Representative Neutronics Models of MCFR Reactors

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REPORT

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Approval

Title	Name	Signature	Date
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TERMINOLOGY

Term	Acronym / Abbreviation	Definition
Cover Gas System	CGS	-
Fuel Handling System	FHS	-
Integrated Effects Test	IET	Non-nuclear chloride salt thermal hydraulics experiment platform to learn how the MCFR technology will scale and behave at larger, commercially relevant sizes.
Reactivity Control System	KCS	-
Molten Chloride Fast Reactor	MCFR	MCFR reactors are molten salt reactors that use high temperature liquid chloride fuel salt as their fissile material.
MCFR Commercial Reactor	MCFR-C	The MCFR-C is a grid-scale, breed-and-burn, chloride fuel salt, MCFR electricity plant.
MCFR Demonstration Reactor	MCFR-D	The MCFR-D the first commercial MCFR electricity power plant product along TerraPower's MCFR technology development roadmap.
Molten Chloride Reactor Experiment	MCRE	The MCRE will be the first nuclear facility along TerraPower's MCFR technology development roadmap
Primary Heat Exchanger	PHX	-

1 PURPOSE

The purpose of this document is to describe the Molten Chloride Fast Reactor Demonstration Reactor (MCFR-D) and Molten Chloride Fast Reactor Commercial Reactor (MCFR-C) design concepts to support the development of neutronics modeling external to TerraPower. These simplified MCFR reactor models present key dimensions and isotopics of these reactors. The designs of the MCFR-D and MCFR-C are still in the pre-conceptual phase and are subject to change.

It is the author's intent to supply enough information to build representative models; however, it is acknowledged that assumptions will likely be needed in order to fill in missing information.

2 SCOPE

The scope of this report is limited to the cores of the MCFR-D and MCFR-C designs. Neutronics models built on these simplified descriptions are useful to design criticality validation benchmarks, assess nuclear data needs, and perform fuel cycle analysis. For details about the Molten Chloride Reactor Experiment (MCRE), contact Dan Walter at dwalter@terrapower.com for access to MCRE-ENG-PRSNT-0029 [1].

References to internal TerraPower documents are included within this report; however, those referenced documents are not available externally.

3 INTRODUCTION

Although MCFR technology builds upon the success of the Molten Salt Reactor program pioneered at Oak Ridge National Laboratory (ORNL), MCFR technology has several key differences from the classical fluoride salt based, thermal spectrum system architecture. As a result, MCFR technology requires significant research and development to progress from the conceptualization to a commercial nuclear power plant. Figure 3-1 shows many elements of the MCFR Technology Development Roadmap [2]. This roadmap includes up to three nuclear reactors: MCRE, MCFR-D and MCFR-C.

