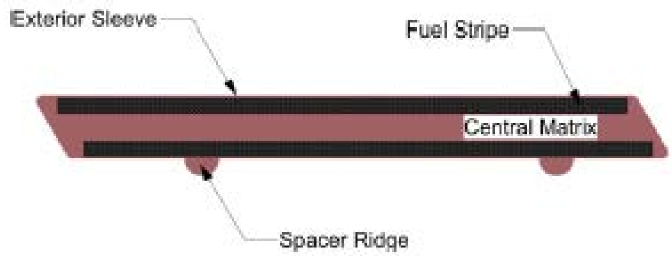

Figure E-22: Geometrical configuration of the AHTR fuel plate. (Varma, et al., 2012)

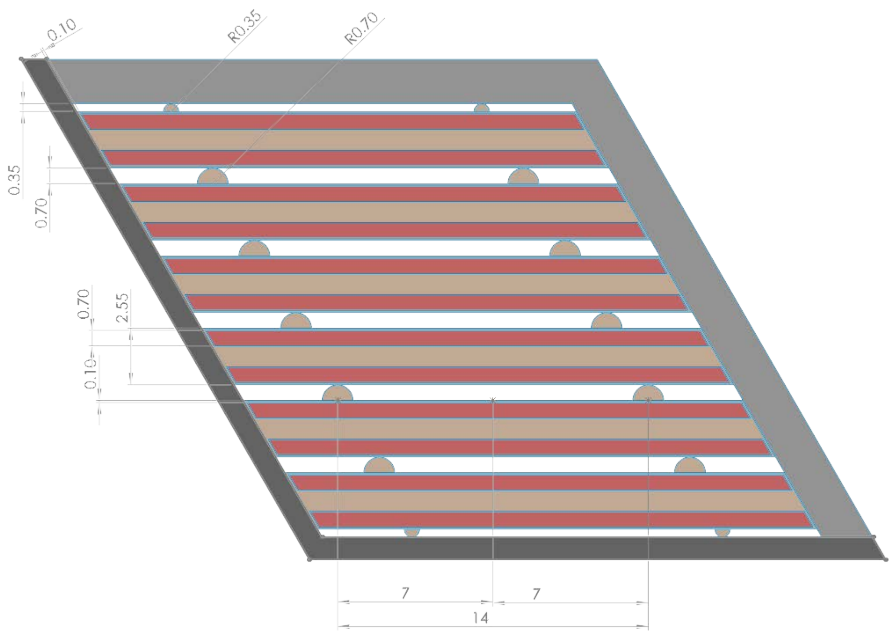

Figure E-23: Dimensions of the AHTR fuel plate. (Varma, et al., 2012)

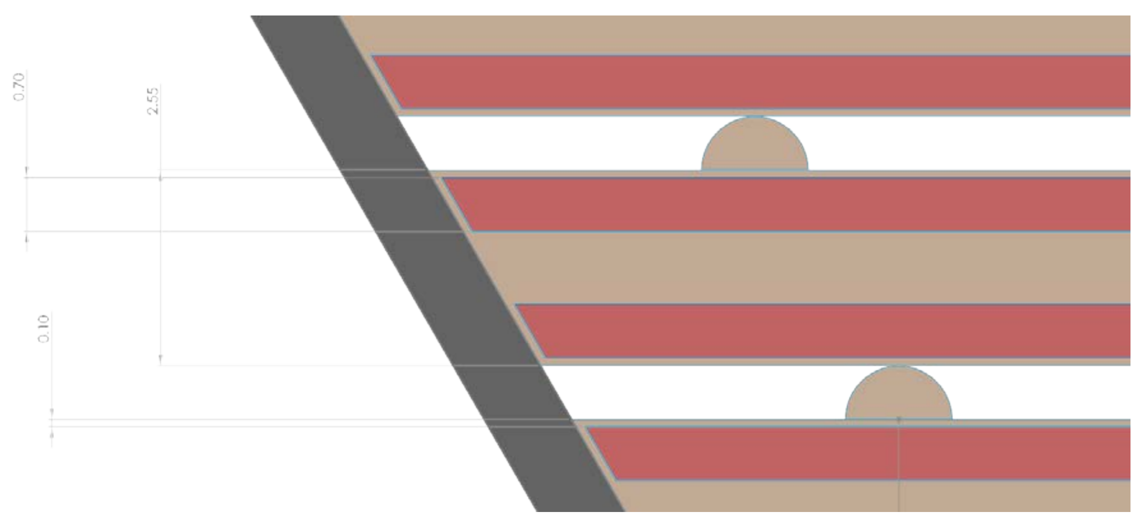

Figure E-24: Dimensions of the AHTR fuel plate in detail. (Varma, et al., 2012)

