

1 The Prismatic Modular Reactors (PMRs)

The history of prismatic High Temperature Gas-Cooled Reactors (HTGRs) or simply PMRs begins in the 1960s with the deployment of the Dragon reactor in the United Kingdom (UK). Its initial objective was to demonstrate the feasibility of the HTGR and to launch the development of the technology. The Dragon reactor experiment first operated in July 1965 and reached full power of 20 MWt in April 1966. The reactor operated for long periods at full power, demonstrated the successful operation of many components, and provided information on fuel and material irradiation tests. Simultaneously, interest in the United States (US) led to the 40 MWe HTGR at Peach Bottom. The reactor achieved initial criticality on March 1966 and went into commercial operation in June 1967. Peach Bottom provided a valuable demonstration of the HTGR concept by confirming the core physics calculations, verifying the design analysis methods, and providing a data base for further design activities. Most importantly, the plant demonstrated the ability of HTGRs to function in a load-following manner [4]. After the deployment of these two prototype reactors came the first HTGR demonstration plant, the Fort St. Vrain (FSV) Generating Station. Its electric power generation started in December 1976, reaching full-power operation in November 1981. The FSV plant generated 842 MWt to achieve a net output of 330 MWe. This reactor laid the foundation for future PMR designs. Beginning with FSV, the US core design included ceramic coated Tristructural Isotropic (TRISO) particles embedded within rods placed in large hexagonal shaped graphite elements [4].

The most fundamental characteristic of the PMR is the unique safety philosophy embodied in its design [9]. The control of radionuclides does not rely on active systems or operator actions. TRISO particles, Figure 1, play a big role in this task. They consist of various layers acting in concert to provide a containment structure that limits radioactive product release. A TRISO particle is a microsphere of about 0.8 mm diameter. It includes a fuel kernel surrounded by a porous carbon layer (or buffer), followed successively by an inner pyrolytic carbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer pyrolytic carbon (OPyC) layer. An additional advantage of the TRISO particles is that they increase the proliferation resistance of HTGRs. They are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials [8].

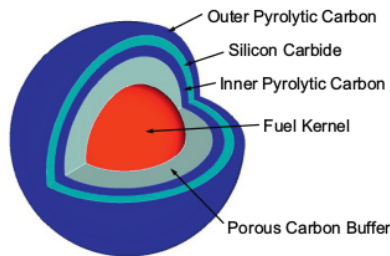


Figure 1: Drawing of a TRISO fuel particle. Image reproduced from [6].

Another contributor to the passive safety of the HTGR design is its materials. The combination of a graphite core structure, ceramic fuel, and inert helium permits very high operating temperatures [1]. Graphite has a high heat capacity and maintains its strength at temperatures beyond 2760 °C. As a result, temperature changes in the core occur very slowly and without damage to the core structure during transients. Besides, the annular core geometry and a low core power density enable passive heat transfer mechanisms to remove the decay heat following postulated accidents [13]. These passive heat transfer mechanisms rely primarily on the natural processes of conduction, thermal radiation, and convection.

A desirable feature of the HTGR is its higher operating temperature. Higher temperatures offer increased cycle efficiencies. The early HTGR designs converted their heat into electricity using the Rankine steam cycle [7]. In such system, the helium coolant passes through a heat exchanger generating steam to drive a turbine. This arrangement is around 38% efficient [3]. Some of these designs would superheat the steam to increase their efficiency, but this complicates the plant layout [1]. A practical temperature limit is around 300-400 °C. To

take advantage of the high core outlet temperature of the HTGR, the Brayton cycle is a better option, where the helium coolant directly drives a gas turbine in a closed cycle. With such configuration, the system can achieve an energy conversion efficiency of around 48% [3]. Additionally, having helium circulating in a closed cycle removes external sources of contamination of the nuclear circuit. Thus, the need for on-line clean up systems is largely reduced [9].

