FROM THE HISTORY OF PHYSICS

50 Years of Manned Astronautics —
a Milestone in the History of Rocket and Space Technology

Selecting and using materials for a nuclear rocket engine reactor

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Abstract. This paper provides a historical account of how the nuclear rocket engine reactor was created and discusses the problem of selecting materials for a gas environment at the temperature up to 3100 K and energy release 30 MW per liter.

1. Introduction

The high pace of development and the high scientific and technological level of atomic power engineering achieved in the USSR in the second half of the 1950s created objective prerequisites for the construction of fundamentally new types of stationary and mobile nuclear energy reactors and facilities intended, in particular, for cosmic purposes, such as nuclear rocket engines (NREs) and small-size nuclear–electric energy converters [1, 2].

The development of NREs in the USSR was initiated in 1955 when I V Kurchatov, S P Korolev, and M V Keldysh met to discuss the possibility of creating a rocket with an atomic engine to enhance the defensive power of the country in response to the Rover program for developing NREs, started in the USA. In 1956 and 1958, two government acts for the development of work with the aim of building nuclear rocket engines were signed in the USSR [2]. At this stage, preliminary

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design work was started to create a mounting base for testing NREs, and material technology investigations were initiated. The heat exchange and hydrodynamic conditions were studied at Research Institute 1 [currently, the Research Institute of Thermal Processes (RITP)]. Studies in the field of neutron physics and reactor control were performed at the Obninsk Physical Energy Institute (PEI) and at the Kurchatov Atomic Energy Institute (AEI). The technology of refractory materials and heat-releasing elements (HREs) was developed at Research Institute 9 (currently, the Bochvar All-Union Research Institute of Inorganic Materials, ARIIM). The problems of selecting materials for NREs based on carbides of transition metals and graphite in gas media were also partially investigated, beginning from the 1960s, at the All-Union Institute of Aviation Materials (AIAM), the State Institute of Applied Chemistry (SIAC), the Institute of High Temperatures (IHT), the Grafit Research Institute, and the Ceramics Department of the Leningrad Technological Institute.

In 1957, researchers at the RIPT proposed a principle of refining individual elements of units of the NRE reactor on electrothermal and plasmatron mounts, which reduced the extent of reactor tests. Different NRE schemes were considered. The simplest NRE with a reactor with a solid-state core (named the A scheme) can produce a specific thrust 800–900 s [the best liquid-propellant rocket engines (LREs) give 450 s]. The NRE with a gas-phase reactor (the B scheme) could produce a specific thrust up to 2000 s, but problems to be solved in its construction, namely, the confinement of a uranium plasma with the temperature up to tens of thousands of degrees and the protection of the walls of a heat releasing assembly (HRA) from the plasma, were much more severe than those in the construction of the A scheme. It was decided to begin the development of the

A scheme (while the work related to the B scheme was continued as a research study).

Within two years, two teams were actively involved in the development of the first NREs. A ground-based IVG-1 (research high-temperature gas-cooled) reactor, a prototype of an in-flight NRE version, was developed at the Research and Development Institute of Energy Technology (RDIET) headed by N A Dollezhal' and at AEI under the supervision of N N Ponomarev-Stepnoi. The second team developing a ground-based IR-100 engine was headed by V M Ievlev, the scientific chief of RITP, A D Konopatov, the chief designer of the engine at the Development Laboratory of Chemical Automation (DLCA), Voronezh, and V Ya Pupko, the scientific chief of the reactor at the Physical Energy Institute (PEI), Obninsk. The first carbide-based HREs were proposed and manufactured at Research Institute 9. The expansion of NRE studies required the manufacture of a great number of HREs for experimental HRAs. In August 1962, the Ministry of Medium Machine Building of the USSR decided to create the Research Institute of Heat Releasing Elements (RIHRE) [currently, the Luch Research and Production Association (RPA), a Federal State Unitary Enterprise (FSUE)] with an experimental plant providing technological possibilities for the rapid complex development and production of new types of nuclear fuel and HREs [3]. This resolution was preceded by the very important decision of 30 December 1959 about the inexpediency of further developments of military nuclear ballistic rockets (due to progress in the development of chemical-fuel engines) and the necessity of continuing NRE developments for space launchers [2].

The basic challenge encountered by the developers of NREs was to prevent damage to the ceramic active core and, most of all, HREs caused by thermal stresses. It is known that thermal stresses are proportional to the product of the energy-release density, the elastic modulus of the material, the linear expansion coefficient, and the square of the characteristic transverse size of the construction. The energy release cannot be strongly reduced because such a reduction would result in an increase in the reactor weight with protection and would reduce the NRE advantages to a minimum. Reducing the HRE characteristic size can be done efficiently, but this is restricted by the fact that elements of very small sizes would be severely damaged by vibrational stresses, which are significant in rocket engines. In this case, the limiting characteristic transverse size of HREs is 2–3 mm. An alternative to the carbide HRE is the graphite HRE. Graphite has a unique thermal strength because its elastic modulus is almost two orders of magnitude smaller than that of carbides. However, a substantial disadvantage of graphite is that it quite actively interacts with hydrogen (everything comes at a price).

Unlike American scientists, Soviet researchers began to develop the NRE core using HREs made not of graphite, which is thermally stable but unstable in the hydrogen medium, but of carbides, which are fragile but are more stable in hydrogen [2]. While in many other scientific fields Soviet scientists had to 'overtake' foreign investigations, the NRE was developed without blindly copying 'foreign' samples, the experience of predecessors being critically analyzed. Soviet researchers decided (correctly, as the result showed) that protecting HREs from interaction with hydrogen is more difficult than providing its acceptable thermal strength. Although graphite HREs were also developed in the USSR, they were regarded as a backup.

In 1962–1969, under the supervision of M V Yakutovich, director of the RIHRE, the material technology, technological, theoretical, and test departments were created to solve the following problems [3]:

● selection of the fuel and construction materials for NREs;

● development of the technological foundations for manufacturing devices from these materials;

● construction and computational and experimental demonstration of the efficiency of elements of the active core;

● preparation of project documentation and organization of semicommercial production.

These problems were successfully solved by using a systematic and complex approach. Detailed theoretical estimates of the operational conditions of the devices, the required technological studies of the properties of materials, and the working out of technological versions were realized in the form of technological chains developed together with the experimental plant. In turn, experimental and test samples of devices were subjected to thermal, hydraulic, and resource tests in the IVG reactor of the Joint Expedition, a branch of the RIHRE located on the nuclear proving ground in the Semipalatinsk region (Semipalatinsk-21, later Kurchatov, Kazakhstan).

This paper is devoted to the history of material technology developments for manufacturing elements for the NRE reactor core at the RIHRE [Luch Research and Production Association (RPA), Federal State Unitary Enterprise (FSUE)] from 1962 to 1991. Because the results of NRE studies are scattered over numerous publications in periodicals or special collections of papers that are not easily accessible, we decided to generalize the data on the characteristics of the materials and the efficiency of elements of the NRE core in this paper. Clearly, the scope of problems considered here is limited. For example, we do not discuss issues concerning the design and the radiation and thermal protection of the nuclear engine, or the neutron-physical and hydrodynamic characteristics of the reactor. These issues were partially considered in the book *Nuclear Rocket Engines* published in 2001 [2].

Because of the high brittleness of the materials based on interstitial phases (carbides and hydrides), which are used in construction, special attention is paid to manufacturing active-core elements that are stable under the action of high thermal and neutron fluxes, stresses, aggressive gas media, and ultrahigh temperatures. Such a variety of operating parameters required the development of a number of new pre-reactor physico-mechanical methods for testing materials at the Luch RPA, where diffusion-controlled processes (creep, corrosion, and radiation) were investigated in fuel and construction materials based on interstitial phases.

Beginning from 1976, HRAs developed for NREs were tested in the IVG-1 reactor, which was used to work out the elements of the reactor core. Later, a mount was constructed for testing an 'engine' version of the IR-100 reactor, which was tested for several years at different powers and was then converted into a material technology research low-power reactor, which is still working successfully to date.

