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GT-MHR AS ECONOMICAL HIGHLY EFFICIENT INHERENTLY SAFE MODULAR GAS COOLED REACTOR FOR ELECTRIC POWER GENERATION

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Abstract

The Gas Turbine Modular Helium Reactor (GT-MHR) project is a joint effort of organisations in the Russian Federation co-ordinated by the the Ministry on Atomic Energy (MINATOM), General Atomics in the United States, Framatome in France, and Fuji Electric in Japan. This paper describes the structure, objectives and history of the GT-MHR project, as well as the plant design, including plant layout, components and fuel. It summarises the results of evaluations of the design safety characteristics and economics, for both a plutonium fueled single module and a uranium fueled four module plant. The plans and anticipated structure for an international project to construct the plant are also summarised.

INTRODUCTION

The GT-MHR project is a joint elaboration of organizations belonging to Russian Ministry on Atomic Energy (MINATOM), and companies of General Atomics, Framatome and Fuji Electric that have experience and knowledge in areas of HTGR technology and fabrication of large-size components. An interest to this project is called due to its economic effectiveness, inherent safety features, production of minimum amount of long-lived radioactive wastes, minimum heat environment impact and possibility to be applied in different configurations for both electricity and high potential heat generation.

International cooperation in development of components and systems and possibility to vary total power of module-composed plant and choose options of generated energy use (electricity, technology heat for chemistry, metallurgy, oil refining, synthetic and hydrogen fuel production, etc.) should decrease technical and economic risk of elaboration. Replacement of fossil burn to nuclear energy source should make favourable ecological effect for environment and towns.

All that might be applied both to the reactor itself with its inherent safety properties ensuring prevention of impermissible releases of radiotoxic substances and to the fuel cycle. Application of ceramic materials in HTGR fuel elements ensures minimum relative generation of long-lived radioactive wastes. These materials are resistant against a corrosion under final deployment conditions. Therefore, safety of radwaste storing is ensured for the very long period of time independently of final deployment cask integrity.

A perfection in such complicated engineering system as GT-MHR is, might be achieved only as a result of a large volume of work on stages of designing, researches and engineering development

1. GT-MHR PROJECT

The GT-MHR project development was started in 1995 accordingly to the Agreement on designing and development of the GT-MHR plant and its further construction in Russia, signed by MINATOM and General Atomics. In 1996 the Framatome company joined the Agreement, and in 1997 the Fuji Electric company joined too. In 1997 the GT-MHR Conceptual Design had been completed.

Most engineering decisions accepted in the GT-MHR are based on the ones mastered in construction and exploitation of Peach-Bottom and Fort St. Vrain reactors, and on thirty-year Russian experience of HTGR designing (the VG-400 reactor plant of loop configuration and the modular pebble bed core reactors VGR-50 and VGM).

The GT-MHR program aims a creation of the prototype for commercial nuclear power plants on the base of the modular helium-cooled reactor and the direct cycle gas turbine, that are competitive to existing energy sources, including LWRs and fossil fuel plants, in criteria of safe, reliability, manoeuverability and economy.

The GT-MHR high economic indices ensuring its competitiveness are caused by the following four main factors accepted in the concept of the project:

- modular arrangement;
- inherent safety;
- direct closed gas turbine cycle with ensuring the efficiency about 48%;
- use of the advanced modern technologies such as the high efficient gas turbine, electromagnetic bearings operating without friction, plate and finned tube high effiective compact heat exchangers.

You can see the GT-MHR major parameters in the **Table 1.**

The GT-MHR reactor is designed taking into account use of the plutonium fuel based on the WGPu oxide. The degree of Pu burnup is accepted sufficiently high (up to 90% of initial loaded Pu-239) to eliminate both technical and economic expediency of its conversion and repeated use in the reactor and make impossible its military employment.

The design of the prototype nuclear power plant (NPP) with one GT-MHR Pu loaded modular reactor is destined to be arranged on the Siberian Chemical Combine (SCC) site at the town of Seversk.

Commercial NPPs are supposed as U loaded four-module (4x600 MWt) ones.

The GT-MHR reactor module layout is shown in the **Figure 1.**

The prototype GT-MHR NPP has one reactor module placed within the underground containment. The components of the reactor module primary circuit are arranged within the pressure vessel system consisting of the reactor vessel and the Power Conversion System vessel connected by the cross vessel.