Another advantage of the HTGR over other reactor designs is that higher outlet temperatures and increased cycle efficiencies enable a wide range of process heat applications. Some applications use steam for coal gasification processes, oil refinery processes, and production of synthesis gas, methanol, and hydrogen. Several hydrogen production processes benefit from high temperatures, such as high temperature electrolysis or the thermochemical splitting of water. Utilizing the HTGR as the energy source of the process eliminates the need to burn fossil fuels to generate the steam [9].

This thesis focuses primarily on the Modular High-Temperature Gas-Cooled Reactor (MHTGR)-350 [13] [18]. Under the sponsorship of the US Department of Energy (DOE), a team consisting of General Atomics, Combustion Engineering, General Electric, Bechtel National, Stone & Webster Engineering, and Oak Ridge National Laboratory (ORNL) developed the MHTGR [13]. They designed the basic module to deliver superheated steam at 17.3 MPa and 538 °C. Based on both economical and technological considerations, a 350 MW(t) modular reactor defines the optimal configuration. The team completed in 1986 the preliminary safety information document for the MHTGR and the complete draft pre-application in 1989 [8].

2 MHTGR-350 Reactor Description

This section provides a description of the MHTGR-350 reactor. Table 1 lists its main characteristics. The core consists of an array of hexagonal fuel elements in a cylindrical arrangement, Figure 2. Nineteen graphite replaceable reflector elements compose the inner reflector region. A ring of identically sized graphite replaceable reflector elements surrounds the fuel elements. Then, a region of permanent reflector elements follows the replaceable reflectors. The reactor vessel encases all the elements.

Table 1: MHTGR350 Characteristics [12].

Characteristics	Value
Installed Thermal Capacity	350 MWt
Installed Electric Capacity	165 MWe
Core inlet/outlet Temperature	259/687°C
Power Density	5.9 MW/m ³
Reactor Vessel Outside diam.	6.8 m
Reactor Vessel Height	22 m
Active core radius	2.97 m
Active core height	7.93 m
Top reflector height	1.20 m
Bottom reflector height	1.60 m
Number of fuel columns	66
Number of inner reflector columns	19
Number of outer reflector columns	78

Ten layers of fuel elements stacked on top of each other compose the 66 fuel columns that integrate the active core. Figure 2b shows an axial view of the reactor. The core has two types of fuel elements: a standard element, and a reserve shutdown element that contains a channel for Reserve Shutdown Control (RSC). Table 2 specifies the details of the MHTGR-350 fuel elements. Twelve columns in the core contain RSC channels