The results of numerous studies performed at the Luch RPA for many years allowed constructing a scientific system of knowledge about the nature of refractory compounds, mechanisms of their deformation and damage, and the features of their behavior in construction and fuel hardware during variation of the operational parameters of reactors.
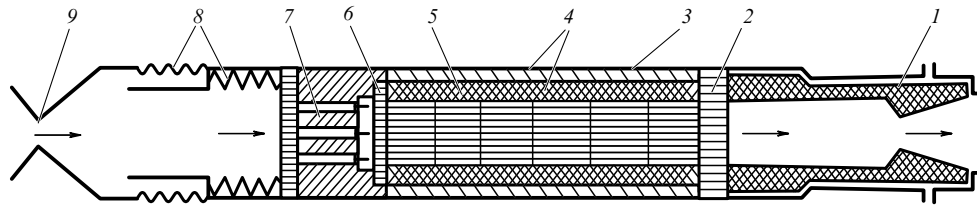
Figure 1. Principal HRA scheme: (*1*) nozzle unit; (*2*) bearing grid; (*3*) beryllium-steel bilayer housing; (*4*) heat-insulating packet; (*5*) heating units; (*6*) input grid; (*7*) end reflector; (*8*) thermal-expansion compensation unit; (*9*) throttle [4].

Many developments at the Luch RPA have been acknowledged at international conferences, symposia, and exhibitions. A group of scientists has grown who have defended more than 30 Doctor of Science and 200 PhD dissertations and published a few dozen monographs and a few hundred scientific papers on high-temperature materials and their applications. Some researchers became laureates of State Prizes of the USSR and Government Prizes and received titles of Honored Scientist, Honored Technologist, and Honored Inventor.

2. Construction of the heat-releasing assembly (HRA) of a nuclear rocket engine

The concept of a nuclear rocket engine is simple and consists in using a nuclear reactor instead of a combustion chamber for heating gas producing the thrust during its escape from a supersonic nozzle. The efficiency of a rocket engine is determined by the ejection rate of gas from the nozzle, which is inversely proportional to the square root of the molecular weight of the gas. Hydrogen has the smallest weight (2 a.m.u.). The ejection rate of hydrogen heated up to 3000 K is more than twice that of the best chemical fuels for LREs. This is an advantage of the NRE, which can heat pure hydrogen (the mean molecular weight of combustion products in LREs always exceeds 10 a.m.u.). Instead of the ejection rate, the engine efficiency is often characterized by the specific thrust, equal to the ratio of the momentum imparted to the rocket engine to the mass flow rate of the working substance. (The specific thrust is also defined as the ratio of the thrust to the weight flow rate of the fuel and is measured in this case in seconds.) According to calculations, the mass delivered from a circumterrestrial orbit to the geostationary orbit by an interorbital spacecraft equipped with an NRE having a specific thrust in the range from 850 to 4400 s is three times larger than the mass delivered by a spacecraft with an LRE.

Aside from these important advantages, the NRE has substantial disadvantages. The main disadvantages are as follows. First, the NRE reactor is considerably heavier than the LRE combustion chamber. Second, the reactor is a high-power radiation source requiring a radiation shield. This makes the engine even heavier and considerably complicates its operation. The requirement of the stability in hydrogen at high temperatures and neutron-physics restrictions strongly reduce the choice of materials that can be used for manufacturing HREs and high-temperature elements of the HRA. Because the NRE is an air-borne reactor, it should be light enough. Therefore, this reactor should provide a very high energy density, exceeding the energy density of ground energy reactors by a few orders of magnitude [2, 4].

A number of important principles for using brittle carbide materials in HRAs were formulated during the construction

of the HRA. The HRA should be made of functionally autonomous units and remain operable even if some of its units are damaged. Each unit is made as a technologically independent aggregate that does not require complicated connections with adjacent units during its mounting into the assembly.

Such a functional, technological assembly of HRAs considerably reduced the time of experimental studies, reduced the cost of the unit, unified the unit manufacturing quality control, improved the prediction of its efficiency, and provided the maximal stability with respect to this load. The basic construction of the first-generation HRA in a heterogeneous NRE is shown in Fig. 1. In the HRA housing is placed an ordered set of ceramic elements that are not attached to each other.

The bench IBG-1 reactor, constructed to work out the HRA design for the NRE operation parameters [4], is a heterogeneous gas-cooled reactor with a water moderator and a beryllium reflector (Fig. 2). It consists of stationary and removable parts. The stationary part includes housing *1* of the rector with lid *2*, reflector *7*, barrels *3* for power control, biological protection units *6*, and screens *8*. The removable part of the reactor core contains central assembly *9* with a set of 30 technological channels (TCs) *5* and central channel *4*. The HRAs under study can be placed in both the TC group and the central channel, where the thermal neutron flux can be approximately doubled compared to its cross-section averaged value owing to a beryllium reflector surrounding the channel, which allows testing HRAs mounted in the central channel at forced (up to damaging) loads. The use of water in the bench NRE prototype instead of a hydride–zirconium moderator, which is close in its nuclear physical
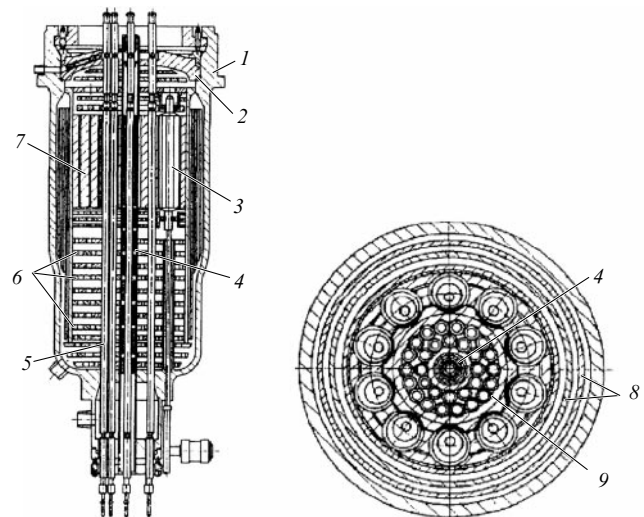

Figure 2. Longitudinal and transverse sections of the IVG-1 reactor [3].
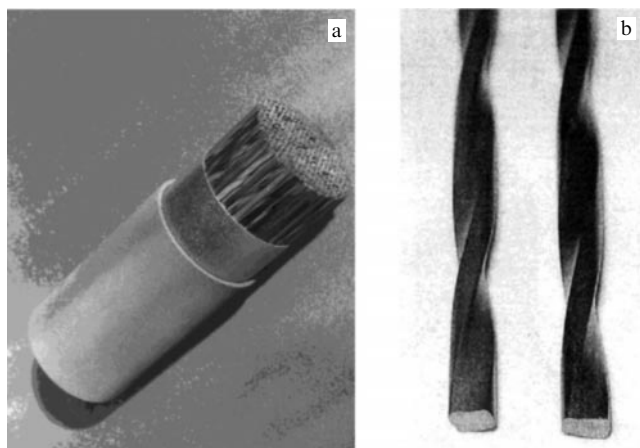
Figure 3. Photographs of a heating unit (a) and twisted-rod two-blade HREs 2.2 mm in diameter (b) [3].

Figure 4. Variation of the heat release q_i/q_{max} and temperature T along the HRA length L [4, 5].

properties to zirconium hydride, expands the experimental possibilities of the reactor, allowing the replacement of units under study without constructive finishing, and improving the reliability of the reactor operation.

Heat releasing elements are located in the HRA heating unit 29.7 mm in diameter and 600 mm in length (Fig. 3). The heating section (HS) is divided into 6 heating parts, each of which contains 151 twisted-rod HREs and 12 semicylindrical fillers. Heat releasing elements and fillers are close-packed into a triangle lattice. The HRE cross section is a plate with a narrow side describing a circle. The plate is twisted along the axis. The relative diameter of the HRE is 2.2 mm, the blade thickness is 1.24 mm, and the twisting step is 30 mm.

The specific heat release and temperature in the HRE along the HRA length are distributed nonuniformly, with a maximum at the central part of the HRA in the third heating section, while the temperature drop in the hydrogen medium monotonically decreases towards the nozzle output (Fig. 4).

Heating sections are intended for heating the working substance up to a specified temperature. The first four HSs, counting from the entrance of the working substance into the HRA, consist of HREs made of a double solution of carbide–graphites; the two last of the HSs contain HREs made of a triple $(ZrC + NbC + UC)$ solution. Each section is assembled from HREs of three types containing uranium in different amounts and located in three zones. Profiling by the uranium load was performed to level the temperature field over the HS cross section [5].