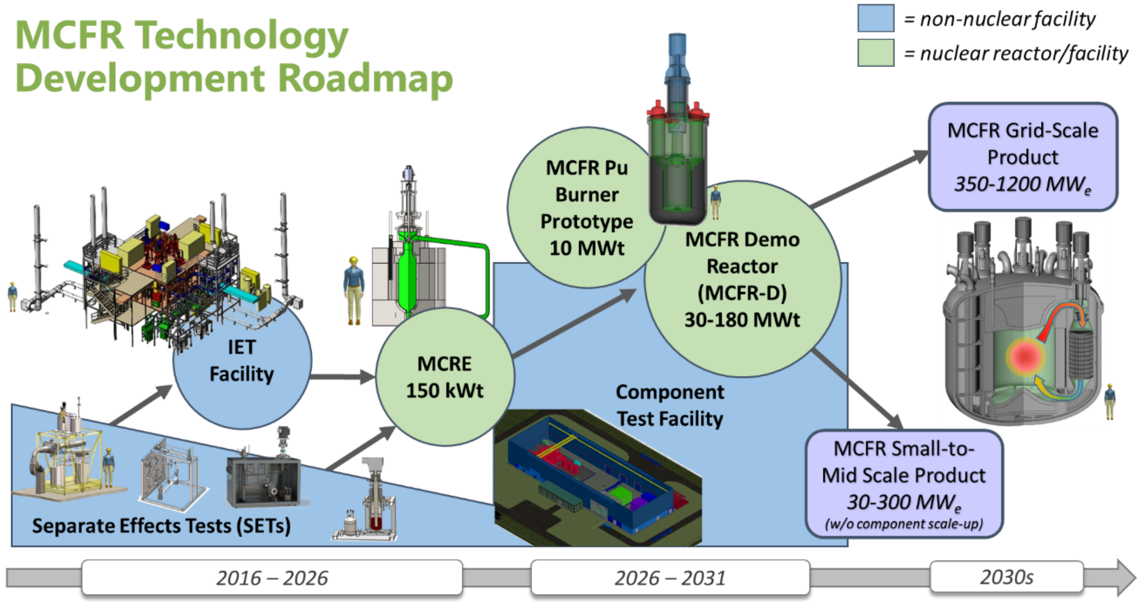

Figure 3-1.MCFR Technology Development Roadmap [2]

3.1 MCFR Reactor Descriptions

3.1.1 MCRE

In October 2021, Southern Company Services, Inc. (SCS) was contracted with the Department of Energy (DOE) for Risk Reduction of TerraPower's Molten Chloride Fast Reactor project under the Advanced Reactor Demonstration Program (ARDP). SCS leads the project along with: TerraPower, Idaho National Laboratory (INL), Orano Federal Services, Core Power, 3M Company, and the Electric Power Research Institute.

With the long-term objective to commercialize the MCFR technology, the ARDP Risk Reduction award is primarily focused on design and operation of MCRE. MCRE will be the first nuclear facility along TerraPower's MCFR technology development roadmap. MCRE builds on the legacy of the Aircraft Reactor Experiment (ARE) and the Molten Salt Reactor Experiment (MSRE) [3] [4] (both of which were thermal spectrum fluoride salt reactors), as the world's first fast spectrum molten (chloride) salt reactor.

MCRE will be sited at INL in the Laboratory for Operation and Testing in the U.S. (LOTUS) Test Bed. The LOTUS Test Bed is intended to be built in the historical Zero-Power Physics Reactor (ZPPR) cell; however, a formal Analysis of Alternatives (AoA) must be completed before the location is finalized.

At the time of issuing this document, the MCRE plant design is in the middle of the Preliminary Design (60%) phase. Figure 3-2 presents the design of the MCRE [1].

