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MODULAR HTGR FOR COUNTRIES AND REGIONS WITH SMALL AND MEDIUM POWER NETWORKS

/Overview on the Basis of Materials of GTDC Conferences/

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Abstract

Based on materials of the GTDC symposia and workshops, the paper discusses the situation with power supply of countries and world regions with small and medium power networks. A proposal is made on the use of low power NPP for such regions. Characteristics of modular gas-turbine high temperature gas cooled reactors are presented, which can be used as a basis for development of environmentally friendly and safe NPP for power production.

1. Introduction

GTDC, with the focus on analysis and dissemination of advanced scientific and technology knowledge for establishment of equal opportunities all over the world, among other activities held a discussion of two subjects, closely associated with the topical area of the present conference.

These are:

1. "HTGR. Modular High Temperature Gas Cooled Reactors. Option for Future Nuclear Power Generation", GTDC Workshop, July 13-14, 1995, Vienna.
2. "Options for Electric Power Generation and Distribution in Developing Countries, GTDC Symposium, November 13-15, 1995, Trivandrum, Kerala, India.

Upon the GTDC's request, this paper presents basic results of these discussions.

2. Peculiarities of Power Supply of Countries and World Regions with Small and Medium Power Networks.

Development and integration of power networks is the natural avenue for integration of the power industry. At the same time, for economic reasons local power networks still exist and will remain in existence in many world regions, which networks operate independently, or only slightly linked to major centralized power networks.

About 1/3 of the Earth population, or 2 million people are presently out of access to centralized electric power sources.

In the most part of developing countries and in remote areas of industrially developed countries local networks cover consumers with the net load no more than 1000 MW(e). The use of high power NPP is not considered for such power networks.

In this connection, in terms of the wide spread in local conditions of power supply, options of using nuclear power sources in such power networks can be implemented based on nuclear power plants of power level from 5-10 MW(e) to 500-600 MW(e).

In Russia, the power production is integrated in an Electric Power Grid (EPG), which includes 69 regional power systems. Their integration provides for reliable power supply to consumers practically over the entire territory of Russia with spinning reserve of generating capacity reduced to 5-6%, allows to combine loads in different time zones, save fuel through optimization of supervisor load curves for all electric power plants, concentrate unit capacities of power-generating units. Automatics that serves the entire system allows maximum use of the electric power line capacity with minimum costs of electric power transmission.

Out of 202.5 GW (1993) of installed capacity of the Russian Federation electric power industry, including 11.2 GW of the Eastern power system that operates separately, only 0.92 GW fell on autonomously operating small power systems, regions and electric power plants. [3].

On the whole, the zone of decentralized power supply occupies about 2/3 of the Russian territory, and is characterized by its population of minority nations, whose life standard is tens of years behind that of communities in industrially developed countries. Along with this, it is precisely these areas where mineral deposits are located, which mining is hindered by the lack of necessary conditions and infrastructure - power supply, communications, transport.

The similar situation comes about in other countries of vast territory.

The regional nonuniformity in infrastructure development results in the fact that even in developing countries with relatively high level of the power industry development there exist power systems of relatively low power (up to 2-3 GW), for which low and medium power NPP can be considered.

In China, where centralized electric power supply is not available for 93 million people, such systems are located on the south and east of the country, with the installed capacity (for power systems) being 4.231 GW in Guangxi province, 4.083 in Yunan, 3.254 GW in Guizhou, 1.057 in Hainan, 2.865 GW in Xinjiang, and 0.177 GW in Xizang [4]. And the major part of installed capacity in such countries falls on hydroelectric plants and diesel plants that occupy the variable part of the load curve. In this case possible power of base-load power systems can be as high as 0.5-1.0 GW in such systems. Based on a demand for reserving and on possible pace of development of power systems with account for decommissioning of obsolete power units, unit power of power plants to be put in operation lies in the range between 50 and 150-200 MW.

Considerable irregularity in location of power systems is characteristic of Indonesia, where more than 2/3 of power sources fall on the Java region, with about 30 GW to be installed by the year 2011.

In India, even in the regions with NPP already put into operation, according to conditions of development of power systems, the share of base-load nuclear power units in the region power supply lies at a level of 5-10%. Analysis made by experts showed that the availability of such nuclear sources with electric power transmitted through 200 kV lines allows to ensure steady operation of a power unit and network even when electric power lines are shut off due to their overloading or failure in the vicinity of a NPP. In view of this, India focused on NPP with reactors of 235 and 500 MW electric power [5].