The reactor vessel is surrounded by the surface cooler of the Reactor Cavity Cooling System. This passive activity system ensures cooling of the cavity concrete and heat removal out of the reactor vessel under natural circulation both in normal and emergency operating modes.

Looking on the **Figure 2,** you can see the layout of the GT-MHR reactor module components.

TABLE 1

GT-MHR MAJOR TECHNICAL CHARACTERISTICS

• Thermal power, MW	600
• Electricity generation efficiency (net), %	up to 47.6
• Helium temperature (core inlet / outlet), °C	490 / 850
• Core configuration	annular core consisting of prismatic graphite blocks
• Fuel	Plutonium oxide
• Fuel type	coated particles
• Initial Plutonium load, kg	750
• Pu-239 destruction level, %	~ 90
• Annual Plutonium consumption, kg per year	250
• Quantity of WGPu processed for reactor lifetime (60 years), t	15

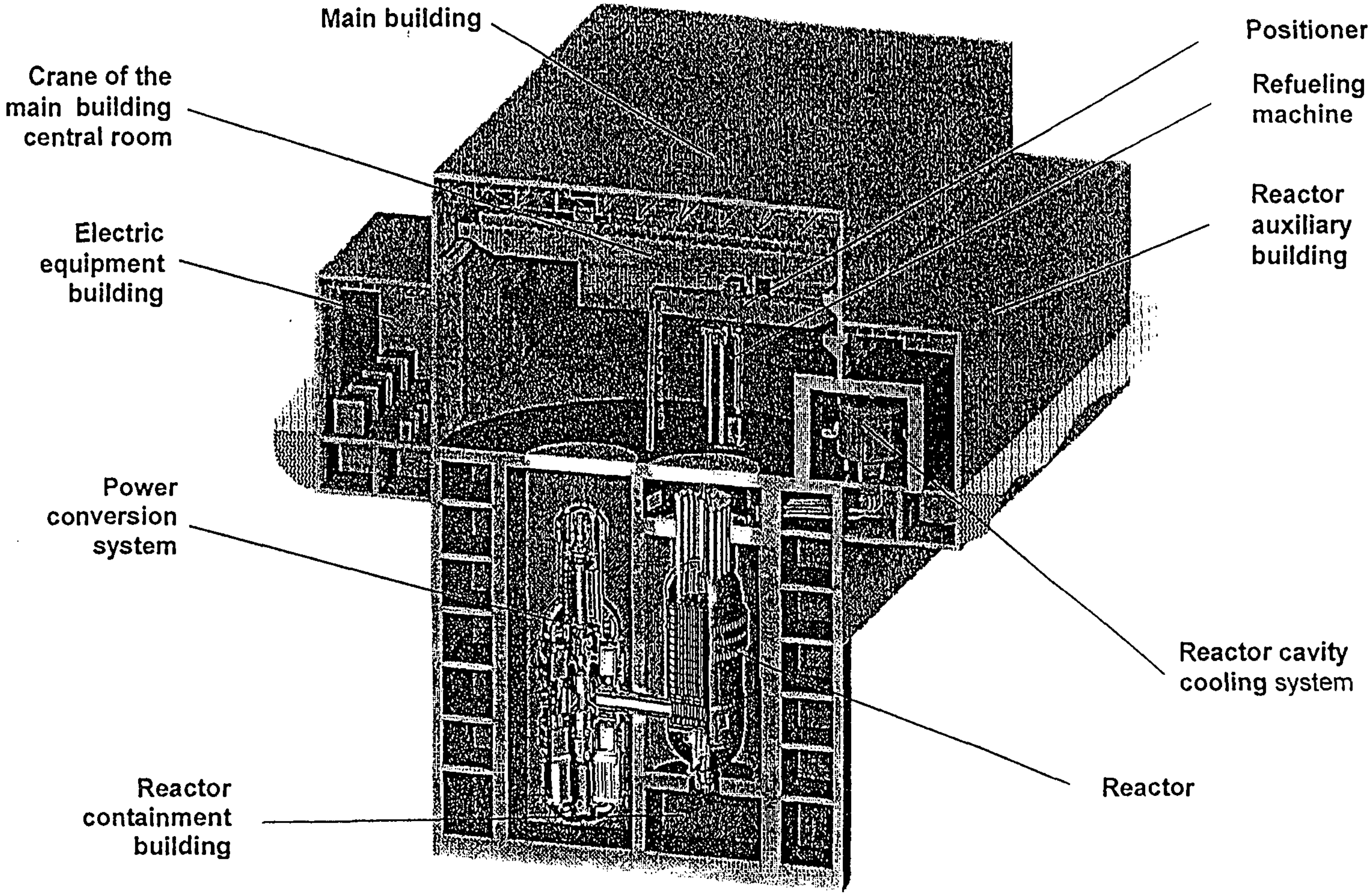


FIG. 1. GT-MHR reactor module arrangement in reactor building.

