FAST-NEUTRON GAS-COOLED REACTOR FOR THE MEGAWATT-CLASS SPACE BIMODAL NUCLEAR THERMAL SYSTEM

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Current tasks involved in the exploration and use of outer space require space systems to be equipped with power sources of a higher capacity than the existing solar batteries [1]. To this end, a project is currently developed in the Russian Federation to build a transport and energy module (TEM) based on a megawatt-class nuclear power and propulsion system (NPPS) [2].

The key component of the TEM is a nuclear reactor intended for generation of thermal power to be further converted to electric power and used in different consumption systems of a space vehicle. There were numerous earlier attempts worldwide to build reactors for such applications. A space high-temperature gas-cooled fast-neutron reactor (SGFR) was chosen for the TEM project based on the previous experience and preliminary studies. The overall view of the reactor system is shown in Fig. 1.

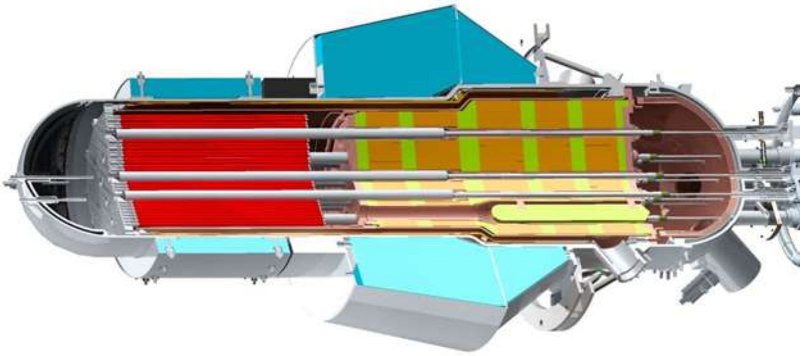

Fig. 1. Overall view of the space SGFR

Basically, the reactor specific features are as follows: the use of refractory materials in the core, as small reactor weight and dimensions as possible, no need for the reactor refueling during its operating life, as well as nuclear and radiation safety of the reactor system ensured throughout the lifecycle, including the startup stage [2]. The main design characteristics of the reactor are as follows: thermal power up to 3.5 MW; service life of no less than 10 years; reactor outlet gas temperature up to 1500 K.

Uranium dioxide enriched in uranium-235 is used as the reactor core fuel. The fuel cladding material is an alloy based on monocrystalline molybdenum. Refractory alloys based on polycrystalline molybdenum are used as the materials for the other core components (support and spacer grids, control and protection system member thimbles and others). The reactor reflector is metallic beryllium, and the reactor vessel is made of a nickel-iron alloy. Other Russian-made materials are used for the fabrication of the reactor parts and components.

The key issue in the creation of the reactor system for the outer space applications is that nuclear and radiation safety is ensured at all lifecycle stages (including in emergencies). The concept of ensuring the safety of space NPPS application is based on the Principles Relevant to the Use of Nuclear Power Sources in Outer Space adopted by the UN General Assembly in its resolution 47/68 of 14.12.1992. Its major requirements are: the keeping of the NPPS reactor in a subcritical state (without a fission chain reaction) until the nuclear-propelled spacecraft enters a radiation-safe orbit; start of the reactor only in a radiation-safe orbit; shutdown of the reactor after the spacecraft completes the flight mission or in an emergency; transportation of the TEM into a far-out orbit after its life is over with further disposal in such way that ensures the safety of the Earth's population. All these requirements have been taken into account in the development of the SGFR design.

As part of the SGFR project, the following regulatory documents were developed and will be put into effect to govern the assurance of nuclear and radiation safety of space nuclear power systems (SNPS): General Provisions for Ensuring the Safety of Space Nuclear Power Systems (OPB KYaEU); Nuclear Safety Rules for Space Nuclear Power Systems (PBYa KYaEU); Requirements to the Content of the Safety Analysis Report for Space Nuclear Power Systems (TS OOB KYaEU); Sanitary Rules for Ensuring the Radiation Safety of Space Nuclear Power Systems.

In terms of engineering implementation, most of the efforts in the process of the SGFR creation are aimed at the accomplishment of the following tasks:

- choice of the reactor core materials making it possible for the gas coolant to be heated up to the temperature of 1500 K;
- development of the technology for manufacturing and connecting materials based in molybdenum and nickel alloys in similar and dissimilar combinations;
- development of structural elements for the reactor parts and components that ensure long-term operation of the reactor in operating modes without refueling and operator intervention;
- substantiation of the lifetime serviceability of structural parts in operating conditions and in emergencies.

Over 30 Russian enterprises and organizations are involved in the TEM reactor system creation activities. A large-scale research and production cooperation has been formed, comprising leading research and production organizations, including nuclear centers, institutes of the Russian Academy of Sciences, and Russia's leading educational institutes.

The design is developed with the use of modern computer capabilities making it possible, based on 3D simulation, to improve greatly the quality of design and optimize experiments to be conducted as part a program for the experimental development of the reactor system. All calculations are performed using an advanced Russian computer of the capacity 1 Tflops and a data processing center of the capacity 10 Tflops. Precision codes were specifically developed, upgraded and verified for being used in the given project. In particular, the reactor core was profiled in physical terms using these codes, which has made it possible to level off the power density distribution and reduce the maximum fuel element temperature. The axial core temperature distributions are shown in Fig. 2.