The key issue of advisability of commissioning a nuclear power unit in such countries consists in its competitiveness with locally available power sources, such as coal, natural gas, petroleum products. System studies carried out at KFA (Julich, Germany) indicated that, in view of high capital costs, nuclear power sources fall into an optimum plan when economic conditions are characterized by a relatively low discounting rate. Thus, for example, at a discounting rate of 6% in Indonesia the optimum plan for the period of 2004-2011 includes NPP with the combined power of about 11 GW, and at the rate of 10% NPP do not get into the plan [6].

Power supply of many countries and individual world regions with small and medium power networks is accomplished, as a rule, through the use of organic fuel. Thus, foe example, capacities in the remote regions of Russia are mostly based on the use of diesel fuel.

There is an alternative way to provide power supply of such regions on the basis of low and medium power NPP. Economic indicators of low power reactors are of course lower than those of large power units, which successfully compete with conventional power in the world.

However, in terms of sharp growth of prices for organic fuel over the last years and high transportation costs of said fuel, low and medium power reactors might prove to be competitive with respect to power plants based on organic fuel.

One of possible reactor types that could be used as a basis for power supply of such regions, are high temperature reactors with helium coolant (HTGR) that are characterized by high safety and self-protection with respect to different accidents.

Basic features and advantages of HTGR are determined by the use of helium coolant, fuel elements on the basis of particles of uranium compounds with multi-layer protective coating, and graphite as the core structural material. These factors provide for high level of safety, and allow to achieve in HTGR high coolant temperatures at the reactor outlet, which fits well a direct gas turbine cycle that ensures high power conversion efficiency.

Interest in low and medium power HTGR was noted at a workshop held by GTDC in 1995, attended by IAEA and countries involved in development of HTGR.

3. Concepts of Medium and Low Power HTGR.

Experimental reactors and NPP with HTGR built and operated in Germany, USA and Britain attested to high efficiency when using such reactors for electric power production, excellent performance of fuel on the basis of coated fuel particles, high level of nuclear and radiation safety [7].

The present state of activities on HTGR and development prospects in this field were discussed at the GTDC Workshop in July 1995, Vienna. The Workshop was attended by representatives from the countries (Germany, Japan, USA, Russia, China) where HTGR activities are pursued, representatives of IAEA and some countries which may shows interest in the use of such reactors.

At the present time a number of countries in the world, including Japan, USA, Russia, China, Germany, etc. go on with the efforts to master technology of the second generation modular HTGR. A considerable scientific and technology potential for development and deployment of reactors of this type have been created, extensive research activities have been carried out to develop fuel elements on the basis of coated fuel particles, test the equipment components, validate safety, and so on.

A number of developing countries, such as Indonesia, Venezuela, etc. express their interest in HTGR as a source of electric and thermal power with the aim to save organic fuel.

Near-completed construction of the 30 MW(t) HTTR experimental reactor in Japan, and initial stage of construction of low power 10 MW(t) HTR reactor in China should be noted as good points in development of this technology.

A broad range of issues relating to the HTGR technology was discussed at the GTDC Workshop.

New concepts of the modular type HTGR were considered, that are characterized by inherent safety and low impact on the environment. High nuclear, thermal and chemical steadiness intrinsic in this reactor type provides for its resistance to various severe accidents, precludes the core meltdown and fuel element burning at accidents with air or water ingress in the core. This is due to high stability of fuel elements made of fuel particles with multi-layer protective coatings, including that on the basis of silicon carbide.

Different fuel element designs (spherical and prismatic) used in HTGR in different countries were considered.

The important feature of fuel elements on the basis of fuel particles is the possibility of a long-term storage of the spent fuel discharged from the reactor without radiation effect on the environment.

Technical-and-economic indices of HTGR with steam turbine and gas turbine cycles were discussed at the Workshop. It was demonstrated that the cost of power production and capital costs of power for HTGR with gas turbine could be made not higher than for reactors of the VVER type. The previously operated systems used the steam turbine cycle, mastered by the industry, which provided higher efficiency of nuclear plants with HTGR (~38%) as compared to light water reactors, but did not take full advantage of the high temperature potential of helium coolant at the reactor outlet. The HTGR advantages can show up to a greater extent with the use of a closed gas turbine cycle, allowing to achieve higher plant efficiency (~48%), and to provide for further increase in the safety level and reduction of capital costs as compared with the steam turbine cycle.

The use of the gas turbine cycle is discussed in conjunction with HTGR of different power levels.

600 MW(t) HT-MGR (Russia, USA, France)

A conceptual design of this reactor is being jointly developed by Russian and American specialists within the frames of an Agreement concluded between MINATOM and General Atomics in 1995. Recently the project was joined by Framatome.