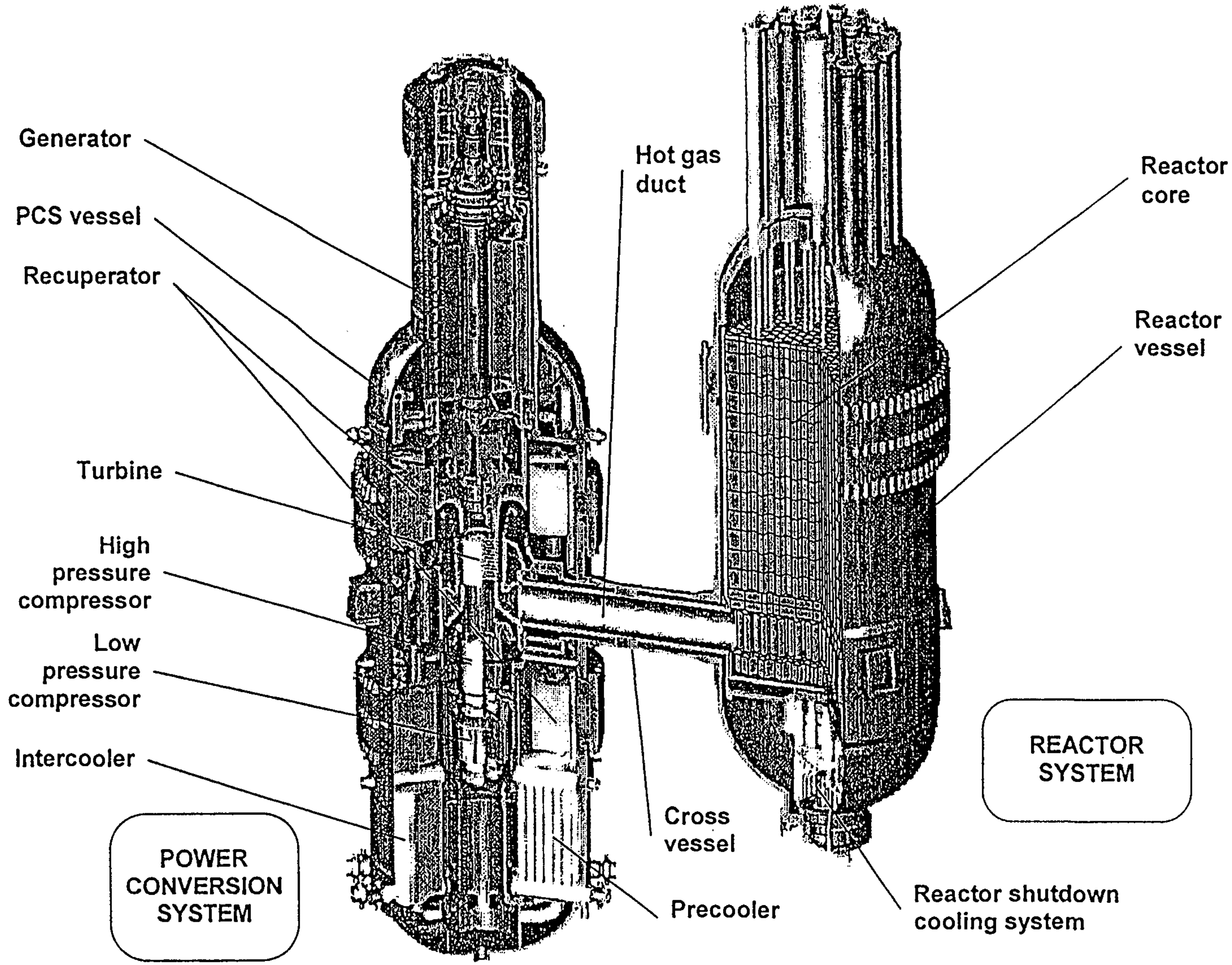


FIG. 2. GT-MHR reactor module layout.

