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 eeactor 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 pyrolitic carbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer pyrolitic 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].

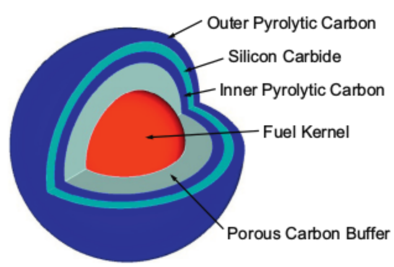


Figure 1: Drawing of a TRISO fuel particle. Image reproduced from [6].

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 [12]. 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 [12] [13]. 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 [12]. 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].

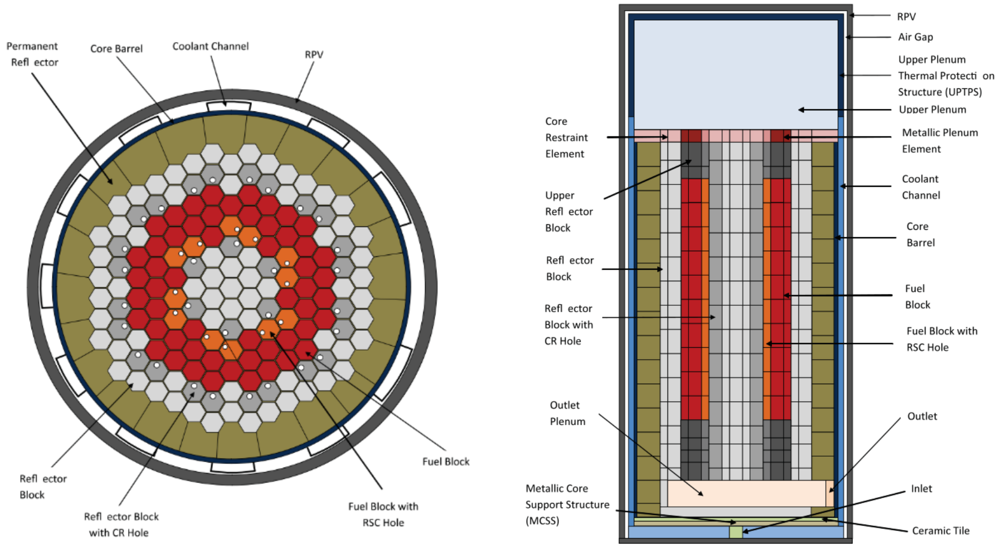
2 MHTGR-350 Reactor Description

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 [11].

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	2.973 m
Height of the active core	7.93 m
Number of RSC fuel columns	12
Number of inner reflector columns	19
Number of outer reflector columns	78

Ten 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 **??** contains the main characteristics of the core. Twelve columns in the core contain RSC channels 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 [11]. Thirty reflector columns contain channels for CRs.



(a) Core radial layout. Image reproduced from [11].

(b) Core axial layout. Image reproduced from [11].

Figure 2: MHTGR reactor layout.

Control rods fabricated from natural boron in annular graphite compacts with metal cladding carry out the reactivity control. Lumped burnable poison (LBP) contributes to the reactivity control.

The active core consists of hexagonal graphite fuel elements containing blind holes for fuel compacts and full-length channels for helium coolant flow.

3 Fuel Compact

Table 2 specifies details of the TRISO particle and fuel compact designs of the MHTGR-350.

4 Fuel Assembly

Table 3 specifies details of the fuel elements of the MHTGR-350.

5 GT-MHR Reactor Summary

6 Motivation

The focus of this report is on utilization of the modular high temperature gas cooled reactor (HTGR) to support the goal of meeting the energy demands of the future in an efficient, safe and more economic and environmentally acceptable manner than the present methods of energy production and utilization. The international status and planning associated with development of the HTGR for the production of electricity and utilization in achieving a wide range of process heat applications is examined herein as an advanced source of energy for the twenty-first century. [9]

HTGR reactors require core simulation techniques not typically utilized in Light Water Reactor (LWR) analysis due to several unique features, such as double heterogeneous fuel design including TRISO fuel particles, large graphite quantities, and high operational temperatures [2].

Table 2: TRISO and Fuel Compact Characteristics [11].

Characteristic	Value	Units
Fuel	$UC_{0.5}O_{1.5}$	-
Enrichment (average)	15.5	wt%
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
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
Packing Fraction (average)	0.35	-
Compact radius	0.6223	cm
Compact Gap radius	0.6350	cm
Compact length	4.9280	cm
Helium density	4.19	10^{-3} g/cm^3
Block graphite density	1.85	g/cm^3

Table 3: MHTGR350 fuel element characteristics [11].

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
Large coolant hole radius	0.794	cm
Small coolant hole radius	0.635	cm
Compacts per hole	15	-
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	-

Systems of Partial Differential Equations (PDEs) describe the behavior of nuclear reactor processes. Historically, linking a neutronics solver to a thermal-hydraulics solver allowed for the simulation of an entire reactor. Nonetheless, HTGRs have a strong temperature feedback, causing increased coupling between the different physics phenomena. Because of the large time-scale separation, multiphysics transient simulations coupled via the operator-splitting approach may introduce significant numerical errors [?] [?]. Multiphysics Object-Oriented Simulation Environment (MOOSE) [?] is a computational framework targeted at solving fully coupled systems and allows for great flexibility even with large variance in time scales.