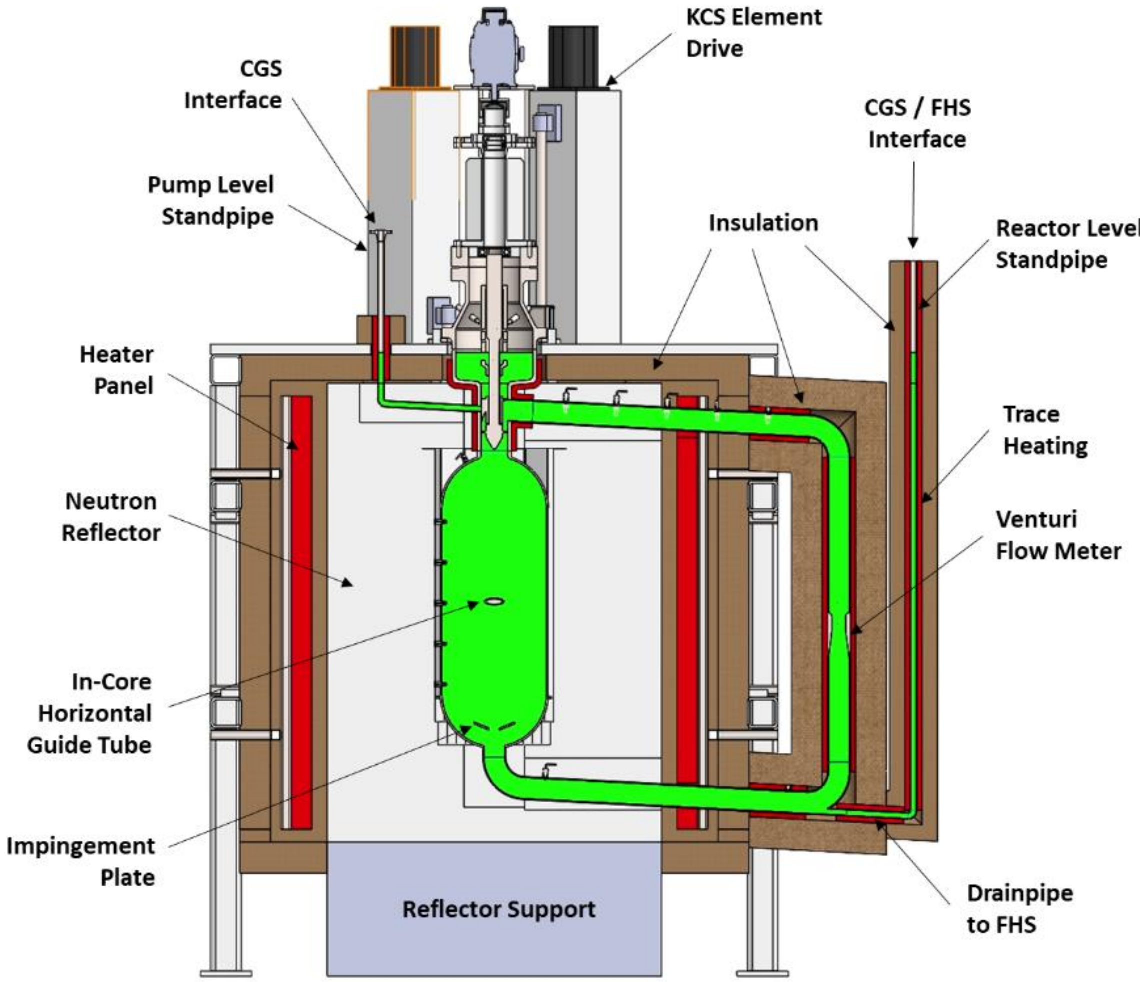

Figure 3-2: MCRE at preliminary design iteration 1

3.1.2 MCFR-D

The MCFR-D product is a 180 MWth molten salt reactor (MSR) design. It was designed as the minimum product (i.e., the reactor design of the lowest power level) with an active, relevant commercial mark. In addition to producing electricity, MCFR-D will demonstrate and qualify components relevant to a broad range of MCFR offerings.

The critical “active core” region of the MCFR-D reactor is comprised of the lower portion of the fuel salt circuit made up of an open central, cylindrical chamber surrounded by an annular downcomer. This active core is surrounded both radially and below by a neutron reflector as well as a reflector plug at the top of the core. The chloride fuel salt used in the MCFR-D is incredibly flexible in terms of how much fissile material can be loaded into the fuel salt, what fissile material can be burned, and the maximum fission product concentration that can be tolerated in the solution. The reference fuel for this concept is High Assay Low Enriched Uranium (HALEU). Figure 3-3 presents a pre-conceptual rendering of the MCFR-D reactor vessel and reactor core system.

