PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Possibility to Use Different Fuel Cycles in GT-MHR

Nickolai N. Kodochigov*[1], Yury P. Sukharev[1], Elena V. Marova[1],
Nickolai N. Ponomarev-Stepnoy[2], Evgeny S. Glushkov[2], Peter A. Fomichenko[2]
[1]*OKB Mechanical Engineering, 15, Burnakovsky proezd, Nizhny Novgorod, 603074, Russia*
[2]*RRC Kurchatov Institute, 1, Kurchatov sq., Moscow, 123182, Russia*

The GT-MHR reactor core is characterized by flexibility of neutronic characteristics at the given average power density and fixed geometrical dimensions of the reactor core. Such flexibility makes it possible to start the reactor operation with one fuel, and then to turn to another type of fuel without changes of main reactor elements: fuel block design, core and reflector dimensions, number control rods and their positions etc.

Preliminary analysis reindicates the commercial viability of the GT-MHR concept, part of which is due to its ability to accommodate different fuel types and cycles. This paper presents the results of studies of the neutronic characteristics of GT-MHR cores using different types of fuel (low- and highly-enriched uranium, pure weapons or civil plutonium, MOX fuel).

Comparison of different fuel cycles is carried out for a three-batch refueling option with respect to following characteristics: discharged fuel burnup, reactivity change during one partial cycle of fuel burnup, consumption of fissile isotopes per unit of produced energy, power distribution, reactivity effects, control rods worth.

It is shown, that the considered options of fuel loads provide the three-year core lifetime (with account for the load factor ~0,8) without changes of core design, number and design of control rods at transition from one fuel type to another.

KEYWORDS: GT-MHR gas-turbine modular helium reactor; fuel type, core design, neutron-physical characteristics

1. Introduction

High-temperature gas-cooled reactors (HTGR) with helium coolant possessing properties of high safety and self-protection with respect to different accidents are among the possible types of reactors on which basis the electricity supply of different regions in the world could be implemented.

The main HTGR features and advantages are determined by the use of fuel in the form of coated fuel particles (200-500 μm diameter) with a multilayer protective coating, use of helium coolant, and use of graphite not only as a moderator but also as a structure material of reactor components, thus enabling elimination of metals from the active core. These factors allow to reach in HTGRs high temperature at the reactor outlet, that in combination with the direct gas-turbine cycle provides high economic performance.

* Corresponding author, Tel: ++7 (8312) 462132, Fax: ++7 (8312) 418772, E-mail: marova@okbm.nnov.ru

Constructed and operated in Germany, UK and the USA, experimental reactors and nuclear plants with HTGRs have confirmed the excellent performance of the fuel on the basis of multilayer coated particles, high nuclear and radiation safety of operation. The considerable technological potential in development and construction of reactors of this type has been accumulated, and extensive researches have been conducted on the development of fuel elements, testing of main plant components, safety qualification and other problems. Nowadays a number of countries in the world, such as Japan, the USA, Russia, China, South Africa, Germany and others, continue the efforts on developing technologies of modular HTGRs of a new generation.

The prospects for using HTGRs to generate electricity are enhanced by their ability to use different fuel cycles with little or no change in the core geometry. Every fissile material can be used in coated fuel particles either together with fertile material (U-238 or Th-232) or without it. In so doing, it is possible to vary the concentration of fissile material in relation to graphite moderator, ratio of fissile and fertile materials, as well as the level of heterogeneity of a HTGR active core in a wide range by changing fuel enrichment, sizes of fuel particles, volume occupied by them etc., that is difficult for other types of reactors.