E.6.1. TRISO Particle

The TRISO fuel particle consists of four layers, an outer pyrocarbon layer, silicon carbide layer, an inner pyrocarbon layer, and a less dense carbon buffer layer. Inside of these layers is a uranium oxycarbide fuel kernel, Figure E-25 shows the geometry with the outer layers cut out of the TRISO fuel particle. This fuel is the same as the Advanced Gas Reactor (AGR) fuel developed under DOE-NE sponsorship. The reference irradiation experiment for the fuel type used for the AHTR is AGR-5/6. Fuel enrichment is 9 wt%. Table E-4 shows the respective dimensions of the TRISO fuel particle.

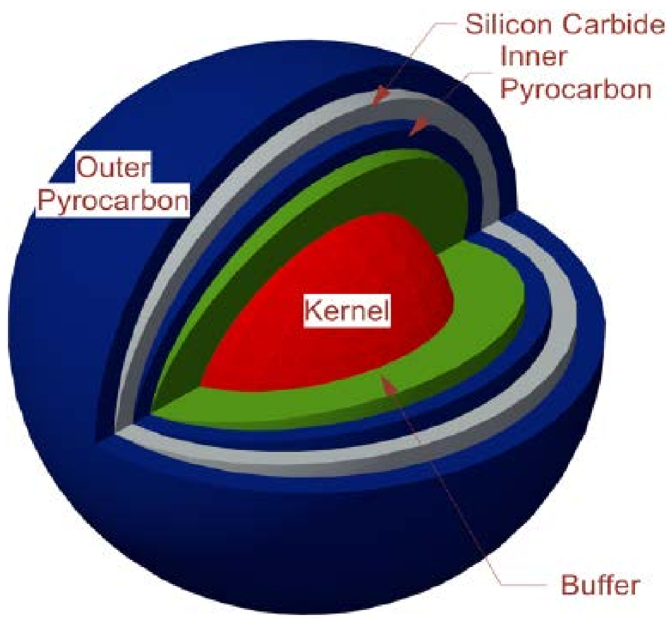

Figure E-25: TRISO particle geometry configuration. (Varma, et al., 2012)

Table E-4: TRISO particle parameters.

Region	Parameter	value µm	Material	ρ (g/cm³)
Kernel	diameter	427	UCO	10.9
Buffer	thickness	100	Porous graphite	1
IPyC	thickness	35	Pyrolitic graphite	1.9
SiC	thickness	35	SiC	3.2
OPyC	thickness	40	Pyrolitic graphite	1.87
Fuel Particle	diameter	847	----	----

E.6.2. Burnable Poison

The burnable poison is located in Pyrocarbon overcoated sintered grains of Eu_2O_3 powder; these grains are placed at the center of the plate (Figure E-26).

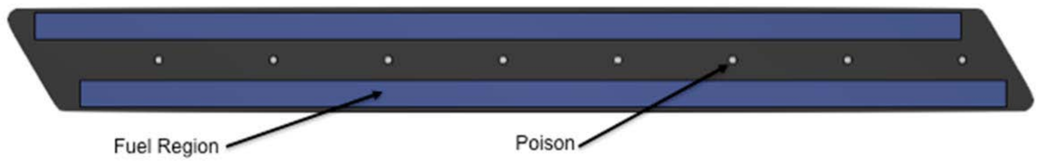

Figure E-26: Burnable poison grains in the AHTR fuel plate. (Varma, et al., 2012)

Eu_2O_3 has high thermal stability. The melting point is 2,350°C and the density of Eu_2O_3 is 5.0 g/cm^3 (68% of theoretical density). The size and number of Eu_2O_3 grains can be optimized (although, studies available are not very accurate). The final reference design would be 5 grains with radius of 350 micron, In order to provide the required 6 months cycle. (Varma, et al., 2012) For this configuration, the excess reactivity of the core is maintained below 5% for the entire equilibrium cycle.

E.7. Primary Coolant

FLiBe (2LiF-BeF$_2$) is used as coolant for the primary system and flows over the AHTR core. The Beryllium provides some moderation, while the lithium is ideally isotopically pure ^{7}Li to minimize tritium production. 99.995 wt% ^{7}Li enrichment is generally considered the reference enrichment that can be practically achieved. The salt is transparent and has a density of 1,950 kg/m^3 at 700°C (it is temperature dependent) and a melting point of 459°C. Thus the salt is in the liquid phase in the primary loop while the reactor is operating, since the core inlet temperature is considered to be 650°C.