The GT-MGR presents a block-structured modular system, consisting of a high-temperature helium reactor and a gas turbine (Figure 1).

The reactor and gas turbine system components are housed in steel vessels, connected to each other by a coaxial gas pipe.

The annular reactor core contains fuel elements of a prismatic shape, based on fuel particles with refractory protective coatings that ensure retention of radioactive fission products up to high temperatures (≤ 1600°C).

Helium, which is used in the GT-MGR reactor as the primary circuit coolant, is an inert working medium that does not undergo any phase transitions in the process of the power system operation. This allows to go to considerably higher coolant temperatures (800°C and above) compared to other reactor types.

At these temperatures thermodynamic cycle of the helium turbine is much more efficient than that of steam turbines, conventional for the power industry, and the GT-MGR plant can ensure thermal efficiency of about 50%.

Table 1 presents main parameters of the reactor system.

The GT-MGR is versatile with respect to the fuel cycle due to the use of coated fuel particles and low neutron absorption in reactor materials (graphite, helium). It can use uranium, thorium, as well as power or weapons-grade plutonium [8].

An essential advantage of the GT-MGR is the high level of nuclear safety. It stems from the negative temperature reactivity coefficient of the core. In addition, the GT-MGR reactor has a unique feature - it is capable to withstand full loss of coolant without meltdown of the core. Low power density in the core and the appropriate modular design provide passive, with no additional systems for emergency shutdown, dissipation of residual heat in the ambiance without damage to the fuel elements.

The GT-MGR is well adapted for batch production in terms of engineering works, which ensures high quality workmanship when fabricating the modules, characteristic of articles produced by the Russian atomic and aircraft industry. Batch production of the modular reactors is an essential factor allowing to reduce costs at NPP, for with a batch of 10-12 reactors the costs decrease by more than one half as against the first unit. The simplicity of the GT-MGR principle schematic assures reliability. The inherent safety features of the GT-MGR, based on passive removal of residual heat and relatively slow transients, establish good prerequisites for favorable acceptance of power systems of this type by the public.

200 MW(t) MHTGR-GT (Russia)

Design development of MHTGR-GT (200 MW) has been carried out in Russia. The MHTGR-GT presents a nuclear plant consisting of a high-temperature gas cooled reactor, and a closed cycle gas turbine system. All of the key reactor components are enclosed in a pressurized steel vessel. The reactor has a cylindrical core made of spherical fuel elements.

Design features implemented in the reactor system, along with reactor materials used allow steady-state operation with helium temperature at the reactor outlet lying in the range from 850 to 950°C. Figure 2 gives general view of the reactor.

Two alternative layouts of the reactor combined with the gas turbine plant were considered:

- with a direct cycle, and turbines, compressors and heat exchange equipment accommodated in a single power vessel (Figure 3);
- with an indirect cycle, and power and heat exchange equipment enclosed in separate vessels (Figure 4).

The first alternative is preferable in terms of compactness and leak-proofness, but the second one has a simpler and more reliable design, and is easily accessible for maintenance and repair.

At the stage of the pilot plant fabrication, the layout with the indirect cycle and 850°C at the reactor outlet was taken as a basis.

Table 2 presents main parameters of the plant with the MHTGR-GT reactor.

The plant employs a more efficient cycle with a two-stage intermediate cooling of the compressors.

The gas turbine system is made according to a 2-shaft schematic, wherein the driving turbine, high-, medium-, and low-pressure compressors and the start-up electric motor are arranged on a high-speed shaft (15,000 rpm), and the low-pressure power turbine and electric generator - on a low-speed shaft (3,000 rpm).

HTTR (Japan)

The HTTR is a high-temperature gas cooled reactor of 30 MW thermal power, designed for experimental purposes (Figure 5).

The reactor is enclosed in a metal vessel, connected to an intermediate high-temperature heat exchanger and auxiliary water cooling system by a gas pipe.

The core of diameter 2.3 m consists of hexagonal graphite blocks, wherein cylindrical compacts of particle fuel are located. Several bunches of control rods are located both in the reflector and the core.

It is proposed to operate the reactor with helium temperature at the reactor outlet between 850 and 950°C.

Table 3 presents main parameters of the HTTR reactor.

Construction of the HTTR reactor started in 1992 at JAERI premises. At the present time installation of equipment and systems is near completed.

Physical start-up of the reactor is scheduled for 1997.

HTR-10 (China)

The HTR is an experimental high-temperature gas-cooled reactor with spherical fuel elements (Figure 6). The reactor and steam generator are accommodated in steel vessels connected together by a coaxial gas pipe.