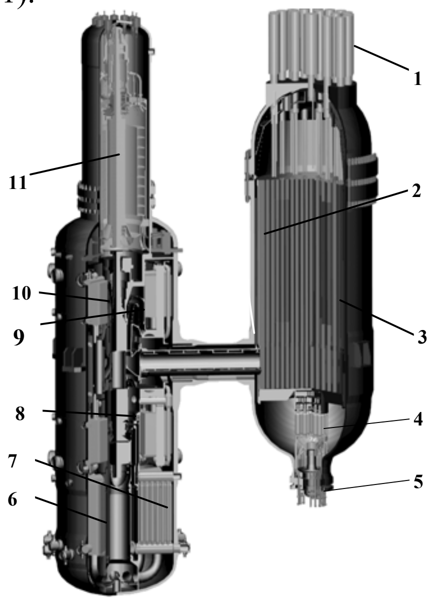
The GT-MHR [1] design is the result of the international collaboration involving Russia (MINATOM institutions, OKBM, RRC Kurchatov Institute), the USA (General Atomics, ORNL, LANL), France (Framatome ANP), and Japan (Fuji Electric).

In this connection, in the present paper reactor discusses the performance of GT-MHR active cores using different types of fuel (low and high-enriched uranium, pure weapons and civil Pu, MOX fuel).

All these different fuel cycles are considered in a three-batch refueling scheme option, and comparison is carried out with respect to the following characteristics: spent fuel burnup, change of reactivity during one partial fuel cycle, consumption of fissile isotopes per unit of produced energy, power distributions, effects of reactivity, worth of control rods, etc.

2. Concept of the GT-MHR Reactor Plant

The GT-MHR is a modular plant consisting of a high-temperature helium reactor and a gas turbine (Figure 1).



1 – control rod driver;
2 – reactor vessel;
3 – annular core;
4 – heat exchanger of shutdown cooling system;
5 – gas circulator of shutdown cooling system;
6 – precooler;
7 - intercooler;
8 - compressor;
9 - turbine;
10 - recuperator;
11 - generator

Fig. 1 The GT-MHR module

The reactor and components of the gas-turbine machine are located in the steel vessels connected by the coaxial gas pipeline.

In the annular type active core fuel blocks of prismatic form are applied, with fuel elements (compacts) on the basis of coated fuel particles with ceramic protective coatings ensuring the retention of fission products up to high temperatures (≤ 1600^{O}C).

Helium used in the GT-MHR reactor as a coolant of primary circuit is an inert coolant not undergoing phase transitions at nuclear plant operation. Contrary to reactors of other types, it allows using high coolant temperatures (800–900^{O}C and more).

At such temperatures the thermodynamic cycle of the helium turbine is much more effective than for steam turbines traditionally used in power engineering, and the GT-MHR plant can ensure thermal efficiency about 48 %.

The main parameters of reactor plant are listed in Table 1.

Table 1 Basic parameters of the GT-MHR reactor [2]

Parameter	Value
Full thermal reactor power, MW	600
Inlet helium temperature, ^{o}C	490
Outlet helium temperature, ^{o}C	850
Core dimensions:	
- equivalent core diameter, inner/outer, m	2.96 / 4.84
- core height, m	8.00
Average core specific power, MW/m^3	6.5
Number of fuel blocks	1020
Dimensions of a prismatic fuel block:	
- height, m	0.80
- size across flats, m	0.36
- number of fuel compacts per fuel block (average in the core)	2862
Fuel temperature design limit, o C	≤ 1600
Number of reactivity control rods:	
- in active core	12
- in side reflector	36
Number of reserve shutdown system channels	18

Because of application of coated fuel particles and due to weak absorption of neutrons in graphite structure materials, the GT-MHR possesses versatility in relation to the fuel cycle from the viewpoint of fuel type. Uranium, thorium, as well as civil or weapons grade plutonium can be used for core loading.

An essential advantage of the GT-MHR is the high level of nuclear safety. It is stipulated by a negative temperature reactivity coefficient of the core. Additionally, the GT-MHR has a unique feature - the capability to survive the total loss of coolant without core melting. Low power density in the active core and modular type design provide passive, without any auxiliary safety cooling systems, removal of decay heat from the core without damage to fuel elements.