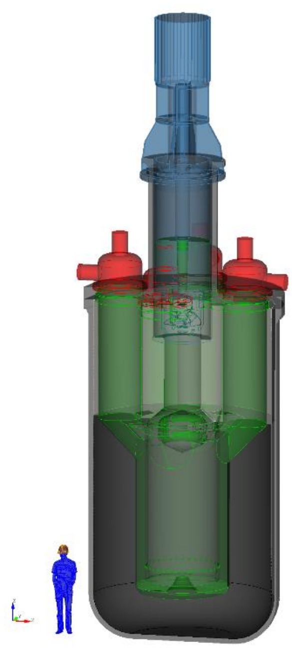

Figure 3-3: MCFR-D at pre-conceptual design

3.1.3 MCFR-C

The MCFR-C is a high-temperature breed-and-burn MSR electricity plant. Traditional MSRs use fertile thorium fuel to breed U-233 in a thermal spectrum, and subsequently utilize chemical reprocessing to remove fission products and mitigate parasitic absorption in Pa-233 (the precursor to U-233). The MCFR-C obviates reprocessing by operating in the fast spectrum with the U-238/Pu-239 fuel cycle. This fuel cycle relies on the U-239 ($T_{\frac{1}{2}} = 23.45$ minutes) created from U-238 fast neutron capture to β^- decay to Np-239 ($T_{\frac{1}{2}} = 2.356$ days), which itself will also β^- decay, this time to fissile Pu-239. As compared to the (approximately) 28 days required for a neutron capture in Th-232 to become U-233 in the thermal spectrum, the fast breeding of Pu-239 from U-238 takes less than three days. Additionally, nearly all fission product poison neutron capture cross sections become negligible in the fast spectrum, so their continued residence within the fuel salt does not impact reactivity. These differences simplify the plant design of the MCFR-C and increase the weapons proliferation resistance of the MCFR-C.

The MCFR-C leverages inherent safety to simplify the design. The inherent reactivity feedback mechanisms limit the requirements for the reactivity control and protection systems. Natural circulation decay heat removal obviates the need for safety grade backup generators and reduces requirements on the containment systems. The MCFR-C utilizes pool-type topology to obviate loss of coolant accidents.

The baseline Reactor Core System (RCS) in the MCFR-C is comprised of the fuel salt within the reactor vessel, the Neutron Reflector System (NRS), eight primary heat exchangers (PHX), eight fuel salt pumps, the fuel salt expansion system, the reactivity control system, and nuclear instrumentation. Figure 3-4 presents a conceptual rendering of MCFR-C reactor core system.

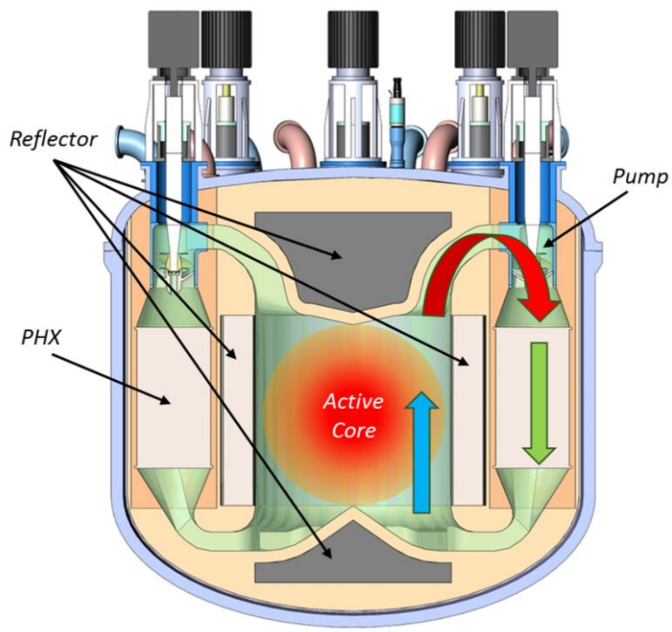

Figure 3-4: MCFR-C at pre-conceptual design [5]

3.2 Chlorine Nuclear Data

The uncertainty around chlorine nuclear data is a key uncertainty for MCFR analysis [6]. TerraPower and Los Alamos National Laboratory have been awarded a Gateway for Advanced Innovation in Nuclear (GAIN) voucher to measure the Cl-35 (n,p) cross section at the Los Alamos Neutron Science Center (LANSCE) and integrate that new measurement with other recent measurements to generate a new nuclear data evaluations for Cl-35 and Cl-37 [7]. Utilizing these updated nuclear data evaluations should eliminate any Cl-35 bias and significantly reduce the nuclear data uncertainty due to chlorine.