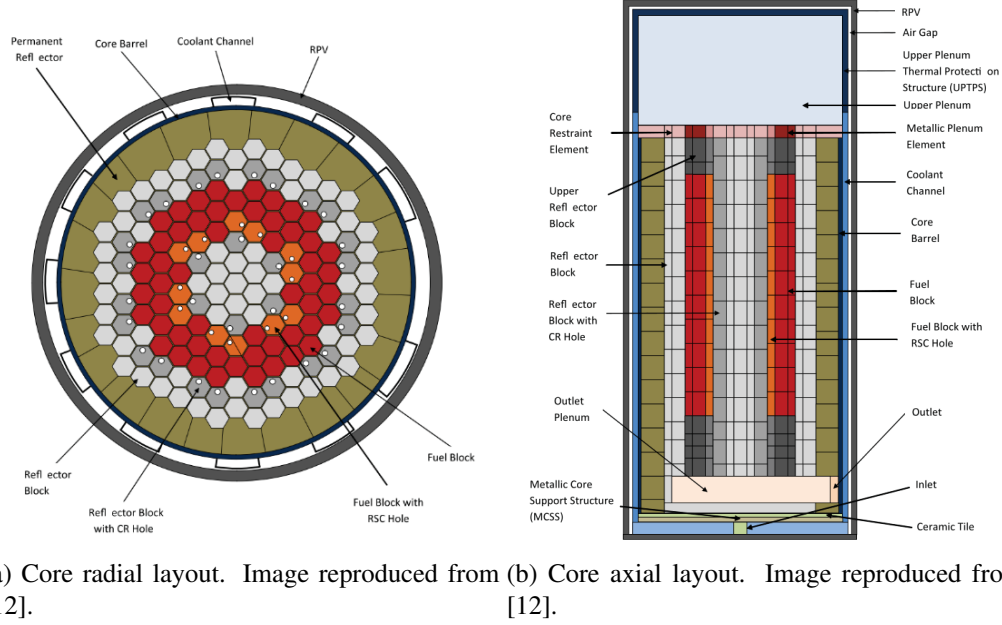


Figure 2: MHTGR reactor layout.

for reserve shutdown borated graphite pellets. Hoppers above the core house the pellets, and if the control rods (CRs) become inoperable, the pellets drop into the channels [12].

The fuel elements contain blind holes for fuel compacts and full-length channels for helium coolant flow. Table 3 specifies details of the TRISO particle and fuel compact designs of the MHTGR-350.

A combination of Lumped Burnable Poison (LBP) and CRs controls the core reactivity. The LBP consists of boron carbide (B₄C) granules dispersed in graphite compacts. The current design uses six LBP rods per element. Table 4 displays the characteristics of the LBP compacts.

The reactor counts with 30 CRs. Six of them are start-up CRs and their location is the inner reflector. The remaining 24 are operating CRs and control the reactivity during power operation and in case of a reactor trip.

3 Motivation

This work's ultimate goal is to support the development of HTGR technology. More specifically, we focus on the development of computational methods for modeling HTGRs. We use *Moltres* as our main analysis tool.

The Generation IV Roadmap project identified reactor concepts that could meet the energy demands of the future in an efficient, economic, and environmentally safe manner [11]. One of these reactor concepts is the Very High Temperature Gas Cooled Reactor (VHTR). VHTR is distinct from HTGR as its coolant outlet temperature reaches higher temperatures. However, the literature often uses these terms interchangeably. In this work, the term HTGR encompasses both terms. The DOE had selected this reactor concept for the, now canceled, Next Generation Nuclear Power (NGNP) Project. This project intended to demonstrate emissions-free nuclear-assisted electricity and hydrogen production by 2015.

Although the DOE has canceled the NGNP Project, HTGRs will become a reality in the near future. Some microreactor designs embody this type technology and may be operational before 2030. Additionally, as the introduction has already described, the HTGR technology has several favorable characteristics. To recapitulate the most important features, the HTGR relies on passive heat transfer mechanisms, uses TRISO particles as its fuel, has a high proliferation resistance, has the ability to achieve high temperatures, and benefits from increased cycle efficiencies. Other beneficial characteristics are that high temperatures enable a wide range of process heat applications, among which we find hydrogen production.

Table 2: MHTGR350 fuel element characteristics [12].

Shared characteristics	Value	Units
Block pitch (flat-to-flat)	36	cm
Fuel length	79.3	cm
Fuel handling diameter	3.5	cm
Fuel handling length	26.4	cm
RSC hole diameter	9.525	cm
RSC center to assembly center	9.756	cm
Fuel/coolant pitch	1.879	cm
Fuel hole radius	0.635	cm
Compacts per fuel hole	15	-
Large coolant hole radius	0.794	cm
Small coolant hole radius	0.635	cm
LBP hole radius	0.635	cm
Block graphite density	1.85	g/cm ³
Standard element		
Number of large coolant holes	120	-
Number of small coolant holes	6	-
Number of fuel holes	210	-
RSC element		
Number of large coolant holes	88	-
Number of small coolant holes	7	-
Number of fuel holes	186	-

Table 3: TRISO and fuel compact characteristics [12].

