GT-MHR international project of high-temperature helium cooled reactor with direct gas-turbine power conversion cycle

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Abstract. The international project of gas-turbine modular helium-cooled reactor (GT-MHR) presented in the report is a realization of high-temperature technology and is based on the experience with helium-cooled reactors with ceramic fuel particles and on innovative solutions concerning power conversion system with closed gas-turbine cycle and turbomachine with electromagnetic bearings. The international GT-MHR Project is currently being jointly developed by USA and Russia for disposition of excessive weapon-grade plutonium. For commercial electricity generation, the reactor will use uranium fuel. The GT-MHR combines a gas-cooled modular helium reactor (MHR) and a highly efficient integrated gas-turbine power conversion system (Brayton cycle) with expected cycle efficiency up to 48%. The reactor and power conversion unit are located in an underground concrete silo.

The GT-MHR technical characteristics and design features assure:
- high level of passive safety that completely prevents core melting in accidents with any scenario, including full loss of inert coolant;
- low level of thermal and radiation impact to the environment;
- capability to use various fuels in the core (e.g. low-enriched uranium, mixed uranium-thorium and uranium-plutonium fuel, or plutonium fuel) without modifying the core design;
- meeting the non-proliferation requirements through technology and properties of ceramic fuel particles;
- capability to achieve coolant temperatures of up to 1000 °C, which is needed for various industrial processes;
- high efficiency of electricity generation.

A whole complex of research and development activities is being carried out by RRC KI, OKBM, VNIINM, “Lutch”, and other Russian organizations in order to support key design solutions, primarily on fuel, turbomachine with electromagnetic bearings, structural materials, vessels and computer codes.

At present, the GT-MHR capability to generate high-grade heat at temperatures up to 1000 °C makes it the only existing nuclear technology that can assure supply of high-temperature heat for thermal processes used for production of hydrogen (including hydrogen production from water), synthetic fuels, fertilizers, etc.

1 HTGR development experience

First success of the HTGR technology with helium coolant is achieved in the middle of 60-s: experimental reactors of small power Dragon (England), Peach - Bottom (USA), AVR (Germany) were created (see Table 1). First two reactors have operated more than 10 years, the latter – more than 20 years, thus showing reliable operation, high availability and safety, low radioactive contamination of the primary circuit, stability in transients, capability to obtain helium temperature to 950 °C for a long time.
In the second half of 70-s prototype power reactors FSV (USA) and THTR-300 (Germany) of electric power ~ 300 MW were started. These reactors had been operated till the second half of 80-s.

In 1998 Japan started HTTR experimental reactor where their application technologies are investigated to obtain high-grade heat, supply heat for industrial purposes and test the power generation unit in gas turbine cycle. By the present moment reactor outlet temperature 950 °C is achieved.

In 2003 China started operation of HTR-10 experimental reactor where both reactor technologies and possibilities of their future commercial application will be studied.

In USA the program of creating high-temperature reactor as heat source for hydrogen production from water has been started again.

Table 1 HTGR Plants Constructed and Operated

<table>
<thead>
<tr>
<th>Feature</th>
<th>Dragon (UK)</th>
<th>Peach Bottom (USA)</th>
<th>AVR (Germany)</th>
<th>Fort St. Vrain (USA)</th>
<th>THTR (Germany)</th>
<th>HTTR (Japan)</th>
<th>HTR-10 (China)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MWt/MWe)</td>
<td>20/-115/40</td>
<td>46/15</td>
<td>842/330</td>
<td>750/300</td>
<td>30/-10/-</td>
<td>10/-</td>
<td></td>
</tr>
<tr>
<td>Fuel Elements</td>
<td>Cylindrical</td>
<td>Cylindrical</td>
<td>Spherical</td>
<td>Hexagonal</td>
<td>Spherical</td>
<td>Hexagonal</td>
<td>Spherical</td>
</tr>
<tr>
<td>He Temp (In/Out°C)</td>
<td>350/750</td>
<td>270/950</td>
<td>400/775</td>
<td>270/750</td>
<td>395/950</td>
<td>300/900</td>
<td></td>
</tr>
<tr>
<td>He Press (Bar)</td>
<td>20</td>
<td>11</td>
<td>48</td>
<td>40</td>
<td>40</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

In Russia HTGR activities were started in 60-s by development of ABTU-15 and ABTUs-50 plans design (VNIIAM, RRC KI in Moscow) /2/. The latter was designed to generate electricity and for radiation modification of materials. In OKBM (Nizhny Novgorod) starting from 1973 the following designs of pilot-industrial plants have been developed: VG-400 of reactor thermal power 1000 MW, VGM with modular reactor - 200 MW, which represented basic designs when developing industrial plants of various power purpose: VG-400T – for process heat production; VG-400GT – for electricity production in gas turbine cycle; VGM-P – for heat supply to oil refineries (see Table 2).