At the initial stage of the HRA development, different types of HREs, in particular, spherical ones, were considered. Spherical HRE systems have a high hydraulic resistance to the cooling gas flow, and therefore rod HREs were preferred. At the final stage, the shape of the cross section for rod-like HREs was chosen. Stresses in a twisted HRE with a two-blade or four-blade geometry were calculated numerically because the inhomogeneity of the stress state was larger than that in a common circular cylinder. We note that the tensile stress on the contour of a twisted HRE cooled from the surface, all other conditions being equal, is 29.6% lower than that in a circular rod with the same diameter. Stresses produced by axial forces appearing due to the pressure decrease in the HRA channel are almost two orders of magnitude lower than temperature stresses in HREs.
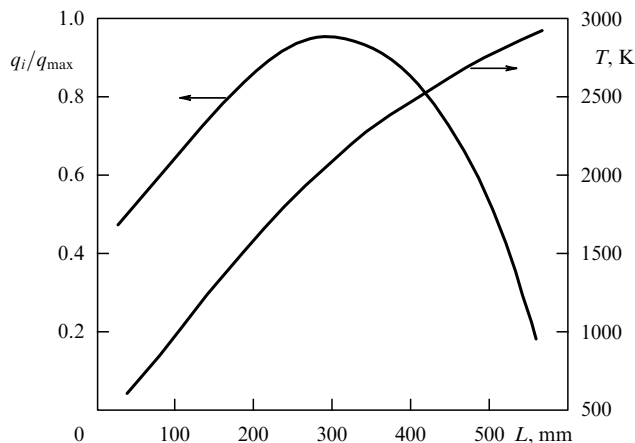
A heat-insulating packet (HIP) protects the housing from the thermal action of the working substance. Its constructive feature is a multilayer sectional packet structure that minimizes the possibility of penetrating cracks (to the housing) and allows varying the HIP material composition over both its length and its thickness. The outer casings of the HIP made of pyrolytic graphite provide, along with heat insulation, a 'soft' contact with the housing, thereby facilitating the assembling of the construction and minimizing the abrasive action of heat insulation on the housing. The inner casings are thin-wall carbide–graphite cylinders. In the low-temperature region, they are made of zirconium carbide, and in the high-temperature region, are based on niobium carbide. These casings serve as the supporting frame of the HRA preventing the entry of fragments of heat-insulation elements into the channel of the heating sections. The cases ensure the assembling of HSs and their mounting into a heat-insulating packet and reduce the erosion and chemical action of the working substance flow on the heat insulation. Casings made of low-density pyrographite and porous zirconium and niobium carbides are placed between pyrographite casings and cases. Casings made of low-density pyrographite are located in the low-temperature region ($T = 1500-2000$ K). At higher temperatures, casings made of the so-called foliation consisting of carbide layers in a graphite matrix were arranged in the first version of the construction. In the second version, they were replaced by casings made of porous zirconium and niobium carbides.

For the thermal flow density in the cooling channel up to $q_s \approx (2 + 2.5)$ MW m^{-2} and the maximum temperature on the surface of the inner case of the packet 3000 K, the heat insulation should ensure the temperature on the metal housing of the channel not more than 760 K, which means that the effective heat conduction of the packet should not exceed 3 W mK^{-1}1 at $T = 1500$ K.

The temperature distribution over the heat-insulating packet thickness is determined by four heat transfer mechanisms in the gaps: molecular, convection, radiation, and contact resistance. The heat transfer depends on the gas composition and pressure in the gaps, the gap width, the wall temperature, and the gap eccentricity between the walls [6]. Estimates made for two versions of the HIP design (Fig. 5) show that the gap between the walls of the casings has the strongest effect on the heat transfer.
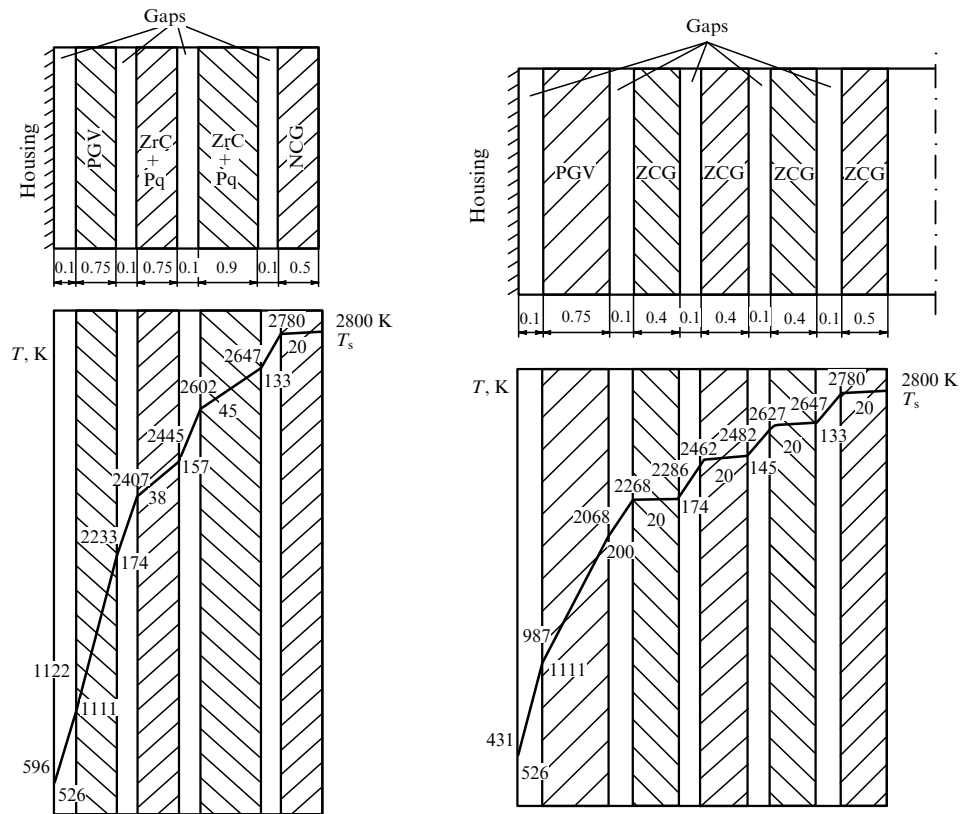
Figure 5. Temperature field in the hydrogen atmosphere in a four-layer packet with two casings made of ZrC + Pq flaking (a) and in a five-layer HIP based on three ZrC + C casings (b) for the thermal flow through the packet 2×10^6 W m^{-2} [6] (PGV: pyrographite type, NCG: niobium-based carbographite, ZCG: zirconium-based carbographite).

A bearing nozzle unit (BNU) supports the HSs and partially supports the HIP. All the axial stresses produced by the pressure drop are transferred through this unit along the hot HRA channel to the housing. In addition, the BNU provides the ejection of the working substance with specified parameters. To minimize the effect of possible cracking, the BNU consists of sections. It contains a bearing grid (BG), a bearing socket (BS), and a nozzle unit. Bearing grids are in the form of a 'sintered' unit of four-blade rods made of solid ZrC and NbC carbide solutions of equimolar composition. To increase the bearing area and provide a cylindrical surface, segment facings are attached to the side surfaces of the rod unit. The bearing socket consists of three successively arranged inserts made of carbide–graphite with a carbide protective covering. The nozzle is made of a set of conical carbide–graphite inserts.

The input unit is intended to produce a uniform gas velocity field at the input to the HSs, face screening of the neutron flux, compensation for thermal expansions of HSs, HIP, and BNU, and tracing of pulsed tubes and thermocouples used for measuring the working substance parameters. The input unit contains springs for compensating temperature expansions, a pyrographite casing, a beryllium cup serving as a face reflector, a gas inlet, and an input grid consisting of a high-pass grid and four grid rows.

The force elements of the HRA operating at high pressure drops are made of hydrogen-compatible materials having a high specific strength, high radiation resistance, and low hydrogen embrittlement, especially in the soldering and welding joints. The metal housing of the HRA in the IVG-1 reactor in the active core region was made of an AMG-5

aluminum alloy and of 18–10 steel in other regions. The HRA housing in the IR-100 reactor, which should be at the external pressure of the order of 10 MPa during flight, has two layers. The inner layer consisting of beryllium inserts provided the housing stability, while the outer layer, a thin steel jacket, provided the HRA sealing.

Among the zirconium hydride moderators developed and proposed so far, the simplest moderator contains a vertical set of thirteen perforated zirconium hydride discs that are closely adjacent to each other and have the diameter equal to that of the reactor core and thickness 50 mm each. The discs have 37 holes 41 mm in diameter for the HRA and 372 holes 3 mm in diameter for the flow of cooling hydrogen, which provides the required temperature field in the discs. This construction offers a simple solution to the problem of profiling the cooling system of the moderator with the energy release up to 1 MW cm^{-3}.