Characteristic	Value	Units
Fuel	UC _{0.5} O _{1.5}	-
Enrichment (average)	15.5	wt%
Packing fraction (average)	0.35	-
Kernel radius	0.02125	cm
Buffer radius	0.03125	cm
IPyC radius	0.03475	cm
SiC radius	0.03825	cm
OPyC radius	0.04225	cm
Compact radius	0.6225	cm
Compact gap radius	0.6350	cm
Compact length	4.9280	cm
Kernel density	10.50	g/cm ³
Buffer density	1.00	g/cm ³
IPyC density	1.90	g/cm ³
SiC density	3.20	g/cm ³
OPyC density	1.90	g/cm ³
Compact matrix density	1.74	g/cm ³

Table 4: LBP compact characteristics [12].

Characteristic	Value	Units
Absorber	B ₄ C	-
Packing fraction	0.109	-
Kernel radius	0.0100	cm
Buffer radius	0.0118	cm
PyC radius	0.0141	cm
Compact radius	0.5715	cm
Compact gap radius	0.6350	cm
Rod length	72.187	cm
Kernel density	2.47	g/cm ³
Buffer density	1.00	g/cm ³
PyC density	1.87	g/cm ³
Compact matrix density	0.94	g/cm ³

Modeling and prediction of core thermal-hydraulic behavior is necessary for assessing the safety characteristics of a reactor. Determining the temperature inside a reactor, for both normal and transient operation, is of paramount importance as the integrity of several materials depends on it. Most importantly, undesirably high temperatures endanger the integrity of the TRISO particles and, consequently, jeopardize a fission product release [19]. Furthermore, the complex geometry of the fuel blocks hinders accurate evaluations of the fuel temperatures requiring elaborate numerical calculations.

The characteristics of a HTGR are different from those of conventional Light Water Reactors (LWRs). Such differences create a demand for new reactor analysis tools. This new tools should take into account the following peculiarities of HTGRs [17][2]:

- Hexagonal structure: the shape of the fuel blocks does not conform to any orthogonal coordinate system.
- Double heterogeneity: the TRISO particles form the first level of heterogeneity, as they consist of four layers. The second level arises from the fuel elements, as they encompass the compacts, the coolant, and the moderator.
- Strong dependence of the neutron spectrum and the macroscopic cross sections on the fuel temperatures.
- Long transients caused by high thermal inertia of the reactor core due to the presence of large graphite structures.

Historically, linking a stand-alone neutronics solver to a thermal-hydraulics solver allowed for the simulation of an entire reactor. The coupling of the codes occurred in a black-box fashion, where the output of one code served as the input of the other, and vice versa. This coupling technique is commonly known as the operator-splitting technique. In such approach, each individual physics isolates the action of the governing equations upon the variables. Nonetheless, these physical models, in reality, describe processes that rely heavily on the solution of one another's. The power distribution has a strong influence on the temperature field. Due to the HTGR strong temperature feedback, the other way around is true as well, the temperature affects the power distribution in the core. Because of a large time-scale separation between the different phenomena, multiphysics transient simulations coupled via the operator-splitting approach may introduce significant numerical errors [16] [15].

Multiphysics Object-Oriented Simulation Environment (MOOSE) [5] is a computational framework targeted at solving fully coupled systems. All the software built on the MOOSE framework shares a common code base. These feature facilitates relatively easy coupling between different phenomena and allows for great flexibility even with large variance in time scales [14]. Additionally, all codes use MPI for parallel communication and allow for deployment on massively-parallel cluster-computing platforms.

Moltres [10] is a Finite Element Method (FEM) simulation code built within the MOOSE framework. *Moltres* solves arbitrary-group neutron diffusion, precursor, and temperature governing equations. Besides, this simulation tool is open source. All these characteristics make *Moltres* suitable for solving the type of physical phenomena described above.

4 Objectives

This thesis focuses on steady-state calculations and also intends to set a roadmap for the transient simulations.

Finally, we will compare the results to the already published results from the benchmark.

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