The GT-MHR reactor is well adapted to serial fabrication in conditions of machine building works. This provides excellence of manufacturing of modules, typical for hardware products of the Russian nuclear and aircraft industries. The serial fabrication of modular reactors is the essential factor of cost reduction. The simplicity of the principal GT-MHR scheme guarantees the reliability. Inherent safety features of the GT-MHR based on passive removal of decay heat and rather slowly progressing transients provide good premises for the favorable public perception.

3. Results of the Analysis of Core Characteristics with Different Fuel Types

The main purpose of the GT-MHR plant at the use of each type of fuel is the generation of electricity. From this position, the reactor fuel load should ensure maximum power generation at minimum consumption of initially loaded fuel. In the present work, the choice of fuel loading for different options of GT-MHR fuel compositions was carried out according to this requirement.

Repeatability of basic parameters of the active core and reactor, along with fulfillment of the regulatory requirements on safety, allows using fuel of a different type without changes of the core design. In the Table 2 the initial isotopic composition of used fuel types are shown. The compositions of weapons grade Pu, civil Pu, Pu in MOX fuel, and also fuel on the basis of low- and high-enriched uranium (LEU and HEU) were considered.

Table 2 Isotopic compositions of fresh fuels

Option	Fuel type	Fuel composition	Enrichment on fissile isotopes in U or Pu kernels	Fraction of fertile material in fuel composition
1	LEU	U-235 (14 %) + U-238 (86 %)	14 % (U-235)	~ 86 % (U-238)
2	HEU + Th	WGU[a] (15 %) + Th (85 %)	93 % (U-235)	~ 85 % (Th) ~ 1 % (U-238)
3	WGPu[b]	Pu-238 (0.1%)+Pu-239 (91.7%) + Pu-240 (6.6%) + Pu-241 (1.2%) + Pu-242 (0.4%)	~ 93 % (Pu fissile)	7 % (Pu-240 and Pu-242)
4	Civil Pu	Pu-238 (1%)+Pu-239 (59%) + Pu-240 (24%) + Pu-241 (11%)+ Pu-242 (5%)	70 % (Pu fissile)	29 % (Pu-240 and Pu-242)
5	MOX	WGPu (50 %) + U-nat (50 %)	~ 47 % (Pu fissile)	~ 50 % (U-nat) + 3.5 % (Pu-240 and Pu-242)

[a] weapons grade uranium
[b] weapons grade plutonium

The comparative analysis of fuel cycles of the GT-MHR was conducted with the use of WIMS-D4 and JAR codes.

The WIMS-D4 code [3] with enhanced neutron cross-section libraries was used for tracking the burnup of fissile and fertile isotopes and depletion of burnable poisons (natural boron or erbium) in multigroup approximation, as well as for preparation of few-group macroscopic cross-sections for individual physical zones included in the full-scale GT-MHR core model.

At these cell calculations, the fuel blocks were modeled by equivalent unit cells with heterogeneous setting of fuel and burnable poison compacts. On the initial stages of studies, double heterogeneity of the fuel composition was taken into account by Dancoff-factor for coated particles in a fuel compact and cluster setting of fuel compacts in a fuel block [4]. Burnable poison (BP) compacts were subdivided into concentric zones. Heterogeneity of poison particles inside the BP compacts was neglected during analyses. Currently, for preparing the group homogeneous cross sections of the fuel block with the use of WIMS-D4 an alternative step-by-step method elaborated in [5] is chosen as a basis for studies. This approach consists in consecutive application of separate models for calculation of fuel burnup, depletion of burnable poison isotopes, and calculation of fuel assemblies at several values of burnup for preparation of few-group macroscopic cross-sections.

The estimations of reactivity effects, power distribution and worth of control rods were performed in calculations of a full-scale reactor model by the JAR code [6, 7] in the few-group finite-difference diffusion approximation. Calculations were performed with a rather coarse mesh (six triangles in section per fuel block or reflector graphite block). Currently, such full core calculations are performed either in a nodal approximation [8] or with fine-mesh presentation.