4 FUEL SALT

MCFR-D and MCFR-C use NaCl-UCl_3 binary eutectic as its fuel salt. Table 4-1 summarizes the fuel salt composition [8]. Table 4-2 summarizes the thermophysical properties [9].

Table 4-1: Fuel salt composition [8]

Parameter	Value	Unit
UCl_3	33.3	mol%
NaCl	66.7	mol%

Table 4-2: Fuel salt liquid thermophysical properties [9]

<table>
<tr><th>Property</th><th>Correlation</th><th>T(K) Range</th></tr>
<tr><td>Melting temperature</td><td>523°C</td><td>n/a</td></tr>
<tr><td>Density</td><td>$$\rho\left(\frac{kg}{m^3}\right) = A - B \cdot T(K)$$
<table><tr><th>Function</th><th>A</th><th>B</th></tr><tr><td>Mean</td><td>4.2126E+03</td><td>1.0686E+00</td></tr></table></td><td>$[800, 1100]$</td></tr>
<tr><td>Specific heat capacity</td><td>$$c_p\left(\frac{J}{kg \cdot K}\right) = A + B \cdot T(K) + C \cdot T(K)^2 + \frac{D}{T(K)^2}$$
<table><tr><th>Function</th><th>A</th><th>B</th><th>C</th><th>D</th></tr><tr><td>Mean</td><td>8.900439E+03</td><td>-1.377936E+01</td><td>6.400369E-03</td><td>-8.443758E+08</td></tr></table></td><td>$[800, 1000]$</td></tr>
<tr><td>Thermal conductivity</td><td>$$k\left(\frac{W}{m \cdot K}\right) = A + B \cdot T(K) + C \cdot T(K)^2 + \frac{D}{T(K)^2}$$
<table><tr><th>Function</th><th>A</th><th>B</th><th>C</th><th>D</th></tr><tr><td>Mean</td><td>5.6820E+00</td><td>-8.7832E-03</td><td>4.0967E-06</td><td>-5.7642E+05</td></tr></table></td><td>$[800, 1000]$</td></tr>
<tr><td>Dynamic viscosity</td><td>$$\mu(Pa \cdot s) = A \cdot \exp\left(\frac{E_a}{R \cdot T(K)}\right)$$
<table><tr><th></th><th>A</th><th>E_a</th><th>R</th></tr><tr><td>Mean</td><td>1.505E-04</td><td>2.666E+04</td><td>8.314E+00</td></tr></table></td><td>$[800, 1100]$</td></tr>
</table>

5 CORE DESIGN

5.1 MCFR-D

The neutronics of the MCFR-D core can be well represented by a right cylindrical active core which is enveloped by a thin reflector clad which in turn is surrounded by a thick neutron reflector as shown in Figure 5-1. Table 5-1 presents design parameters for the MCFR-D model.