The history of PMRs begins in the 1960s with the deployment of the Dragon reactor (1965) in the UK and Peach Bottom (1966) in the US. Later, the Fort St. Vrain Generating Station (1976) in the US laid the foundation for future prismatic HTGR designs [?]. Modern HTGR designs still use variants of its fuel assembly block.

The PMR design concept has existed for some time. However, the computational tools available for the analysis of HTGRs have lagged behind, compared to the state of the art of other reactor technologies. The history of deterministic diffusion solvers begins in the late 1950s with the Finite Difference Method (FDM) applied to Light Water Reactors (LWRs). Using FDM causes the mesh points to reach intractable numbers when large multi-dimensional problems are under consideration [?]. The computational expense associated with these calculations motivated the development of more computationally efficient techniques [?]. The most common methods fall into two broad categories: nodal methods and Finite Element Method (FEM). In the 1970s, nodal methods proved to be a highly efficient and accurate technique in Cartesian geometries. In 1981, a formulation based on Nodal Expansion Method (NEM) first demonstrated the feasibility of nodal methods in hexagonal geometries [?]. Nevertheless, this method introduces non-physical singular terms that requires the utilization of discontinuous polynomials. This motivated the development of HEXNOD [?] and HEXPEDITE [?], more effective formulations introduced in the late 1980s and early 1990s. HEXPEDITE's use still prevails in the analysis of HTGRs [?]. Some modern codes still use this technique. DIF3D [?] and PARCS [?] are examples of those codes. The FEM is a well-established method in applied mathematics and engineering. Most applications make FEM preferable due to its flexibility in the treatment of curved or irregular geometries. Also, the use of high order elements attains higher rates of convergence [?]. The first prototype engineering application of FEM was in the field structural engineering and dates back to 1956. In the 1960s, FEM became the most extensively used technique in almost every branch of engineering. In 1981, [?] described the first application of FEM to the neutron diffusion theory. Some examples of current FEM diffusion solvers are Rattlesnake [?] and CAPP [?].

Historically, linking a stand-alone neutronics solver to a thermal-hydraulics solver allowed for the simulation of an entire reactor. For example, coupling PARCS, DIREKT, and THERMIX [?] allowed for solving a Pebble Bed Modular Reactor (PBMR)-400 Benchmark [?]. Nonetheless, HTGRs have a strong temperature feedback, causing increased coupling between the different physics phenomena. Because of the large time-scale separation, multiphysics transient simulations coupled via the operator-splitting approach may introduce significant numerical errors [?] [?]. MOOSE [?] [?] is a computational framework targeted at solving fully coupled systems. All the software built on the MOOSE framework shares a common code base. This facilitates relatively easy coupling [?] between different phenomena and allows for great flexibility even with large variance in time scales. *Moltres* [10] is a FEM simulation code built on the MOOSE framework. It solves arbitrary-group neutron diffusion, precursor, and temperature governing equations on a single mesh. Moltres can solve the equations in a fully-coupled way or solve each system independently allowing for great flexibility and making it applicable to a wide range of nuclear engineering problems.

In addition to the development of new methods, it is essential to define appropriate benchmarks to compare the capabilities of various computer codes. The Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) defined such benchmark for the MHTGR-350 MW reactor [11]. The scope of the benchmark is twofold: 1) to establish a well-defined problem, based on a common given data set, to compare methods and tools in core simulation and thermal fluids analysis, 2) to test the depletion capabilities of various lattice physics codes available for PMRs. The objective of this work is to conduct Exercise 1 of Phase I of the benchmark with Moltres. Finally, we will compare the results to the already published results from the benchmark.

7 Objectives

OECD PBMR400 Coupled Code Benchmark OECD/NEA MHTGR-350 Benchmark CRP on Uncertainty Analysis in HTRs [5]

PHISICS (INL) Computes the time-dependent flux and power distribution in the core. Depletes and shuffles fuel elements.

User-specified P n nodal transport (INSTANT). Coupled to RELAP5-D for thermal-fluid analysis.

SPH treatment? Diffusion codes may work if the cross sections are properly prepared using a lattice code that captures all layers of heterogeneity including spectral penetration between blocks. Monte Carlo codes are suitable for steady state design and high fidelity reference solutions (SERPENT, MCNP-ORIGEN, MONTE-BURN)

Others: PARCS (NRC), DIF3D-REBUS (ANL), APOLLO-CRONOS (AREVA) [5]

SCALE 6.2 Recent upgrade treats double heterogeneity. [5]

RELAP-3D Coupled to PHISICS for prismatic reactor steady-state and transient analysis. Others: GRSAC (ORNL), GRSAC (ORNL), FLOWNEX (flownex.com), RELAP-7(INL), AGREE(NRC), MGT (FZ-Jülich), THERMIX-DIREKT (FZ-Jülich).

[5]

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