Table 3 illustrates the efficiency of different fuel types. The consumption of fissile isotopes is shown in the same operational conditions (e.g. limitations on operating reactivity margin).

As follows from the Table 3 for the fuel types considered, the lowest fissile isotope consumption is in the fuel made of civil plutonium. This is a result of a relative high rate of uneven Pu isotopes production. Fuel made of highly-enriched U diluted with Th also shows this feature. The option with pure WGPu is characterized by the maximum consumption of fissile isotopes.

Table 3 Characteristics of different fuel cycles for the GT-MHR core

Characteristic	LEU	HEU + Th fuel	Fuel based on WGPu	Fuel based on civil Pu	MOX fuel based on WGPu
Number of refuelings in a fuel cycle	3	3	3	3	3
Loading of B / Er per fuel block, g	14.7 / -	41.5 / -	- / 440	26.5 /-	- / 230
Loading of U-235, or Pu-fissile per fuel block, kg	0.7	0.7	0.64	0.54	0.77
Total loading of heavy isotopes (U, Th, Pu) per fuel block, kg	5.0	5.0	0.69	0.77	1.64
Average burnup, MW·day/kg.	120	129	640	680	420
Interval between refuelings, EFPD	308	330	250	280	370
Consumption of fissile isotopes, g/(MW·day)	1.17	1.08	1.45	1.03	1.12

Obtained results show that the GT-MHR reactor possesses a flexibility to use different fuel cycles. It is possible to use different fuel types without changing the main GT-MHR core components: fuel block design, sizes of the active core and reflectors, number of control rods. This is determined by following aspects:

- all calculated neutronic characteristics for different fuel types (reactivity effects and control system efficiency) satisfy the regulatory requirements;
- power peaking factors provide allowable fuel temperatures, ensuring proper fuel performance under base irradiation.

Results of calculations of main reactivity effects for the cores with considered fuel loadings are presented in Table 4.

Table 4 Reactivity effects

Characteristic	LEU	HEU + Th fuel	Fuel based on WGPu	Fuel based on civil Pu	MOX fuel based on WGPu
Full temperature effect, % Δk/k	7.7	5.8	4.1	3.4	4.3
Reactivity temperature coefficient at normal operation, 10^{-5}, 1/K	-9.0	-4.5	-5.0	-3.6	-5.6
Xe poisoning , %Δk/k	3.5	3.1	2.1	1.9	1.8
Reactivity swing between fuel reloading, %Δk/k	2.5	2.1	1.8	0.8	~0.2

Results of calculations of control rods worth in the reactor in beginning of equilibrium fuel cycle at room temperature are shown in Table 5.

Table 5 Control rods worth

Characteristic	LEU	HEU + Th fuel	Fuel based on WGPu	Fuel based on civil Pu	MOX fuel based on WGPu
Worth of 12 control rods in active core, % Δk/k	7.3	9.1	4.7	4.0	7.0
Worth of 36 control rods in side reflector, %Δk/k	9.3	8.5	10.8	9.9	7.7
Total worth of control rods system, %Δk/k	19.9	18.0	16.8	16.5	16.6
Worth of reserve shutdown system, %Δk/k	15.4	15.6	12.6	12.1	14.8

Results of calculations of radial and axial power peaking factors are presented in Table 6.

Table 6 Power distribution peaking factors

	LEU	HEU + Th fuel	Fuel based on WGPu	Fuel based on civil Pu	MOX fuel based on WGPu
Radial peaking factor, rel. unit	1.20	1.35	1.45	1.24	1.36
Axial peaking factor, rel. unit.	1.25	1.39	1.56	1.27	1.39
Annual neutron fluence (E≥0,18 MeV) on graphite, 1025, 1/m2	1.1	1.2	1.3	1.1	1.2

Estimations of isotopic content of spent fuel for different options are shown in Table 7.