Table 2 – Main characteristics of HTGR RP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VGR-50</th>
<th>VG-400</th>
<th>VG-400GT</th>
<th>VG-400T</th>
<th>VGM</th>
<th>VGM-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrangement</td>
<td>module</td>
<td>integral</td>
<td>integral</td>
<td>integral</td>
<td>module</td>
<td>module</td>
</tr>
<tr>
<td>Thermal power, MW</td>
<td>136</td>
<td>1060</td>
<td>1000</td>
<td>1000</td>
<td>200</td>
<td>215</td>
</tr>
<tr>
<td>Electric power, MW</td>
<td>50</td>
<td>300</td>
<td>383</td>
<td>-</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Helium temperature, °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core inlet</td>
<td>296</td>
<td>350</td>
<td>536</td>
<td>400</td>
<td>300</td>
<td>750...950</td>
</tr>
<tr>
<td>core outlet</td>
<td>810</td>
<td>950</td>
<td>950</td>
<td>950</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>Helium pressure, MPa</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>4.9</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Core type</td>
<td>pebble bed with spherical fuel elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The gas-turbine-modular helium reactor (GT-MHR) concept is based on the experience in the area of helium-cooled reactors with prismatic fuel assemblies (FA) and ceramic fuel particles and on innovations in the power conversion system with the closed gas-turbine cycle and turbomachine with electromagnetic bearings (EMB).

The international GT-MHR project was started in 1995 by Minatom of Russia and General Atomics company. Later, Framatome and Fuji Electric also joined the project. In 1997, the GT-MHR Conceptual Design was developed. In 1999 it successfully passed the expert review in Russia and in USA, as well as the international expert review by independent experts representing USA, Japan, Germany, France and Russia. The review proved that there are no insurmountable obstacles to project realization.

Research carried out by the project participants at the Conceptual Design stage proved that it is possible to achieve deep burnup of weapon-grade plutonium in the GT-MHR, with subsequent burial of spent fuel without additional processing. Therefore, the GT-MHR project was suggested as additional means to solve this task, and the GT-MHR Preliminary Design was developed under the “Agreement Between the Government of the United States of America and the Government of the Russian Federation on Scientific and Technical Cooperation in the Management of Plutonium that has Been Withdrawn from Nuclear Military Programs” dated July 24, 1998. The project was financed on the parity basis by the US DOE and Minatom of Russia. Some activities on the power conversion unit (PCU) were supported by EPRI, as well as by the European Union and Japan via ISTC. Preliminary Design development was completed in the beginning of 2002 [1].

Foreign participants of the project (GA, ORNL, EPRI) contributed to the project by developing the plant concept, transferring a number of technologies, computer codes, equipment deliverables, sharing experience in operation of Fort Saint Vrain reactor, etc.

In 2002, the Preliminary Design was reviewed by Minatom of Russia and approved as an innovative area in reactor technologies. International cooperation allows employment of the existing experience and reduction of technical risks and design development costs.

In Russia, the GT-MHR project is included into the Federal target programme “The Energy Efficient Economics” and into “Russian strategy for the development of nuclear power for the first half of the 21st century” approved by the Government of the Russian Federation as a field of development of new-generation reactor plants assuring high safety and effective generation of electric energy and process heat.

The GT-MHR project coordinating committee decided that before Final Design development starts, all efforts and funds should be concentrated on development work related to fuel, helium turbomachine with EMB, validation of physical codes and fission products transport codes, and their experimental verification.
3 General description of the GT-MHR

The GT-MHR project concept is based on modular helium reactors, high-efficiency gas turbines, EMB, high-efficiency compact heat exchangers. The reactor module consists of two interconnected parts: modular high-temperature reactor and power conversion unit (PCU) with direct closed gas-turbine cycle (Fig. 1).