The basic parameters of the NRE are the temperature, the neutron flux, and the average level of pressure and pressure pulsations of the working substance in different regions of the HRA. A measuring system in the ground IVG prototype [7] provides a reliable control of the working process in the HRA and ensures autonomous emergency protection of the mount over the HRA parameters during tests. In each HRA, two measurements of the gas temperature were provided at the end of the third HS, one measurement of the gas pressure behind the BG and two measurements of the housing temperature in the middle of the HS. The working substance temperature in one cross section of the HS in the HRA is controlled with two to five zone thermoelectric converters (TECs). Zone TECs made of a tungsten–rhenium alloy are

used to measure the inhomogeneous temperature distribution in the radial direction.

3. Methods for model tests of materials

Model tests of the component units of HRAs are, along with calculations, the main tool for the experimental substantiation of the construction at the stage of technical project development. The tests were performed with model samples of component units under laboratory conditions. A specific feature of these studies is the separate influence of different action conditions. The complex action was estimated using the superposition principle by alternating separate tests in stages. This course of action is admissible in the case of the block HRA construction and is caused by the complexity of simulating natural operation conditions. The results obtained on high-temperature testing units allowed optimizing the design and technological solutions used in the HRA development.

At the initial period of NRE development, estimating the efficiency of the construction units of the NRE core was difficult because of the lack of a sufficiently complete information on the physical and mechanical properties of materials, especially at high temperatures. It was necessary to verify the correctness of the design and technological solutions in laboratory studies and pre-reactor tests. To solve these problems, a structure of the experimental equipment was created at the RIHRE, some instruments of the structure being unique.

During the development of methods for testing refractory ceramic materials in a broad temperature range from 20 to 3000 K, a number of difficulties related to the specific properties of these materials were encountered.

(1) The high hardness and high brittleness of carbides, nitrides, and other refractory materials complicating their machining exclude the option of using large samples of a complicated shape because of technological restrictions on their manufacturing.

(2) The easy oxidizability of these materials upon heating in air requires performing tests in a vacuum or inert medium and preventing the possible interaction of samples with heater materials.

For these reasons, standard setups for testing metals could not be used and it was necessary to develop or refine a structure of high-temperature setups satisfying these requirements.

Special setups were developed for measuring the strength and plasticity of ceramic materials during bending, compression, stretching, and creep and the endurance limit at high temperatures up to 3000 K in inert gases or in a vacuum. The thermal properties in different temperature ranges were measured by different methods using different setups. Comparative estimates of the thermal diffusivity a, the heat conduction λ, the heat capacity C, and the electric resistance ρ in the temperature range from 300 to 1000 K were made by fast transient methods with a typical accuracy of $\pm 10\%$. The heat conduction of carbide materials at high temperatures (up to 2800 K) was measured with an accuracy of $\pm 15\%$ by the axial method by passing current through a rod sample or an HRE. Simultaneously, the electric resistance was easily measured.

The bearing capacity of thermally loaded constructions was estimated by methods with parameters closest to the operating conditions of devices. The thermal loading of an HRE was simulated by cooling the heated HRE in water, while the thermal loading of cases in the HIP was simulated by heating in melted tin. The thermal strength of materials at temperatures exceeding $0.3 - 0.5 T_m$ (where T_m is the melting point), at which micro- and macroplasticity can appear, was measured by electron, plasma, and induction heating methods, which require sophisticated equipment. These methods were used to vary and control the level and type of temperature fields and the rate and cycle of their variation, thereby permitting quantitative estimates of the thermal strength of materials under conditions close to operating conditions at high temperatures.

The interaction of the HRA units with hydrogen at working temperatures and changes in the composition, structure, and physicochemical and mechanical properties were investigated using electrothermal setups in which the required temperatures could be produced, up to the melting points of materials directly in HREs made of $Zr - UC + C$ and $UC - ZrC - NbC$. Hydrogen or hydrogen–methane mixture flows passing through working chambers provided the gas rate near the sample surface approximately from 0.1 to 40 m s^{-1} at pressures up to 10 MPa. The hydraulic resistance of the HRA channel in the construction was optimized on hydraulic mounts.

Metallographic and X-ray diffraction analysis was widely used in the investigation of materials. The lattice period and phase components in carbide compositions were determined by standard methods using URS-50IM and DRON-3 X-ray setups. The chemical and phase compositions of materials were studied by the known instrumental methods of chemical, physico-chemical, emission spectroscopy, atomic spectroscopy, and X-ray diffraction analysis. In addition, newly developed methods of porometry, radiometry, mass spectroscopy, and neutron-activation analysis were used.

4. Materials of the reactor core

By the beginning of work in the 1960s, information on the properties and manufacturing technology of materials for the NRE core (based on zirconium, niobium, uranium carbides, and zirconium hydride) was absent or inconsistent. It was known that unlike monocompounds of uranium with a low melting point (2500 K), a fuel based on solid solutions of $UC - ZrC$ and $UC - NbC$ carbides with nearly stochastic composition can provide the heating of hydrogen up to 3000 K.

Therefore, investigations of solid solutions of uranium monocarbide with isomorphous, highly refractory zirconium, niobium, and tantalum monocarbides providing high melting points and compatibility of HREs with heat carriers became the most important material technology direction. The prospects of the development of $UC - ZrC - ZrN$ fuel were also outlined. The manufacturing technology of these refractory materials was based on powder metallurgy methods. Furnaces developed and constructed at the institute for sintering and consolidating powder samples and deposition of coatings on products at high temperatures (up to 2500–2700 K), which were unique for that time, were used to prepare samples required for studies and, later, components of the NRE core.

Thermodynamic studies of the solid solutions of refractory compounds with uranium monocarbide were started at the Luch RPA when no data on the thermodynamic properties in the homogeneity region at high temperatures were

Table 1. Averaged physical characteristics of reactor core materials in the temperature range from 300 to 700 K [10].

Compound formula	Structure type*	Density, g cm^{-3}	Melting point T_{m}, K	Linear expansion coefficient, 10^{-6} deg^{-1}	Heat conduction, W mK^{-1}	Elastic modulus, GPa	Vickers hardness, GPa
Fuel materials							
UC	K	12.9	2500	10.4	19	220	9.0
UN	K	14.4	3074	9.3	18	265	8
ZrC + 5 % UC	K	6.9	3380	11.8	30	380	25
ZrC + 5 % UC + C	K	6.6	3250	11	32	350	20
ZrC + UC + NbC	K	7.6	3520	11	22	320	28
Construction materials							
ZrC	K	6.73	3690	8.6	30	390	27
ZrC + 5 % C	K	6.5	3180	5.5	52	230	18
NbC	K	7.8	3870	7.7	20 – 30	500	20
ZrC + 50 % NbC	K	7.3	3620	5.9	25	470	28
ZrH$_{1.9}$ ε phase	T	5.6	≈ 2470 **	7.0	30	69	0.16
Pyrographite	G	1.7	4000 ***	8.5	70	48	0.1

    * C: cubic structure; T: tetragonal structure, H: hexagonal structure.
    ** Value for the hydrogen pressure 100 MPa.
*** Sublimation temperature.

available in the literature. Only basic approaches for estimating thermodynamic properties were known. The statistical thermodynamic theory of three-component interstitial phases developed at the institute and the established properties of diffusion-controlled processes [8] such as sintering, nitration, carbidizing treatment, and oxidation facilitated the optimization of technologies used in investigations. The first data on the radiation resistance of HREs (integrity, swelling, and strength) at temperatures from 1000 to 3100 K and neutron flux intensities up to $10^{15} - 10^{16}$ cm^{-2} confirmed the expediency of the choice of fuel materials based in solid carbide solutions.

It was decided for the first time in the development of a highly reliable construction in machine building to use short-brittle materials, which required changing construction principles and the established concepts of strength and thermal strength. A new criterion for estimating the bearing ability of thermally loaded products was introduced, which was accepted by the scientific community worldwide [9]. The data on the physico-mechanical properties of many refractory compounds and their compositions (some of them were used in devices for the first time) revealed the possibilities of these materials and influenced the determination of their operating conditions and estimates of their prospects.

4.1 Thermodynamic and structural characteristics of materials

Construction and fuel materials of the reactor core are based on refractory zirconium and niobium carbides, their solid solutions with uranium, carbide compositions with carbon impurities [2–4], and zirconium hydrides for a moderator unit (Table 1). These materials belong to the class of so-called interstitial phases [8].