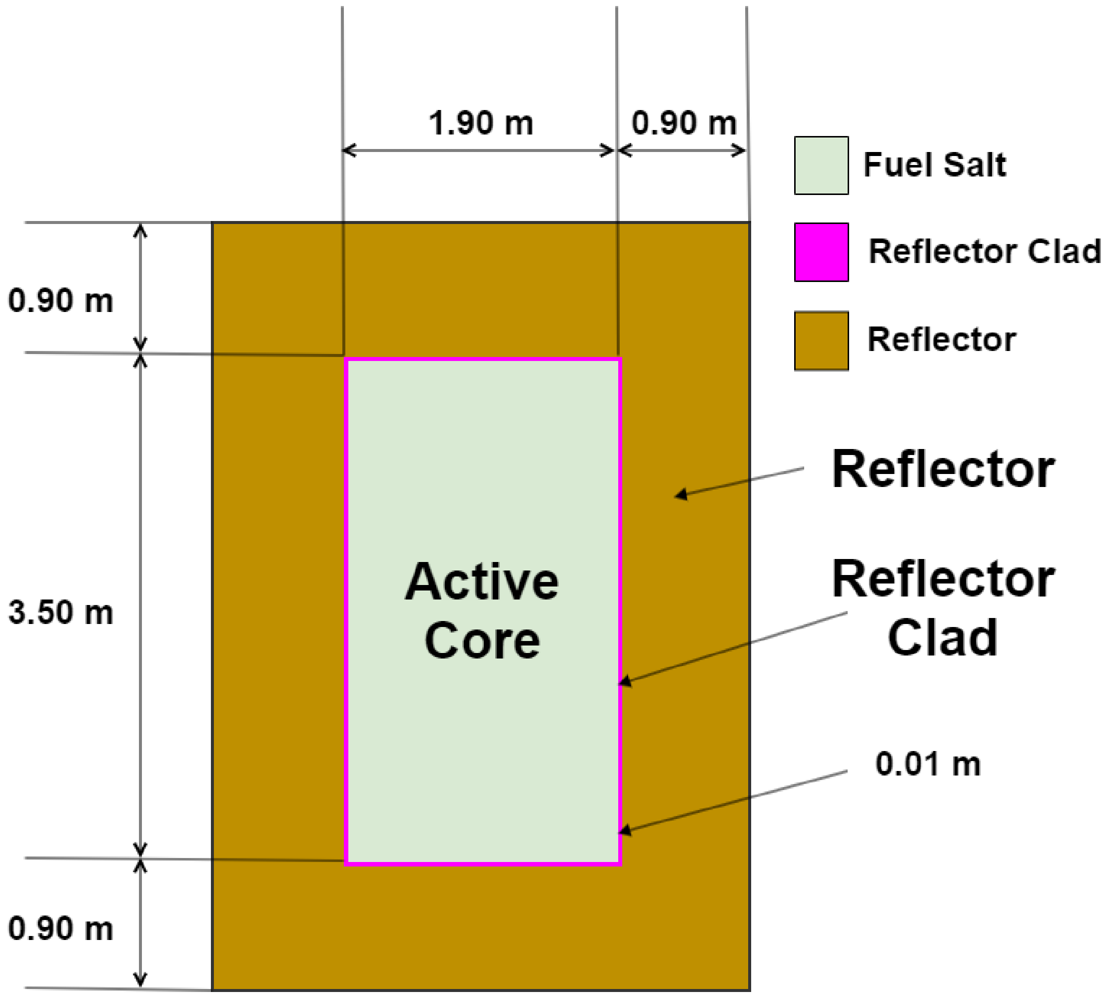

Figure 5-1:MCFR-D Representative Model

Table 5-1: MCFR-D parameters.

Parameter	Value	Unit
Thermal Power	180	MWth
Electrical Power	75	MWe
Uranium Enrichment	19.75	w% U-235
Chlorine Enrichment	99	w% Cl-37
Fuel Salt Average Temperature	695	°C
Active Core Diameter	1.9	m
Active Core Height	3.5	m
Reflector Clad Material	Inconel Alloy 625	-
Reflector Clad Density	8.3	g/cc

Reflector Clad Temperature	695	°C
Reflector Clad Thickness	0.01	m
Reflector Material	MgO	-
Reflector Material Density	3.6	g/cc
Reflector Temperature	695	°C
Reflector Thickness	0.90	m

5.2 MCFR-C

The neutronics of the MCFR-C core can be well represented by a right cylindrical active core which is enveloped by a thin reflector clad which in turn is surrounded by a thick neutron reflector as shown in Figure 5-2. The MCFR-C neutron reflector has two sections: a radial section that is 85% by volume reflector material, 10% by volume fuel salt and 5% by volume structural material, and an axial reflector that is 100% reflecting material. Table 5-2 presents design parameters for the MCFR-C model.