The cylindrical core is loaded with 27 thousand spherical fuel elements, that are charged and discharged at regular intervals. Average burn-up is 80,000 MWday/t.

The reactor is furnished with two control and shutdown systems: control rods and poison spheres of small size.

Table 4 gives main parameters of the HTR-10 reactor. It is proposed to operate the reactor in two phases: with the helium temperature at the reactor outlet of 700°C, and up to 900°C.

Presently the HTR-10 reactor is being constructed not far from Peking. It is anticipated critical experiments will be done in 1998.

The purpose of the experimental reactor is to validate high level of safety, and to produce electric and ,in particular, high potential thermal power for use in different branches of industry (oil, coal, metallurgy, etc.).

10 MW(t) HTGR (Russia)

The HTGR-10 is a high-temperature gas cooled low power reactor, intended for deployment of an autonomous nuclear plant for power supply of remote areas on the North of Russia.

The peculiarity of these areas is low density of population and wide dispersion of small communities (5,000 people). For the most part, populated localities account for 600-2,000 people. It is unfeasible to establish a centralized system of power supply to these areas. The total installed power of power sources in hardly accessible areas of the Russian North is currently 1,200 MW. Coverage of this power through the use of diesel fuel is not economically expedient.

In this connection proposals are being considered in Russia on the use of nuclear power sources for power supply of this areas. Trade studies were performed for power sources based on different types of reactors (water-water, gas cooled, thermionic, etc.), with high safety being the major requirement for nuclear power sources intended for the Arctic areas, which would guarantee reliable protection of the environment from radioactive contamination in the absence of sufficiently qualified operating personnel.

Performed analysis showed that to a considerable extent these requirements are met by the HTGR design with the core of uranium-graphite fuel elements based on fuel particles with multi-layer protective coatings of pyrolitic carbon and silicon carbide.

The HTGR-10 reactor is executed with an intermediate circuit. And combined gas and steam cycles. The NPP schematic is presented in Figure 7.

The core consists of spherical fuel elements and is accommodated in the steel power vessel of diameter 3,250 mm and height 7,650 mm. At the bottom a special device for discharge of fuel elements at the end of life is provided. Helium circulation is accomplished through the use of two blowers, mounted on the vessel side sleeves. The reactor design is shown in Figure 8.

Table 5 presents main parameters of the plant.

The NPP of this type can satisfy the demand for power supply of more than 50% of major communities in the remote northern areas of Russia.

4. Conclusion

The HTGR reactors still remain the most promising reactor type for NPP, in spite of the failure to commercialize them in a number of countries (USA, Germany). The positive experience of their safe and reliable operation gives grounds to expect that an ecologically friendly reactor is feasible that would meet more stringent present-day requirements on protection of humans and the environment from exposure to radiation.

Construction of pilot HTGR-type reactors in Japan and China, joint design activities on HTGR with the gas turbine cycle in USA and Russia, efforts undertaken by these and other countries under the aegis of IAEA bear witness to the continuing desire of developed countries to introduce this promising reactor technology.

There is also a potential market for the use of modular type HTGR in economics of small and developing countries.

Along with this, a number of key issues on mastering the technology of the new generation reactors shall be solved for successful implementation of the HTGR. In this respect it is important to combine experience and efforts of the countries involved in the HTGR activities. Despite the differences in design concepts and specific design features chosen for HTGR in different countries, there is a vast area of common tasks and problems which solution is advisable through vigorous international cooperation. IAEA is making an important contribution to consolidation of a number of countries in the field of HTGR. The International Club established by GTDC in 1995 is an important forum that joins leading HTGR specialists from different countries at the non-governmental level.

Development and implementation of an international project on the modular type HTGR with participation of a number of countries which possess the technology could be a real step forward in this field.

References

1. The Workshop "On the Modular High Temperature Gas Cooled Reactors and Options for Future Nuclear Power Generation", July 13-14, 1995, GTDC, Vienna.
2. Options for Electric Power Generation and Distribution in Developing Countries, GTDC Symposium, 13-15 November, 1995. Trivandrum, Kerala, India.
3. Electric Power Industry in Russia. RJSC "EPG of Russia", Moscow, 1994.
4. Electric Power Industry in China. China Electric Power Press, 1996.
5. Aspects to be Considered for Integrating SMSNRs with Weak Grids, Prasad Y.R.S., Jayaram B.N., Report to the Third Int. Seminar on Small and Medium Nuclear Reactors: Planning for World Energy Demand and Supply, New Delhi, India, 1991.
6. Energy Strategies for Indonesia. Final Report, KFA, BPPT, 1988.
7. V.N. Grebennik, "Status of Works on HTGR in the World", Nuclear Hydrogen Energy and Technology, Issue 7, Energoatomizdat, 1986. 232 p., Moscow.
8. D. Albershtein, W. Simon (USA), F.M. Mitenkov, N.N. Ponomarev-Stepnoi, et al. (Russia). "Increased International Support to Elimination of Russian Weapons-Grade Plutonium Using GT-MGR. The Third Annual International Political Forum, Lansdovn, March 19-22, 1996.