**FIG. 1. GT-MHR reactor unit**
1 – generator; 2 – recuperator; 3 – turbocompressor; 4 – intercooler; 5 – precooler; 6 – control rod drive mechanism assembly; 7 – core; 8 – vessel system; 9 – reactor shutdown cooling system

The gas-turbine energy conversion cycle with a helium turbomachine, recuperator and intermediate cooling assures thermal efficiency at the level of 48 %. Altogether, use of direct closed gas-turbine cycle and modular reactor conditions reduction of capital costs for construction, operation, and maintenance owing to simplification of electricity generation cycle and reduction of the number of safety systems. Successful realization of these advantages depends on actual technical solutions. The GT-MHR flow diagram is given in Fig. 2.

Apart from higher efficiency of electricity generation the NPP with GT-MHR RP has enhanced potential thermal-dynamic and design capabilities of discharged heat application. Discharged heat application for district heating together with converted heat in the cycle allows practically total use of heat from the reactor (heat application coefficient ~ 99 %) without any design changes in the PCU. At heat and power co-generation mode the plant electric power will amount to 191 MW, thermal power removed by heating system water 400 MW.
Main parameters of the GT-MHR are given in Table 3.

Table 3 – Main design parameters of the GT-MHR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Plant power:</td>
<td></td>
</tr>
<tr>
<td>- thermal, MW</td>
<td>600</td>
</tr>
<tr>
<td>- electric, in the electric power generation mode, MW</td>
<td>287.5</td>
</tr>
<tr>
<td>- electric, in heat supply mode, MW</td>
<td>191</td>
</tr>
<tr>
<td>2 Annual energy output</td>
<td></td>
</tr>
<tr>
<td>- in the mode of electricity generation, GW·h</td>
<td>2150</td>
</tr>
<tr>
<td>- in the mode of electricity/ heat generation, GW·h / Gcal</td>
<td>1500/2200</td>
</tr>
<tr>
<td>3 Efficiency of the power conversion system</td>
<td>~ 48</td>
</tr>
<tr>
<td>4 Helium temperature at the core inlet/outlet, °C</td>
<td>490/850</td>
</tr>
<tr>
<td>5 Pressure at the core inlet, °C</td>
<td>7.15</td>
</tr>
<tr>
<td>6 Helium flowrate in the core, kg/s</td>
<td>318.1</td>
</tr>
<tr>
<td>7 Total compression ratio in the cycle</td>
<td>2.86</td>
</tr>
<tr>
<td>8 Core power density, MW/m³</td>
<td>6.5</td>
</tr>
<tr>
<td>9 Average Pu fuel burnup, MW·day/kg</td>
<td>640</td>
</tr>
<tr>
<td>10 Fuel life, days</td>
<td>750</td>
</tr>
<tr>
<td>11 Design service life of main equipment, years</td>
<td>60</td>
</tr>
</tbody>
</table>
The reactor with the PCU and the related primary circuit systems are arranged in an underground reactor building (Fig. 3).

The reactor includes an annular core consisting of 1020 FA. The FA are similar to those of the FSV reactor.

The reactor vessel lower part houses the reactor shutdown cooling system (SCS). SCS is not a safety system.

The power conversion system is arranged within the PCU vessel and includes turbomachine, recuperator, and water-cooled precooler and intercooler. The single-shaft turbomachine with full electromagnetic suspension consists of generator, gas turbine, and two compressor sections.

The reactor vessel is surrounded by the surface cooler of the passive reactor cavity cooling system (RCCS). RCCS assures removal of heat from the reactor in all accidents, including accidents with full loss of primary coolant.

### 4 Safety

Main target of new-generation reactor plants should be guaranteed prevention of serious accidents with radioactive products release into the environment. It may be achieved only if the reactor meets the inherent safety requirements. In the GT-MHR this target is reached owing to physical characteristics of the core, and to the following technical solution:

1) use of small fuel particles (200 μm in diameter) with multi-layer coating of pyrolytic carbon and silicon carbide;

2) negative feedback between the core temperature and reactor power, which leads to reactor self-shutdown in case of emergencies associated with fuel temperature increase;

3) core design characteristics (annular geometry, low specific capacity, large height-over-diameter ratio), which allows decay heat removal via the reactor vessel surface and further to
the ultimate heat sink (atmospheric air) by natural mechanisms: radiation, heat conductivity, and convection;
4) use of graphite and carbon-carbon composite materials (CCCM) as the core structural materials; together with the passive decay heat removal system, it brings about the concept of a core that does not melt in any accident, including beyond-design-basis ones.

At the Preliminary Design stage, safety estimations were performed for normal operation and for accidents.
Main assumptions adopted during analysis of above accidents:
- low-pressure containment (confinement);
- controllable release of the coolant via the stack during depressurization;
- directed release of activity via filters with subsequent fuel heating from initial temperatures to <1600°C.
Population radiation doses during normal operation and in accidents resulting from the estimation are given in Table 4.