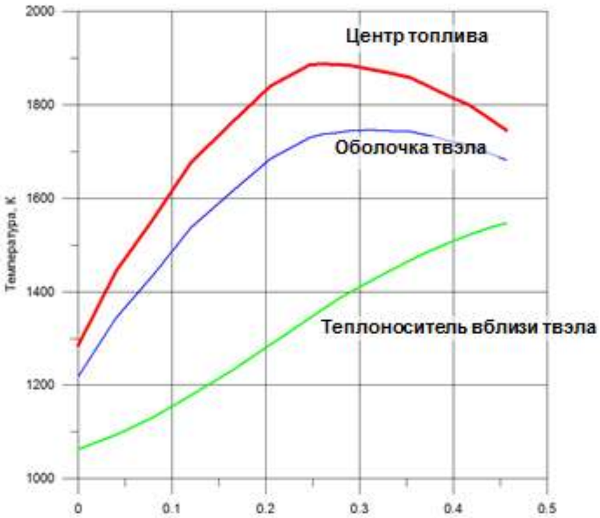

Fig. 2. Temperature distributions in the SGFR
1. Temperature, K; 2. Fuel center; 3. Fuel cladding; 4. Coolant near fuel element

By now, materials have been selected for all reactor components and their service life tests have been started. Optimization studies have been conducted for the reactor's structural parts with regard for the weight and dimension restrictions imposed by the future power system applications in the outer space. A full-scale engineering mockup has been built for the core assembly technology trials (Fig. 3).

Fig. 3. Core mockup assembly

The problem of providing the project with high-temperature refractory materials was solved within a short period of time. The efforts by a number of Russian enterprises led to industrial and semi-industrial technologies having been created for the manufacturing of blanks of monocrystalline and polycrystalline molybdenum alloys, nickel-iron alloys and new heat-insulating materials. Some of the reactor components made of materials inherent to the design are shown in the photographs below (Figs. 4 and 5).

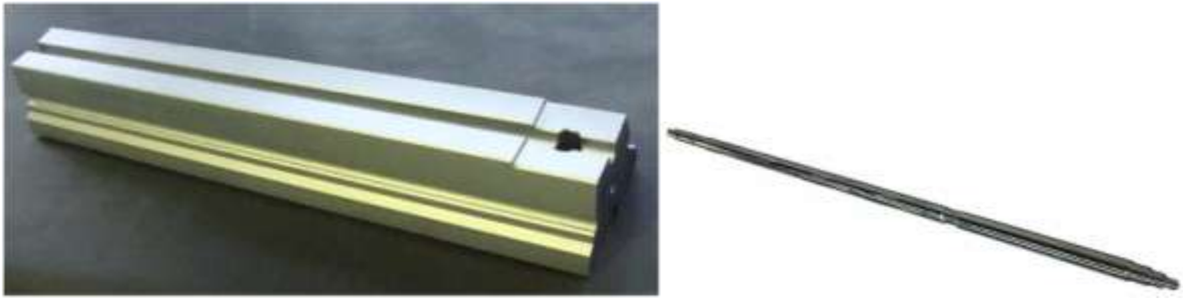

Fig. 4. A reflector component and a fuel element for the SGFR

Fig. 5. A control member for the SGFR

A comprehensive program has been developed for the experimental development of the SGFR and its components. Some of the reactor system's parts and components (structural materials, fuel elements, CPS control members, detectors and so on) have been developed and are being tested within the frameworks of an individual testing program. Test benches and reactor facilities of different agencies (Rosatom, the Russian Academy of Sciences, the Ministry of Education) are used for the testing. The most important tests are in-pile tests at SM-3, MIR-1M and IVV-2M reactors [3].

Ampoule in-pile tests of fuel element dummies have been conducted since 2010. The test parameters in terms of power density and fuel and cladding temperatures are the same as the operating parameters of standard fuel elements. Also, accelerated tests (in terms of the number of uranium fissions) are conducted in dedicated ampoule devices to obtain information on the fuel-cladding interaction as soon as possible (Fig. 6). A test life of about two years has been currently achieved for some of the dummies. For different types of tests, 25 full-size SGFR fuel elements have been manufactured, for six of which in-pile tests and post-irradiation examination have been conducted successfully.

Fig. 6. An ampoule with SGFR fuel elements loading into the reactor

All fuel elements retained their integrity in the course of testing. The results of the post-irradiation examination have showed that the unique fuel element design has made it possible to suppress the processes of the axial mass transfer of uranium dioxide and its solid fission products along the fuel column height, which are rather significant at high temperature gradients in the fuel based on uranium dioxide. No interaction between the monocrystaline cladding and uranium dioxide has been revealed also, and the cladding strength and ductility values are approaching the values close to the initial ones.

Conclusions

At the present time, computer codes have been created and verified for determining the main parameters of the reactor system; R&D activities have been completed, the best options have been selected for the configuration and design of the reactor parts; technologies for the manufacturing of blanks of molybdenum and nickel alloys and functional materials have been tried out; models and mockups of some of the components have been fabricated and are being tested under operating parameters; and production facilities are being prepared for the manufacturing of the reactor prototype. The reactor prototype fabrication completion and test start are scheduled for 2016.

References

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