Materials for NREs should have, along with high melting points, low evaporation rates and should weakly interact with hydrogen. Changes in the material composition caused by evaporation or interaction with hydrogen should not remove the composition from the homogeneity region during a specified operation time resource. Unlike uranium mono-compounds, fuel based on solid solutions of UC − ZrC and UC − NbC carbides with a composition close to the stoichiometric composition provides the heating of hydrogen up to

3000 K. The melting points of the ZrC, NbC, and ZrN fuel compositions decrease upon increasing the UC content. Investigations of fuel compositions and technological possibilities showed that the UC − ZrC − ZrN carbon–nitride fuel is promising for use in nuclear energy engine devices (NEEDs) [3, 4]. The use of uranium monocarbide as a nuclear fuel is complicated because its melting point is not high enough and it has a high reactivity with respect to many materials and working media.

The nonmetal atoms of a dissolved element are located in the interstitials of the crystal lattice of compounds with the characteristic mixed ion-covalent type of the interatomic bond. These features of the interatomic interaction provide high thermodynamic stability and heat resistance, while the low dislocation mobility leads to high hardness and brittleness of compounds. The melting point, elastic properties, and thermal expansion coefficients are independent of the structure and depend in fact on the cohesive energy required for the decomposition of the crystal lattice into separate ions. Mechanical and thermal properties are essentially determined by the structural characteristics and stoichiometry of the material [8, 10].

4.2 Strength of materials with different loading methods used

In constructing NRE elements from carbide materials and estimating their efficiency, it is very important to account for changes in the strength and damage upon variation of the stressed state of a body. The strength in a brittle state increases as $1 : 2 : (8 - 10)$ on passing from stretching to bending or compression, which is determined by the properties of the crack propagation kinetics [10].

When the critical crack stress intensity factor K_{1c} is reached upon stretching, a crack propagates avalanche-like until the complete collapse of the body. Upon compression, a crack, which was also produced when the value of K_{1c} was reached, can propagate in the state of equilibrium along a curvilinear path oriented along the compression axis only when the load is continuously increased. The passage to the supercritical stage of the body collapse became possible during the interaction of cracks grown in the equilibrium at stresses exceeding the crack start stress by more than an order

of magnitude. The total energy storage needed to destroy a compressed body is many times higher than the stored elastic energy of the body destroyed in a uniform stretching field [11].

Because fuel and construction NRE materials prepared predominantly by the methods of powder metallurgy have many structural defects, the level of their strength is quite uncertain, varying within 15–25% near the mean value. The strength level depends on the loading method; but the variation coefficient is in fact independent of the loading method. Changes in the strength of single-phase and hetero-phase carbide materials in passing from stretching to bending calculated by the Weibull method are in good agreement with experimental data. This circumstance is taken into account in determining the reliability of mechanically loaded NRE constructions.

4.3 Temperature dependences of the strength and creep

Because the working temperature of materials in different parts of HRAs in NREs in transient and stationary regimes changes in a broad range from 300 to 3000 K, it is necessary to know the variations in mechanical and physical properties. For construction and fuel materials of the interstitial phase type, the problem of preventing a brittle collapse is of primary importance. Such a collapse is caused by the high brittleness of materials of this class in a broad range of temperatures, loading methods, and rates, along with a relatively low tensile strength (compared, for example, with metal materials). Refractory carbide compounds with a high level of resistance to the motion of dislocations are characterized by a nonmonotonic dependence of the strength [10, 11]. First, the strength is virtually unchanged with increasing the temperature and begins to increase only when microplasticity develops, achieving a maximum (Fig. 6) at the brittle–ductile transition temperature T_{b-d} due to the thermally activated relaxation of local peak stresses near concentrators — structural defects contained in the material. The temperature T_{b-d} for complex solid $ZrC + UC$, $ZrC + NbC + UC$ solutions is higher than that for the single-phase ZrC.

As the temperature was further increased ($T > T_{b-d}$), microplasticity developed in ceramics and their strength monotonically decreased, as in metals. The presence of nonmetal (O_2, N_2, C, Si) or metal impurities (Fe, C, Ni) due

to the formation of phases and low-melting eutectics can change the transcrystalline type of collapse to the intercrystalline one and also change the temperature dependence of the strength. The brittle–ductile transition temperature in ceramics, unlike T_{b-d} in metals, strongly changes (by a few hundred degrees) upon changing the type of the stressed state and the deformation rate. As the deformation rate of ZrC increases upon stretching from 10^{-3} to 10^{-1} s^{-1}, the temperature T_{b-d} increases from $0.6\, T_m$ to $0.8\, T_m$. In the case of shock loadings with rates exceeding the relaxation rates of micro- and macrostresses, the strength remains almost at the level of its value at room temperature. A similar behavior is also observed for oxide materials and weakly plastic Si and Ge metals with strongly manifested covalent bonds.

During long-term loading, the strength decreases compared to that for short-term loading. The time τ until the collapse moment and the established creep rate ε' are related to the applied stress σ and temperature as [12]

$$\tau = B\sigma^m \exp \frac{U}{RT},$$

$$\varepsilon' = A\sigma^n \exp\left(-\frac{Q}{RT}\right),$$

where A, B, n, and m are constants and Q and U are the respective activation energies of the creep and long-term collapse processes. For carbide materials tested in the temperature range from 2500 to 3000 K, the activation energies Q and U and the exponents of stresses virtually coincide. The temperature dependence of the long-term stress for a specified time base is well described by the Ito–Shishokin equation [12]

$$\sigma_\tau = C \exp(-\alpha T),$$

where C and α are constants.

4.4 Influence of structural parameters on the thermal strength

The properties of materials considerably depend on their structural parameters (pores, metal and gas impurities). The number of these parameters is determined to a great extent by the chosen technological parameters. HREs, bearing grids, and HRA cases were manufactured based on dense carbide and carbide–graphite materials, while HIP casings were made of high-porous carbide–graphite compositions and pyrographite. The presence of pores in a material naturally reduces the flow section of a body and its strength, which can be described, for example, by an empirical relation like

$$\sigma = \sigma_0 \exp(-BP),$$

where σ_0 is the strength of a body without pores and B is a coefficient depending on the pore size and configuration [10]. Microstructural defects such as pores, grain boundaries, and microcracks located between grains or phase components influence the resistance to cracks for materials prepared by powder metallurgy methods. The value of K_{1c} for carbide single-phase materials does not exceed 3 MPa m$^{1/2}$. As a rule, K_{1c} nonmonotonically changes with temperature. First, K_{1c} decreases or remains unchanged with increasing the temperature and begins to increase only when plasticity develops. The effective surface energy depends on the environment in a complicated way.
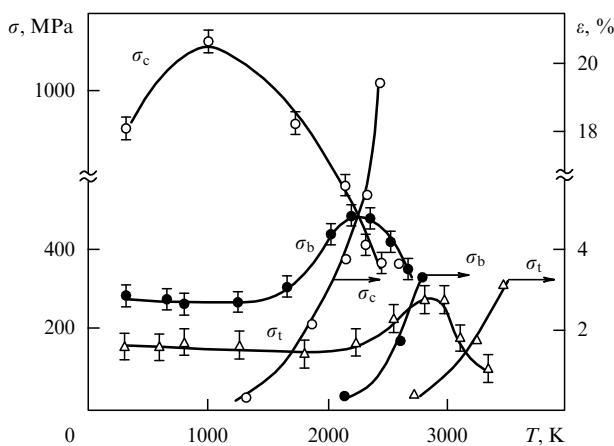
Figure 6. Temperature dependences of the strength of ZrC and the relative deformation ε upon stretching (σ_t), bending (σ_b), and compression (σ_c) for the deformation rate $v = 5 \times 10^{-3}$ s^{-1} [10].

Table 2. Thermal strength R of products made of different carbide materials in the elastic–brittle state* ($T = 600 - 1200$ K) [11].