Session 5

DETERMINISTIC SAFETY ANALYSES

Table 1

Main Parameters of GT-MGR-600

Parameter	Value
Reactor power	600 MW(t)
Helium temperature in the reactor: inlet/outlet	490/850°C
Helium pressure in the primary circuit	7.0 MPa
Number of fuel blocks in the core:	
- in plan	102
- along the height	10
Average power density	6.5 kW/l
Fuel element type	prismatic
Fuel	UO_2 (PuO_x)
Reactor vessel diameter	8.5 m
Turbo-generator	single-shaft vertical
Shaft speed	5160 rpm
Bearings	magnetic
Number of turbine stages	9
Number of compressor stages	11/15
Intermediate cooler	1
Generator asynchronous,	50/60
Diameter of the turbo-generator vessel	8.0 m
Electric generator capacity	298 MW(e)
Net capacity	296 MW(e)
Net efficiency	48%

Table 2

Parameters of the Plant with the MHTGR-GT-200 Reactor

Parameter	Cycle	
	indirect	direct
Thermal power of the reactor, MW	215	215
Temperature		
- at the reactor outlet, °C	850	950
- at the reactor inlet, °C	400	490
Helium pressure in the reactor, MPa	7.5	7.5
Core dimensions, height/diameter, m	9.0/3.0	9.0/3.0
Average power density, MW/m^3	3.0	3.0
Fuel type and size, mm	sphere Ø 60	sphere Ø 60
Fuel	UO_2	UO_2
Enrichment in U-235, %	8.5	8.5
Diameter of the reactor vessel, m	6.0	6.0
Turbo-generator	2-shaft	single-shaft
Shaft speed, rpm	15,000/6,000 (3,000)	6,000
Number of turbine stages	4/7	8
Intermediate cooler	2	1
Helium temperature ahead of the turbine, °C	810	950
Maximum helium pressure in the GTS, MPa	7.7	7.5
Generator capacity, MW(e)	99	105
Housekeeping power, MW(e)	5.5	2.0
Net power, MW(e)	93.5	103
Plant efficiency	0.435	0.479

Table 3

Main Parameters of the HTTR Reactor

Parameter	Value
Reactor thermal power, MW	30
Helium temperature, °C	
- at the outlet	850/950
- at the inlet	395
Fuel	UO_2
Fuel element type	prismatic block
Reactor vessel	steel
Number of cooling loops	1
Pressure in the primary circuit, MPa	4
Container type	steel
Reactor life, yrs	20

Table 4

Main Parameters of the HTR-10 Reactor

Parameter	Value
Reactor thermal power, MW	10
Core volume, m^3	5
Average power density, MW/m^3	2
Helium pressure, MPa	3
Helium temperature, °C	
- at the inlet	250/300
- at the outlet	700/900
Helium flow rate, kg/s	4.3/3.2
Fuel	UO_2
Fuel enrichment, %	17
Diameter of the spherical fuel element, mm	60
Number of fuel elements in the core, pcs	27,000
Mode of loading	at regular intervals
Average burn-up, MWday/t	80,000

Table 5

Main Parameters of the Autonomous NPP with the HTGR-10 Reactor

Parameter	Value
NPP power, MW(t)	20
Number of reactor units	2
Reactor power, MW(t)	10
Temperature of the helium coolant, °C	
- at the core outlet	850
- at the core inlet	300
Pressure in the reactor, MPa	1.0
Fuel element type and size, mm	sphere Ø 60
Fuel enrichment in U-235, %	21
Fuel burn-up, MWday/t	95,000
Average power density in the core, MW/m^3	1.98
Life of one load of the core, effective years	11.3
Secondary circuit coolant	air
Air temperature in the heat exchanger, inlet/outlet, °C	175/800
Working air pressure, MPa	1.0
Power system	gas-steam-turbine
Power of the gas turbine, MW(e)	3.4
Power of the steam turbine, MW(e)	3.9
Net efficiency, %	35
NPP lifetime, yrs	40
Annual electric power production, MW/h	$64 \cdot 10^6$
Annual replacement of diesel fuel	15,000