<table>
<thead>
<tr>
<th>Reactor plant condition</th>
<th>Regulatory documentation requirement, mSv/an [3, 4]</th>
<th>Results of analysis, mSv/an</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation</td>
<td>≤ 2.10^{-2}</td>
<td>2.10^{3}</td>
</tr>
<tr>
<td>Design-basis accident with CPS standpipe rupture</td>
<td>≤ 5 on the border of the restricted area</td>
<td>0.4</td>
</tr>
<tr>
<td>Beyond-design-basis accident with CPS standpipe rupture and failure of emergency protection system actuation</td>
<td>≤ 5 on the border of protection measures planning area</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The safety estimation results show the following:
- allowable level of fuel temperatures (1600 °C) is not exceeded in any accident, including those with failures of all active means of reactor shutdown and cooling (see Figure 4);
- in case of accidents with the worst radiological consequences, evacuation of the population is not required;
- even if all heat removal systems, including RCCS, fail to actuate, there is a considerable time margin (not less than 50 hours from the accident beginning) for the personnel to undertake timely measures to prevent fuel temperature increase above the design limit.
Analyses of the GT-MHR core with various fuel types proved the following:
1) capability to vary fuel inventory type, weight and enrichment;
2) flexible physical characteristics of the core that has an assigned power density and fixed geometrical dimensions.

This permits to start the reactor with one fuel and then change for another.

Comparison of various fuel types in the GT-MHR, which can use various fuel as initial (weapon-grade plutonium, low-enriched (< 20%) uranium, MOX fuel based on weapon-grade and reactor plutonium diluted with uranium or thorium dioxide), proved that it is possible to use these types of fuel without introducing modifications to the core design (arrangement and number of control and protection system rods, dimensions of the core and reflectors).

The GT-MHR fuel cycle concept is based on deep burnup of initially loaded fissionable material and burial of fuel blocks unloaded from the reactor without additional reprocessing. A characteristic feature is low volumetric fraction of fuel in the fuel compact (fuel particles content ~ 13%) and in the fuel block. The quality of the fuel unloaded from the reactor is characterized by the fact that the quantity of Pu-240 isotope, which is a strong absorber, in the unloaded Pu amounts to not less than 30% and the quantity of fissionable isotopes is comparable to the quantity of absorber, even if weapon-grade Pu is used.

In terms of non-proliferation provision it should be noted that in the present time there is no large-scale industrial technology that could be used to reprocess HTGR fuel with ceramic coating.

Thus, taking into account isotopic composition of the unloaded fuel and the technological aspect of fuel reprocessing, it is quite impossible to produce nuclear weapons using the fuel unloaded from the GT-MHR.
6 Program of experiments

Currently the international team of designers focused on developmental work on key project directions (technology demonstration program) to provide the possibility to develop a full-scale Final Design.

The target of the technology demonstration program is to validate key design solutions, mainly concerning fuel, turbomachine, structural materials, vessels and computer codes [5].

6.1 Fuel

Technological research on creation of fuel for the GT-MHR is carried out in VNIINM, SIA Lutch, and RRC Kurchatov Institute. General Atomics and ORNL transfer documentation and share the existing experience in fuel development. At the GT-MHR Conceptual and Preliminary Design stages, a laboratory technology was created for fabrication of fuel particles, coating and manufacture of fuel kernels. A test batch of uranium and plutonium kernels was fabricated. Now, the bench-scale facility (BSF) is being constructed to master fuel particle and compact fabrication.

Experimental research program on fuel includes:
- creation of BSF to master Pu fuel fabrication technology;
- fabrication of experimental uranium and plutonium fuel for pre-reactor, reactor and post-reactor testing;
- fuel reactor tests to confirm its quality;
- confirmation of fuel characteristics with deep burnup;
- prepare and perform research on fission products release and transport in the primary circuit and deposition on the equipment of helium circulation path.

At present, installation activities on BSF protective boxes, equipment and systems are nearing their completion. Preparations are being made for fabrication of main process equipment: coater and compact-producing equipment. In the end of 2004 it is planned to fabricate the first batch of experimental uranium fuel at BSF. Simultaneously, preparations are being made for reactor tests (using RBT and SM-3 reactors in NIIAR) and for creation of post-reactor test facilities.