Product	Material	$\alpha \times 10^6$, deg^{-1}	$E \times 10^{-3}$, MPa	σ_b, MPa	λ, W m^{-1} deg	R, deg	W, %
Casings, $D_{out} = 52$ mm, wall thickness $\delta = 2.2$ mm	Carbo-fiber plastic ZrC, porosity $p = 75$ %	5.1	17	8	0.5	95.0	24.0
	Porous ZrC, $p = 75$ %	6.3	16	11	3.0	68.0	21.0
	Porous ZrC + NbC, $p = 65$ %	5.5	30	22	3.0	72.0	15.0
Cases, $D_{out} = 48$ mm, $\delta = 0.75$ mm	ZrC, $p = 5$ %	5.1	350	250	20.0	50.0	22.0
	NbC, $p = 12$ %	4.8	310	260	35.0	43.0	14.0
	ZrC + NbC, $p = 10$ %	4.9	350	330	25.0	56.0	19.0
	ZrC 'flaking'	5.0 **	3.0 **	6.0	1.0 **	> 400.0	

* Data for other properties correspond to $T = 600$ K.
** For anisotropic 'flaking,' E and α are measured in the direction parallel to the deposition plane, while λ is measured in the direction perpendicular to this plane.

The thermal strength, which is the most important characteristic of the efficiency of HRA construction elements, is determined by a set of physico-mechanical parameters [9, 11] denoted as

$$R = \frac{\sigma_t(1 - \mu)}{\alpha_t E}, \qquad R' = \lambda R,$$

where σ_t is the strength, E is the Young modulus, α_t is the linear expansion coefficient, μ is the Poisson coefficient, and λ is the heat conductivity.

The higher the heat conductivity λ of a material is, the greater the thermal flux that can be withstood by the body without its collapse. We note that the choice of materials for heat insulators in constructions based on the value of R' is meaningless. In this case, it is necessary to use the value of R for estimates because, given two materials with identical heat-insulating properties, the better material is the one capable of withstanding a greater temperature drop.

An important stage in the search for more thermally stable materials for HRAs was technological developments of composites based on a carbide matrix doped with low-modulus carbon impurities. Doping ZrC and NbC carbides with soot doubles the thermal strength ΔT_{av} due to the leading decrease in the elastic modulus E compared to a decrease in the strength σ leading to a decrease in the limit deformation σ/E of the body [10, 11].

Considerable efforts were made to develop different technologies for manufacturing heat-insulating materials and finding the optimal HIP assembly. The increase in porosity from 5 to 70% in zirconium carbide samples reduces the heat conduction by an order of magnitude. Depending on the structure, namely, the framework structure and the closeness or openness of pores, the electric resistance and heat conduction for the same density of the composition can be substantially different. For example, porous carbide-fiber materials prepared by the thermal-diffusion impregnation of a carbonized fiber with zirconium prove to be, for the same density, less heat conducting and less stable than porous carbides prepared by mixing the powders of zirconium carbide and a filler, potassium bromide, followed by sintering in a vacuum to remove the filler. The formation of a special heterophase structure ('flaking') consisting of alternating ZrC + Pq carbide–graphite layers deposited from the gas phase with a porosity of 30% allows preparing a stronger material with heat-insulating properties not inferior to those of high-porosity carbides.

The variety of properties of HRA products made of dense and high-porosity materials is illustrated in Table 2.

Despite the considerable porosity (up to 75%) of high-porosity carbides and carbide-fibers, the strength variation coefficients of these heat-insulating materials are comparable to those for dense carbides, although the mean values of the strength are almost an order of magnitude lower due to the weakening of the body cross section by pores. Only for carbides with graphite impurities does the variation coefficient W almost double, up to 45–50%, compared to that for single-phase carbides. This can be explained by an increase in the number of defects in compositions due to the formation of concentric cracks around graphite impurities in the carbide matrix. The possibility of increasing the thermal strength by doping a carbide matrix with carbon was realized in NRE HREs based on solid ZrC + UC and ZrC + NbC + UC solutions.

4.5 Criteria for the destruction of thermally loaded bodies

Temperature stresses inevitably appearing during the NRE operation are one of the main factors that can cause the destruction of ceramic units of HRAs [13]. In some cases, temperature stresses determine the construction features and output parameters of a device being developed and the possibility of using one material or another. Therefore, to estimate the strength, it is necessary to determine the level of these stresses and the degree of their danger for individual elements and the construction as a whole.

As a rule, the strength is calculated by using admissible normal or tangential stresses that are safe for the product strength or the limit number of loading cycles. For a newly created class of machines or apparatuses, it is necessary to determine the properties of the collapse of materials from which their bearing elements are made and to determine certain criteria for the strength and its limiting values. The strength of a metal HRA housing is estimated by special methods for calculating the strength and the radial and longitudinal stability of cylindrical shells known in rocket building. The bearing capacity of ceramic HREs with a cross section of a complicated shape or of the BNU components was estimated by using the strength criteria for bodies
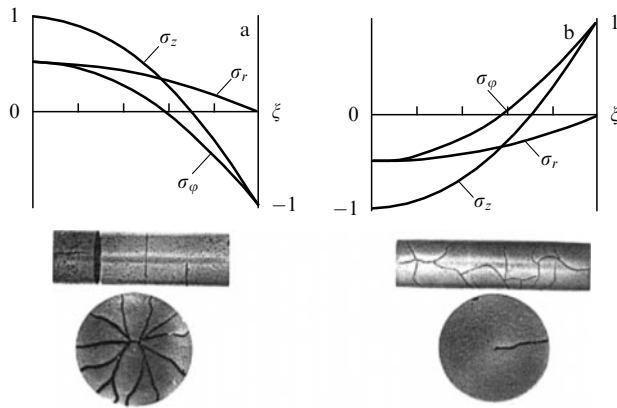
Figure 7. Change in the destruction of ZrC samples from complete fragmentation upon heating the body surface (a) to partial destruction caused by surface cracks appearing upon cooling (b) due to a change in the stressed state of the body [11]. (Three stress components for a cylindrical sample and the absence of the axial component σ_z in a thin disc.)

Figure 8. Destruction of the heated $(Zr_{0.97}U_{0.03})C_{0.96}$ HREs (up to 570 K) after their nonstationary cooling in cold water, estimated from the decrease in the bending strength from the initial state (*1*) after the first loading (*2*), and after 10 (*3*) and 50 (*4*) cycles [11].

Figure 9. Probabilities W (%) of the destruction of ZrC + UC (●) and ZrC + UC + C (○) HREs by surface cracks and of their full fragmentation (□) as functions of the specific thermal flux q at temperatures ≈ 1500 K [4].

operating in the inhomogeneous field of thermal stresses developed at the RIHRE.

The results of studies initiated at the institute as early as 1973 showed that the use of methods of thermal action in different combinations and varying the shape and size of a body changed the thermal strength and the type of body collapse [11]. Based on the concepts of force destruction mechanics, a new criterion factor N was introduced [9, 11] which took the stress distribution into account and determined conditions of the total or partial destruction of bodies upon changing this stressed state. The values of the parameter N for different types of thermal loading were calculated numerically.

Upon heating the side surface of a body made of an elastic-brittle material, a crack appearing in the central tensile region causes the complete fragmentation of the body when the critical stress intensity K_{1c} and values $N \geqslant N_{cr}$ are reached (Fig. 7a). When the side surface of a heated body is cooled (under conditions similar to the operation conditions of HREs according to the scheme presented in Fig. 7b) and the inhomogeneity parameter is $N < N_{cr}$, the nonequilibrium propagation of a crack started in the tensile region at the critical value K_{1c} changes to its equilibrium increase. The total fragmentation of the body becomes possible when stresses (after their substantial redistribution) are 8–10 times higher than the start stress of the crack [11]. In this case, the penetration of the crack into the body is $0.55R$ on average, which agrees with calculations.

The tests of heated HREs of different compositions by the method of nonstationary cooling in water showed that they were partially damaged due to the appearance of surface cracks at stresses exceeding the tensile stress σ_t corresponding to the heat flow $q_s \approx 2.5$ MW m^{-2} by only 15–20% [10]. The bearing capacity of the HRE estimated from a decrease in the strength decreases almost three times after the appearance of surface cracks and remains virtually unchanged after repeated cyclic loadings. We note that the number of cracks per unit surface increases when q_s increases, while their penetration depth in the body and hence the bending strength do not change (Fig. 8).