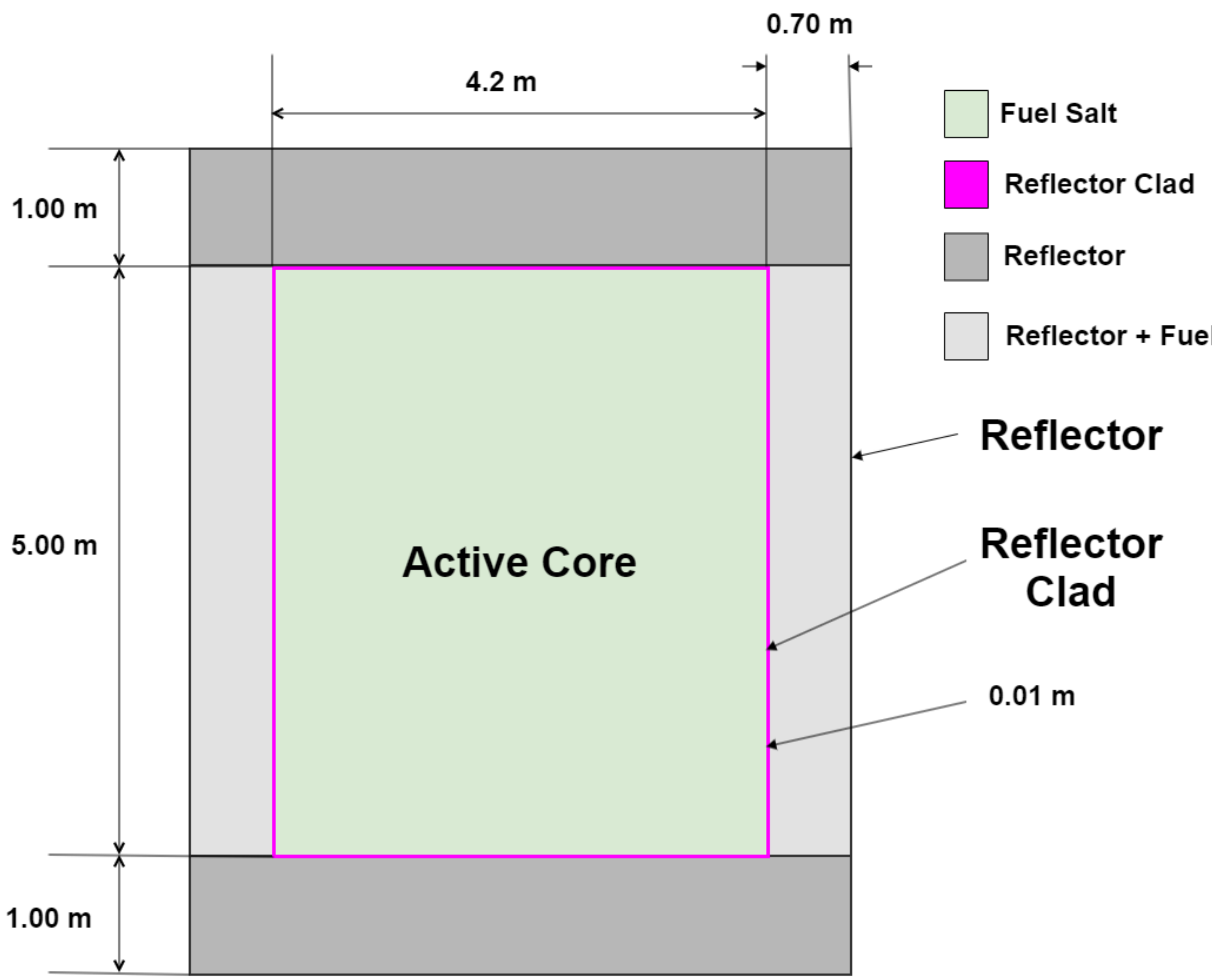

Figure 5-2:MCFR-C Representative Model

Table 5-2: MCFR-C parameters.