The reactor has the annular core assembled of prismatic graphite blocks. The blocks have channels where fuel elements are placed. In the bottom part of the reactor vessel the Reactor Shutdown Cooling System is placed. This system ensures heat removal out of the shutdown reactor core by active means, including modes of core reloading, PCS maintenance and also accidents within the design basis.

The Power Conversion System (PCS) is placed within the pressure vessel, connected with the reactor vessel by the cross vessel, and consists of the one-shaft vertical arranged turbomachine, recuperator, precooler, intercooler and internal gas ducts and supports. The turbomachine consists of gas turbine, electric generator, LP and HP compressors.

The primary circuit helium coolant leaves the reactor core and through the hot gas duct inside of the cross vessel comes to the turbine inlet. The turbine rotates directly the low pressure and high pressure compressors. From the turbine outlet the coolant passes through the recuperator aiming to return the maximum possible amount of heat to the cycle. Then it comes into the precooler for heat removal to sink.

Cooled in the precooler helium comes consecutively to the LP compressor, intercooler and HP compressor. Compressed coolant is heated in the recuperator, and then through the annular gap between the hot gas duct and cross vessel wall moves into the reactor vessel. Through channels of reactor internals it is delivered to the reactor core and, passing through the core from top to bottom, closes the circuit.

The GT-MHR fuel design shown in the **Figure 3** is as fuel micro-particles covered by multi-layer coating of pyrolitic carbon and silicon carbide. The particles are dispersed within a cylindrical graphite matrix (compact) of 12.5 mm diameter and 50 mm length. Compacts are inserted into fuel channels of prismatic graphite fuel blocks.

The fuel micro-particles are plutonium oxide-made spherical kernels of 0.2 mm diameter with coatings. These coatings prevent solid and gaseous fission products release in the process of the reactor exploitation.

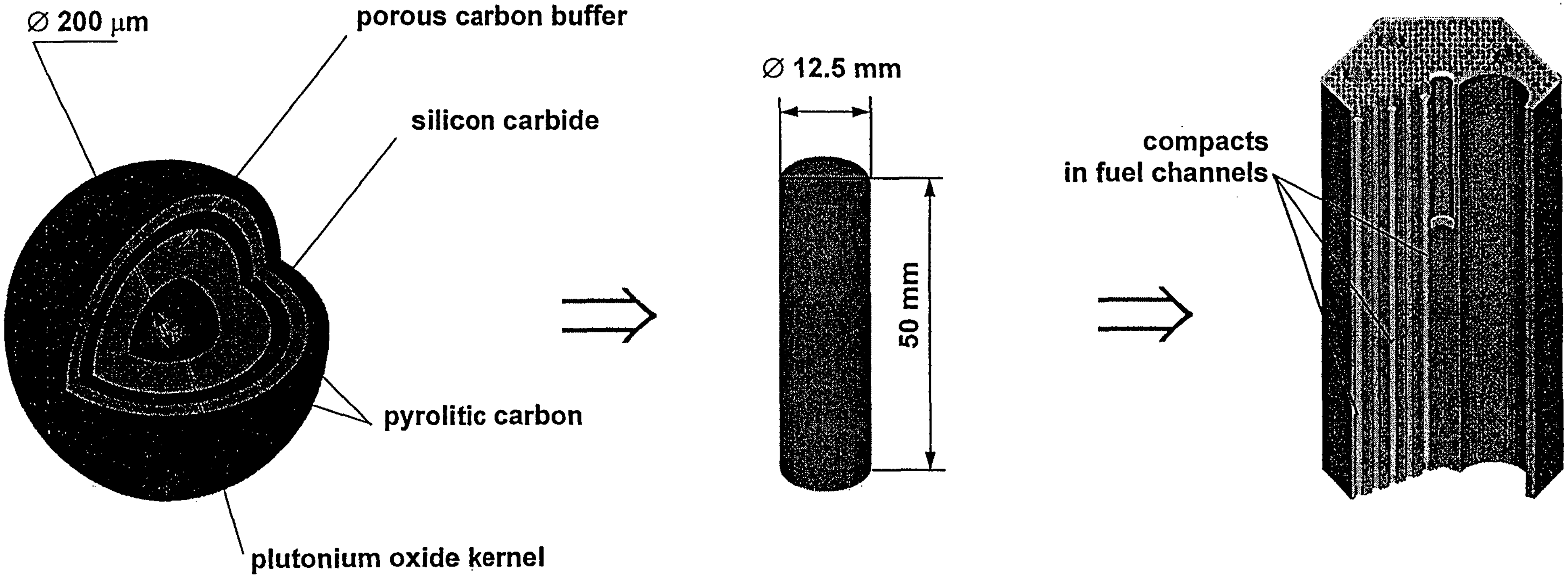
Average content of plutonium is 0.24 grams per a compact.