Table 7 Isotopic content of spent fuel, kg/t

Isotope	LEU	HEU + Th fuel	Fuel based on WGPu	Fuel based on civil Pu	MOX fuel based on WGPu
Th-232	-	793.0	-	-	-
U-233	-	18.0	-	-	-
U-234		4.0	-	-	-
U-235	35.2	16.0	-	-	1.4
U-236	18.2	21.0	-	-	0.5
U-238	805.0	8.0	-	-	416.2
Pu-239	5.6	0.09	97.3	40.7	17.2
Pu-240	3.6	0.09	105.1	46.3	18.7
Pu-241	3.0	0.06	105.5	114.2	34.7
Pu-242	2.40	0.01	38.4	129.1	39.3
Fission products	127.0	139.75	653.7	669.6	472.0

4. Conclusion

The GT-MHR reactor possesses a flexibility to use different fuel cycles. It is possible to use different fuel types without changing the main GT-MHR core components: fuel block design, sizes of the active core and reflectors, number of control rods, etc.

Moreover, the GT-MHR reactor features make it possible to start the reactor operation with one fuel cycle, and then to turn to another type of core fuel load without changes of main reactor elements. For example, after completion of WGPu disposition mission at GT-MHR operation with the use of WGPu fuel without fertile materials, it could be foreseen to continue reactor operation with the use of fuel on the basis of U with ~14 % enrichment.

Comparisons of different fuel cycles were carried out with respect to following characteristics: spent fuel burnup, reactivity change during one partial cycle of fuel burnup, consumption of fissile isotopes per unit of produced energy, power distribution, reactivity effects, control rods efficiency. These comparisons showed that the considered fuel options provide three-year core lifetime (with account for the load factor ~0,8) without change of core design, sizes and design of fuel blocks, number and design of control rods.

It is estimated that the GT-MHR design has good perspectives of commercial use with the loading of the active core by different fuels (low enriched up to 14 % uranium, high enriched uranium with thorium, pure weapons or civil plutonium, MOX fuel).

Acknowledgements

The authors wish to thank their colleagues in RRC Kurchatov Institute and OKB Mechanical Engineering for contributions in elaboration of basic models for neutron-physical calculations and helpful comments for preparation of this paper.

References

1) A.I. Kiryushin, N.N. Ponomarev-Stepnoy et al., "The Project of the GT-MHR High-Temperature Helium Reactor with Gas Turbine", Nucl. Eng. Des., 173, 119-129 (1997).
2) N. Kodochigov, Yu. Sukharev, E. Marova, N. Ponomarev-Stepnoy, E. Glushkov, P. Fomichenko, "Neutronic Features of the GT-MHR Reactor," Nucl. Eng. Des., 2795, 1-11 (2003).
3) J.R. Askew, "A General Description of the Lattice Code WIMS," JBWES, (1966).
4) M. Segev, "An Equivalence Relation for Doubly Heterogeneous Lattice," Nucl. Sci. Eng., 81, 151-160 (1982).
5) V.F. Boyarinov, "Investigations of some models and approximations applied at calculations of GT-MHR fuel assemblies," Proc Int. Conf. M&C2003 "Nuclear Mathematical and Computational Sciences: A Century in Review, A Century Anew", April 6-11, 2003, Gatlinburg, Tennessee (2003).
6) L.N. Yaroslavtseva, "JAR: Complex of Codes for Calculation of Neutron-Physical Characteristics of Nuclear Reactors", VANT, FTYaR series, v 8 (37), p 41, (1983).
7) L.N. Yaroslavtseva, P.A. Fomichenko, A.V. Vasiliev et al., "Methods and algorithms of neutron-physical calculations of nuclear reactors in the JARFR complex of codes", Moscow, Report RRC "Kurchatov Institute", No 90/1-4-95 (1995).
8) A.V. Vasiliev, P.N. Alekseev, P.A. Fomichenko, L.N. Yaroslavtseva, "Development and Evaluation of an Effective Nodal Diffusion Method for Perturbation Theory," Proc. of Annual Meeting on Nuclear Technology-97, Aachen, Germany, May 13-15, 1997, p. 49. (1997).