Parameter	Value	Unit
Thermal Power	1200	MWth
Electrical Power	800	MWe
Uranium Enrichment	12.50	w% U-235
Chlorine Enrichment	99	w% Cl-37
Fuel Salt Average Temperature	700	°C
Active Core Diameter	4.2	m
Active Core Height	5.0	m
Reflector Clad Material	Inconel Alloy 625	-
Reflector Clad Density	8.3	g/cc
Reflector Clad Temperature	700	°C
Reflector Clad Thickness	0.01	m
Axial Reflector Material	Lead	-
Reflector Material Density	10.2	g/cc
Axial Reflector Thickness	1.0	m

6 CONCLUSIONS

The description of the MCFR-D and MCFR-C designs may be used in support of model development external to TerraPower. This report will be revised to coincide with the design progression of the MCFR-D and MCFR-C; more revisions are expected.

Please contact Tommy Cisneros at tcisneros@terrapower.com for questions regarding the content of this report.

7 REFERENCES

[1] MCRE-ENG-PRSNT-0029 Rev 1, "MCRE Design Description in Support of External Model Development," TerraPower, Bellevue, 2022.

[2] MCFR-ENG-PRSNT-0017, "Molten Chloride Fast Reactor Program Overview," TerraPower, Bellevue, 2022.

[3] H. G. MacPherson, "The Molten Salt Reactor Adventure," *Nucl. Sci. & Eng.,* vol. 90, pp. 374-380, 1985.

[4] P. N. Haubenreich and J. R. Engel, "Experience with the Molten-Salt Reactor Experiment," ORNL, 1969.

[5] MCFR-ENG-PRSNT-0004, "MCFR System Description," TerraPower, Bellevue, 2021.

[6] Nuclear Energy Agency, "OECD NEA - Nuclear Data High Priority List; Request ID 119," Nuclear Energy Agency, 17 April 2022. [Online]. Available: https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=540. [Accessed 20 December 2022].

[7] Office of Nuclear Energy, ""Orano and TerraPower Awarded GAIN Vouchers to Help Advance Nuclear Technology"," 22 June 2022. [Online]. Available: https://www.energy.gov/ne/articles/orano-and-terrapower-awarded-gain-vouchers-help-advance-nuclear-technologies. [Accessed 30 August 2022].

[8] MCRE-FUEL-SPEC-0001 Rev 0, "Fuel Salt Specification for MCRE," TerraPower, 2022.

[9] MCFR-FUEL-EDD-0001 Rev D, "NaCl-UCl3 Eutectic Salt Thermophysical Properties," TerraPower, 2022.

[10] MCRE-PLT-EDD-0005 Rev 1, "Modes of Operation for the MCRE," TerraPower, 2022.

[11] MCRE-PLT-EDD-0008 Rev 0, "Plant Architecture Description," TerraPower, 2022.

[12] MCRE-RCS-GA-0002 Rev 0, "Reactor Core System General Arrangement," TerraPower, 2022.

[13] MCRE-PUMP-SPEC-0001 Rev 1, "Fuel Salt Pump Specification," TerraPower, 2022.

[14] MCRE-PLT-EDD-0007 Rev 1, Plant Operating and Design Conditions, TerraPower, 2022.

[15] MCRE-KCS-ASSY-0003 Rev 0, "Control Element Weldment," TerraPower, 2022.

[16] MCRE-RXE-PART-0024 Rev 1, "RXE Vessel and Loop," TerraPower, 2022.

END OF DOCUMENT