2. MODULAR ARRANGEMENT

All NPP projects being developed in last some years are based on the modular arrangement concept independently of the reactor type. The modular arrangement gives nice prospects for improvement of the NPP economic indices, and the GT-MHR design has maximally soaked up all merits of this concept.

The accepted configuration of the reactor island (underground location of reactors and the surface common services building), compact layout of the reactor plant main equipment, including the turbine generator, inside of the high pressure vessel unit, and also the vertical arrangement of the turbine shaft make possible to decrease building volumes and reduce construction time. Time and expenditures for designing of serial plants become minimal. The possibility arises to use some systems and buildings for servicing of several reactor modules. Thus, in the design of the GT-MHR commercial four-module plant one reloading system, two interim spent fuel storage facilities and one services building operate four reactor modules. Unification of components and serial production enable wide use of the international cooperation resources in manufacturing, reduction of manufacturing time and cost by simplification of the license procedure and the learning effect.

GT-MHR FUEL ASSEMBLY COMPONENTS



FUEL PARTICLE

FUEL COMPACT

FUEL ASSEMBLY

FIG. 3.

3. SAFETY

In the GT-MHR design the well-known HTGRs inherent safety characteristics, such as the inert coolant, the core made of graphite materials, the fuel as micro-particles with multi-layer protective coating are supplemented with especial technical decisions directed to ensuring of passive principle based safety. The release of impermissible large quantity of radionuclides out of the fuel is prevented significantly by ceramic coatings of fuel micro-particles that are planned for both normal and probable emergency operational modes.

The integrity of the coating of fuel micro-particles, as the safety barrier, is reached in emergency by elimination of excess of the maximum permissible fuel temperature of 1600 °C (the safe exploitation limit), that is ensured by the following factors:

- low core power density;
- high heat capacity of the graphite-made core and reactor internals;
- large maximum permissible fuel temperature margin (up to 200 °C);
- negative reactivity coefficient;
- core design decisions ensuring heat removal through the reactor vessel wall;
- existence of the effective passive system of emergency heat removal, that is the reactor cavity cooling system;
- limitation of air and water/steam potential impact on fuel microparticles in accidents.

These properties make the significant positively influence on the plant economic effectiveness. So it enables, on the one hand, to refuse some emergency operation systems, such as the emergency core cooling system or the emergency shutdown cooling system that exist at NPPs with LWRs, and, on the other hand, to combine the functions of normal and emergency operation in the same system. For instance, the normal operating cavity concrete cooling system is simultaneously the system of emergency heat removal.

Passive safety properties, design characteristics and the fuel design ensuring prevention of impermissible releases of radioactive substances, allows to refuse the containment construction for the U fuel variant, that amounts up to 7% of the module construction capital cost.

4. SINGLE-MODULE PROTOTYPE PLANT ECONOMICS

The GT-MHR plant technical and economic characteristics applied in estimation of the electricity production cost are shown in the **Table 2.**

The following assumptions were accepted for the estimation:

- the prototype single-module NPP is placed on the SCC site;
- design and engineering development costs on the GT-MHR equipment and fuel are included into the prototype single-module NPP cost;

TABLE 2

GT-MHR ECONOMIC CHARACTERISTICS

	Pu Fuel Single Module Prototype Plant	U Fuel Four Module Commercial Plant
• Power, MW(th) / MW(e)	600 / 293	2400 / 1172
• Annual electricity generation (K = 0.8), 10^6 kWh	2051	8204
• Annual electricity sale, 10^6 kWh	1999	7996
• Operational and Maintenance Staff, persons	230	493
• Plant Design and Engineering Development, $M	180	19
• Plant Capital Cost, $M	273	928
• Fuel Researchs and Engineering Development, $M	70	-
• Fuel Fabrication Capital Cost, $M	45	42
• TOTAL INVESTMENT, $M	568	1031
• POWER GENERATION PRIME COST, mills per kWh	22	17.6