Tests of HREs by passing an electric current through them and blowing off their surface by a gas flow at surface temperatures (1500–1900 K) higher than upon cooling in
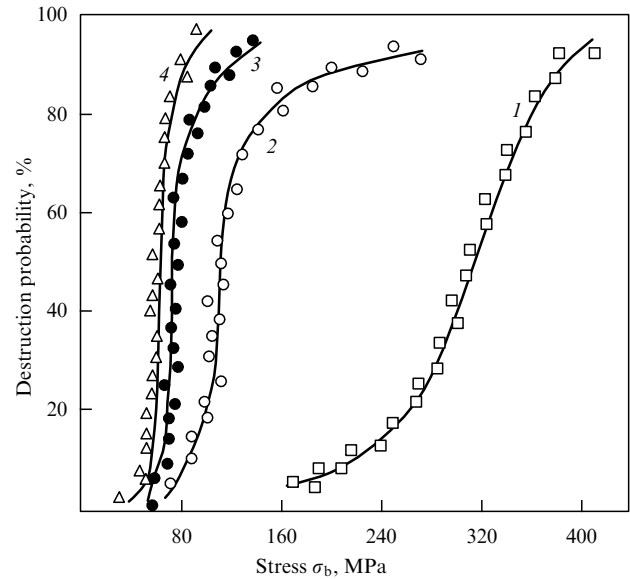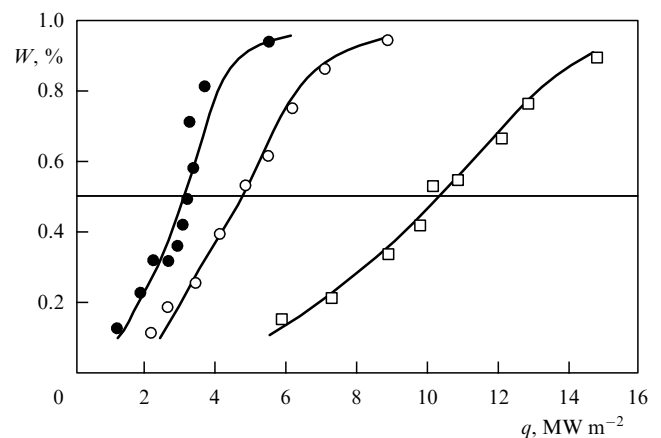
water confirm that ZrC + UC HREs were damaged for $q_c = 2.5-3.0$ MW m^{-2} (Fig. 9). Doping a carbide matrix with carbon impurities almost doubles the damage threshold (up to $q_s \approx 5$ MW m^{-2}). The complete fragmentation of HREs made of ZrC + UC and ZrC + NbC + UC occurs at mean values $q_s = 10-12$ MW m^{-2}.

4.6 Possible methods for increasing the strength parameters of ceramics

The choice of technologies and parameters for manufacturing materials for improving the properties of ceramics with a limited plasticity in a broad temperature range should be performed taking its operation parameters into account. For materials of the first sections of the HRA operating in the brittle-damage temperature range, it is necessary to increase, along with the strength, the fracture toughness, which can be done first of all by decreasing the defectiveness of the

materials and producing a structural state that increases the amount of energy required to produce damage. The thermal strength in this temperature region is increased by the following methods: elimination of structural defects by optimizing the condensation and sintering regimes [14], welding of defects and thermomechanical programmed control, modification of a stressed surface state (for example, by hardening), or carbon doping [11].

In the temperature region where the macroplastic deformation becomes possible, the short- and long-term mechanical thermal-strength parameters can be optimized by almost all methods used for metals. In the temperature region where the deformation process is controlled by the motion of dislocations, the methods are used that reduce the dislocation mobility by substructural strengthening, doping of solid solutions resulting in the formation of stronger chemical bonds in compounds, and doping with the formation of second phases. Under loading conditions, when deformation is mainly caused by grain-boundary sliding in the case of high-temperature creep, the strength can be efficiently increased by recrystallization, providing a considerable decrease in the length of boundaries due to the increase in the grain size. In using strengthening methods, it is necessary to take into account that structural changes intended to improve mechanical characteristics at high temperatures should not impair mechanical properties at temperatures $T < T_{b-d}$.

The optimal choice of the parameters of traditional isothermal sintering of ZrC samples in different media (hydrogen, argon, and vacuum) allows achieving a high density (no less than 95%) and the bending strength about 550 MPa at sintering temperatures 2500–2700 K [14]. A further increase in the sintering temperature up to 2900–3100 K does not lead to an increase in the density or strength, which is explained by the influence of gases in closed pores.

5. Radiation resistance of the HRA elements

The most important characteristic of the radiation resistance of HREs is their dimensional stability. The swelling of HREs made of compositions based on solid solutions of uranium, zirconium, and niobium carbides depends on the fission density and irradiation temperature in a reactor nonmonotonically [15]. An increase in the irradiation dose of $UC + ZrC + NbC$ and $UC + ZrC$ fuel compositions up to 2×10^{19} fissions per cm^3 at the irradiation temperature $T = 1100$ K leads to swelling by 5% and an increase in the electric resistance up to 80% due to the accumulation of radiation defects (mainly vacancies).

An increase in the irradiation temperature of the same fuel compositions from 500 to 2100 K at the constant fission density 2×10^{20} fissions per cm^3 leads to swelling by 6% but reduces the lattice period and the electric resistance to their initial values in the absence of irradiation.

Different concentrations of radiation defects along the HRE radius (higher on the surface and lower at the more heated center) due to annihilation of point defects leads to a parabolic change in the lattice pitch. This gives rise to compressing stresses in the surface layers [16], resulting in an increase in the strength and thermal strength. $UC-ZrC$ and $UC-ZrC-NbC$ HREs irradiated by the neutron flux $J = 10^{14} - 10^{15}$ per cm^2 per s at the fission density $B = 10^{16} - 10^{18}$ per cm^3 and $T < 0.4 T_m$ enhances the strength by 30–50% and the thermal strength by 70–80%. In this case, the strength increment decreases upon increasing
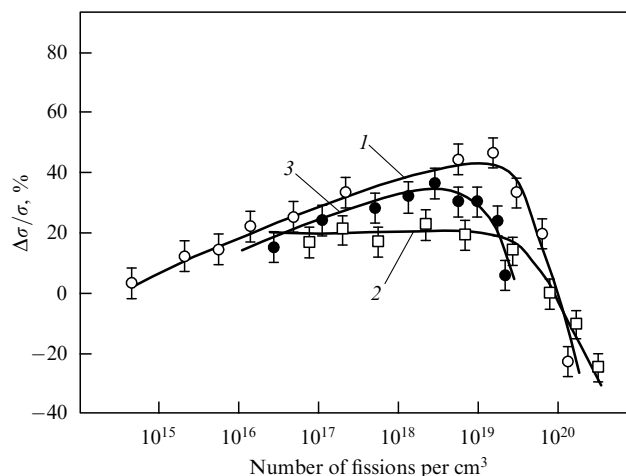

Figure 10. Dependences of changes in the HRE strength on the fission density at temperatures 800–1000 K: (*I*) $UC-ZrC-NbC$; (*2*) $UC-ZrC$; (*3*) $UC-ZrC + 5\%C$ [15].

the fission density above 10^{18} fissions per cm^3 (Fig. 10) due to the formation of vacancy and gas pores and some amorphization of materials.

The isochronous annealings of heated HREs at 1500 K remove the inhomogeneity of swelling and the residual stresses, returning the strength to its initial level before irradiation, whereas the same irradiation doses in the case of construction carbides cause only weak changes in the elastic modulus and strength, along with a noticeable increase in the lattice pitch and electric resistance.

For many types of graphites (except the isotropic MPG-6 graphite based on noncalcined coke) at high irradiation temperatures from 1400 to 1700 K in the interval of the neutron fluxes under study (up to 2.75×10^{25} m^{-2}), the shrinkage of samples was observed in both the parallel and perpendicular directions of the cut with respect to the formation axis. A decrease in the irradiation temperature to 1200–1500 K reduces the shrinkage rate and the anisotropy in the change of geometrical dimensions. At the same time, the relative change in the specific electric resistance for all graphites decreases, while the relative change in the elastic modulus increases. Such a behavior of graphite materials can be explained by considerable damage to the microscopic structure and the appearance of pores and cracks, indicating 'secondary swelling.'

Radiative changes in the moderator material, zirconium hydrate, during NRE operation in the engine regime (1000 s) are insignificant. In the energy regime after the irradiation of zirconium hydride in a reactor by the integral neutron flux of the order of 10^{21} cm^{-2}, hydride swelling by 1.5% is possible. The temperature dependence of the zirconium hydride swelling is nonmonotonic. The minimum of swelling is observed at 550 K and the maximum at 800 K. After 3000 h of irradiation by a fast neutron flux with the density 3×10^{20} cm^{-2} at 855 K, the electric resistance changed by 7%. The heat conduction of $ZrH_{1.8}$ irradiated by a fast neutron flux with the density 3.2×10^{21} cm^{-2} at 320 K decreased from 31 to 18 W mK^{-1}.