6.2 Power conversion unit

The main PCU components are: helium turbomachine, plate-type recuperator, precooler, and intercooler.

Main design features of turbomachine:
- vertical one-shaft arrangement;
- full electromagnetic suspension;
- catcher bearings operating in helium;
- helium-cooled generator;
- sliding seals of the turbocompressor stator that limit leaks between cavities with different pressure.

The main target of the experimental research program on PCU is experimental validation of operability of the turbocompressor with EMB, of the recuperator, etc., as well as validation of their design characteristics.

The following experimental work has been completed by the present moment:
- tests of turbocompressor stator seal mockup in air;
- studies of the rotor vertical model and EMB model at the small-scale test facility, when passing a resonance frequency;
- study of characteristics of EMB with control system;
- tests of various EMB sensor types;
- fabrication of the test facility for TM rotor model scaled 1:3 on electromagnetic suspension has been commenced for further tests of various rotor designs and tests of control system;
- membrane coupling model fabrication has been commenced;
- design development of the test facility for full-scale turbocompressor tests is now in progress.

The compact high-efficiency plate-type recuperator design was developed within the framework of the GT-MHR project.

For support of the recuperator design, experimental studies of the fabrication technology for recuperator heat exchange surface elements with compactness of 1500 m²/m³ was performed. Besides, a technological mockup of a recuperator element and a full-scale recuperator heat exchange element were fabricated.

The recuperator element was subject to comprehensive tests in OKBM at the air and helium test facilities under the operating temperature.

6.3 Materials

Main reactor components use structural materials earlier developed for Russian HTGR designs.

Experimental program on structural materials includes:
• technology development and tests of reactor graphite based on pitch coke; mastering of the technology for structural element fabrication of this graphite;
• technology development, fabrication and tests of CCCM to be used for fabrication of absorber rod elements and in-vessel structure elements;
• tests and certification of materials for turbine and reactor;
• tests of the material for the vessel system, mastering of the fabrication technology, material certification.

7 Possible role of the GT-MHR in nuclear power

- Possible role of the GT-MHR in nuclear power results from its characteristics, which allow expansion of nuclear power application. These characteristics include:
- capability of obtaining coolant temperatures of up to 1000°C at the core outlet;
- high safety that entirely prevents core meltdown without the need for operator actions;
- low level of thermal and radiological releases into the environment;
- flexibility of the fuel cycle, use of various fuel types without modifying the reactor design;

The above-mentioned characteristics allow GT-MHR application for high-efficiency generation of electric energy in the closed gas-turbine cycle. Waste heat can be used for district heating.

GT-MHR reactors can generate process heat that can be used for production of hydrogen from water, for power-intensive engineering processes in chemistry, oil refinery, production of synthetic liquid fuel from coal, etc.

Implementation of these HTGR properties expands possibilities of nuclear power application not only for traditional use in power industry and district heating but also for engine fuel production, in particular from water.
8 MHR reactor – base for hydrogen production

One of most important directions of power industry technical progress, which will facilitate stable development of peaceful community is to master hydrogen application in power industry, produced from water using pure source of primary energy such as nuclear energy. Improved nuclear plants will give energy for hydrogen production and water desalination, hydrogen will provide consumers with energy in the most suitable form. Mastering of this technology will reduce application of carbon fuel for power purposes and influence of its burnup on environment and keep it for non-power application.

Nowadays the main industrially mastered and investigated technologies of hydrogen production for the first stage of their implementation using power from HTGR are water electrolysis and methane vapor conversion, for further stages – for example, thermal-chemical water decomposition and high-temperature steam electrolysis. Having considered specific features of hydrogen production processes it can be concluded that main requirements for the source of high-temperature heat are provision of coolants at temperature to 1000°C and pressure to 5 MPa, and electricity produced with high effectiveness.

HTGR is a single nuclear technology which can supply high-temperature heat to hydrogen production processes.

9 Conclusions

Design and experimental work completed by the present moment confirm that the project meets all requirements to new-generation reactor plants for full-scale nuclear power.
- Reactor technology with the modular helium reactor GT-MHR is characterized by high safety, which prevents fuel meltdown without the need for NPP personnel actions.
- The GT-MHR can be successfully applied in nuclear power for generation of electric energy and for technological purposes, including production of hydrogen from water.
- Minimal amount of equipment and safety systems conditions reduction of capital and operation costs and low cost of generated electric energy.
- The GT-MHR is a good example of international cooperation in the field on innovative nuclear technology development.

Literature