- the fuel cost is accepted equal to its primary cost (without benefit and VAT) because the fuel production and the NPP are the subdivisions in the same enterprise SCC;
- the cost of SCC services for NPP (security, transport, etc.) not accounted in the operating and maintenance (O&M) cost are accounted in the clause "Site owner's expenses";

The composition of the annual exploitation cost is as follows:

- Fuel cost;
- Operating and maintenance cost;
- Capital cost;
- Site owner's (SCC) expenses;
- Decommissioning fund fees;
- Other funds fees quoted from the generation cost.

The prime cost of one kWh electricity generation estimated as 2.2 cent for the prototype Pu-loaded single-module NPP, and 1.76 cent for the commercial U-loaded four-module NPP.

The sale price of the electricity generated by existing energy plants on the SCC site is about 2 cents per kWh (data of July 1998). Thus, taking into account the fact that the prime cost was estimated under a conservative approach, we may say that even the single-module prototype plant repays investments in 60 years.

In the **Table 3** you can see estimated variants of the GT-MHR NPP waste heat utilization for heat supply. In this estimation the following assumptions were accepted:

- the existing heat networks at the site will be employed;
- the costs of modification of the existing heat networks and reactor module design are negligible in comparison with the NPP capital cost (might be included in the Contingency account)

In this conditions we may say about profitability of the GT-MHR prototype single-module NPP, that is a rather rare case in power engineering.

5. INTERNATIONAL COOPERATION

Until the recent time, owing to both objective and subjective reasons, HTGRs were out of the mainstream of the atomic power engineering development. The properties of these reactors had been demonstrated on the plants of AVR, DRAGON, Peach Bottom of the first generation, and then THTR-300 and FSV. But that time was not yet the HTGR time. These projects were too exotic for that period to be used word-wide commercially, and after Chernobyl accident that had influenced extremely negatively on the politicians' and the public relations to atomic energy at whole, these projects were stopped.

In nineties, in conditions of word-wide sudden quality progress in technologies, the idea of HTGRs attracted an attention to itself, and its main direction in development becomes the optimization of designs of modular low and medium power reactors, concentrating on the inherent safety, optimization of their power, maintainability, positive economic effect of serial fabrication, use of the most modern advanced

TABLE 3

VARIANTS OF GT-MHR SINGLE MODULE NPP WASTE HEAT UTILIZATION

	Nominal mode	Hot water supply	Heat supply
• Thermal power, MW	600	600	600
• Net electric power, MW	285	276	226
• Network circuit power, MW	-	314	364
• Annual heat sale volume, 10^3 Gcal	-	1884	2184
Sale price, cents per kWh / dollars per Gcal	2 / 0	2 / 6	2 / 6
• Annual average profit, \$ M per year	0	+ 11,3	+ 13,1
• Investment repaying period, years	60	50	43

technologies, such as high speed turbines, electromagnetic bearings, compact high effective recuperators, corrosion-protected fuel elements.

Many technical problems yet need to be solved in the HTGR development process. So, the technologies of manufacturing of pressure vessels and high effective heat exchangers have to be improved and mastered, the regulatory base must be developed for the HTGRs taking into account their inherent safety, etc.

The principal way for solution of so complicated problems must be an international cooperation giving conditions for consolidation of financial and engineering resources, efforts of various countries designers, developers, manufacturers of NPP components and IAEA, exchange of existing advanced technologies, optimal employment of existing industrial capacities.

The GT-MHR project has a status as the international one from the very beginning. Companies from four countries took part in its development on the Conceptual Design stage. Designing and development were fulfilled by Russian organizations, companies of USA, France and Japan granted their technologies existing in this area. At present, investigations are fulfilled on possibility and expediency of the GT-MHR components manufacturing on the Framatome company plants.

The next stage in the GT-MHR project will be the start of the Preliminary Design development in 1999 and continuation of WGPu-made fuel development. This work is expected to be financed by USA and Russia on a parity basis.

As the next step in the process of the GT-MHR creation, formation of the international technology company MHRCo is now on the stage of completion. This company functions will be collection, storage and capitalization of technologies and know-how in the HTGR area and sale of licenses for their employment.

In the further development of the project it is planned to form the company that will be occupied in construction of plants with GT-MHR-type reactors.