As a whole, the results of radiative studies suggest that the efficiency of the HRA in the NRE in the engine and energy regimes is retained.

6. Corrosion of materials in the working medium

An important factor determining the operation conditions of HRAs is the corrosion resistance of materials in hydrogen with methane added [17].

The interaction of carbides with hydrogen at high temperatures is accompanied by structural changes, the formation of hydrocarbons, and a decrease in the carbide stoichiometry according to the reaction

$$MeC + \frac{y}{2} H_2 = MeC_{1-x} + C_x H_y .$$
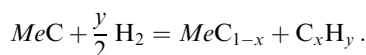
The type of the interaction of $UC-ZrC$, $UC-NbC$, and $UC-ZrC-NbC$ systems with hydrogen is similar. Only the degrees of decarbonation, the carbon concentration gradients over a sample cross section, and recrystallization temperatures are different. This suggests that all the systems under study have the same mechanism of interaction with hydrogen. On the surface of samples, the reaction of carbon with hydrogen proceeds with the formation of CH_4 and C_2H_2 and the evaporation of metal atoms, while the diffusion of carbon from the center to the surface and recrystallization occur in the bulk. Calculating the interaction for the scheme of the process under study requires solving nonstationary diffusion problems with the boundary conditions simulating a mass exchange with the working substance in the presence of heterogeneous chemical reactions. The total entrainment rates for double $ZrC-UC$ and triple $ZrC-NbC-UC$ solid solutions in hydrogen–methane media with 0.656 volume % of CH_4 at 3150 K are approximately the same (0.94×10^{-6} g cm^{-2} s^{-1}). High temperatures in experiments lead not only to a change in the chemical composition of materials but also to a change in the density of carbides and to an increase in the grain size. The appearance of a carbon concentration gradient over the sample cross section at temperatures up to 2500 K for 1000 s leads to the formation of compressing stresses up to 500 MPa and to an increase in the strength due to a change in the lattice parameter.

The interaction of carbides with hydrogen at 3100 K for 1000 s not only produces an inhomogeneous concentration of carbon but also causes a change in the structure, a decrease in the density, and a reduction in the strength to 50% (Fig. 11). The results of model tests agree well with the HRA tests in the IVG-1 reactor.

Apart from the chemical action of a high-rate working substance flowing around an element, a force erosion action of the flow on the surface is also possible; as a result, some weakly attached carbide particles are carried away by the flow.

Based on the dependences of the entrainment rate of the carbon component from carbides, another protection method was proposed in which hydrocarbons are added to hydrogen in the amount at which their mean concentration in the flow becomes equal to their equilibrium concentration over the surface. Then the carbon entrainment must be zero. But the equilibrium composition of hydrogen can be achieved not over the entire HRA length but at individual points only. In other places, either the entrainment or deposition of carbon on the washed surface occurs. Therefore, it is reasonable to regard the method of protective additions as supplementary to the main method of protection with the help of coatings.

As regards the corrosion resistance of cases made of low-density pyrographite (LDP) (1.35–1.6 g cm^{-3}) in the HIP,
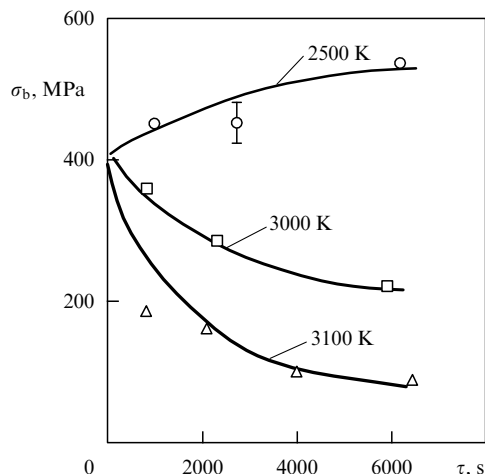

Figure 11. Changes in the bending strength of zirconium carbide samples after exposure to hydrogen at different temperatures [17].

their weight in the hydrogen flow at 1570 K decreases for 6000 s by approximately 3–8%, while the strength decreases by 30%. The loss in the mass of cases made of PGV pyrographite with distinctly anisotropic properties (density from 1.2 to 2.25 g cm^{-3}) in hydrogen at 2300 K for 4000 s reaches 45%. Due to a low porosity, the interaction of uncoated pyrolytic graphite with hydrogen, for example, at 2100 K is two times weaker than that for usual pressed graphite types. Therefore, pyrolytic graphite is optimal for the heat insulation of HRAs.

7. Reactor tests of the HRA

The integrated estimate of the efficiency of different HRA modifications for the NRE upon the combined action of all separately considered factors (radiation, chemical, and thermomechanical action) was performed for natural products in the IVG-1 reactor [15].

The HRA is located in the reactor core (see Fig. 2) in a group of 30 technological channels (TCs) [4] and in the central experimental technological channel (ETC) or experimental direct-flow channel (EDC) in which, due to a beryllium reflector surrounding the channel, the thermal neutron flux is approximately doubled compared to the cross-section-averaged flux. This allows testing HREs at forced loadings. Heating and cooling channels are provided by independent directly flowing gas. The constant flow rate of the working substance upon increasing the hydraulic resistance of the channel was maintained by means of circular flowmeter nozzles.

The time of reliable HRA operation and the degree of its 'viability' in the presence of defects appearing in the units were determined in tests of 34 ETCs, two six-channel EDC modules with moderator fragments, a fire bottom, and an end reflector. The end reflector was made of separate beryllium blocks with longitudinal holes for the coolant flow. In 1975–1988, 12 starts of the IVG-1 were performed with the full operating time up to 4000 s, the maximum hydrogen temperature in individual starts up to 3100 K, and the specific heat release in HREs up to 30 MW l^{-1} [4].

The results of tests in the reactor confirmed the formation of surface cracks and a decrease in the bearing capacity for the same thermal loadings, $q_s = 2.5-3.0$ MW m^{-2}, as in tests

without the reactor. But considerable differences also appeared, such as the complete fragmentation of HREs, especially in the input (low-temperature) HRA sections at thermal loads $q_s = 6-8$ MW m^{-2}, which are lower than those in model electrothermal tests. The destroyed HREs in the first two input HSs after six starts comprised small fragments of the rods remaining in their places. Destruction of this type is caused by bandage stresses. To restrict the production of defects caused by bandage stresses, a method for selecting the appropriate settings of sections in the channel was proposed. Nevertheless, bandage stresses appear in transient processes during the reactor start-up and shut-down due to the different radial thermal expansion of the NS and HIP materials. Laboratory experiments have shown that in order to finish breaking thermally loaded HREs, it suffices to apply a tensile stress amounting only to 10% of the maximal thermal stresses [10]. Heat-releasing elements in the other four high-temperature sections typically remain unbroken due to the appearance of microplasticity at temperatures above 1800 K.

Due to the destruction of HREs and blockage of the flow section by fragments falling out, the hydraulic resistance of the HS increases [15]. The number of HRE breaks increases with the number of the reactor start-ups, and after six start-ups in engine regimes, the number of broken HREs in the first two HSs exceeded 80%. To prevent HRE breaks in the first two HSs, it was proposed to strengthen HREs by thermal and radiative methods [15].

Heat-releasing elements in the HS undergo plastic deformation as the temperature increases. Under the action of force loads appearing during the gas flow and the axial forces exerted by a spring in the HS, HREs in the heating construction can twist around their axis and the HS column can lose its stability. The twisting angle, measured by the relative displacement of the ends of one section, sometimes exceeds 100°, which considerably changes the type of gas flow. The plastic deformation of the fifth HS, assembled from $UC-ZrC-NbC$ HREs with a higher melting point, proved to be smaller than that for HREs of the fourth HS made of $UC-ZrC + C$ carbide–graphites.

During HRE tests in ordinary TCs in weaker regimes than those in the ETC, HREs completely preserve their efficiency. A relatively small number of breaks appear when the hydraulic resistance of cooling channels of the HRA slightly increases. The strengthening of HREs achieves 40–100% in low-temperature HSs, while they exhibit small weakening in high-temperature HSs (Fig. 12).

Resource tests in TCs showed that HREs were efficient enough, to a great extent owing to the radiation-induced strengthening of fuel carbides. The strengthening effect steadily appears in HREs when the burn-up achieves 3×10^{16} fissions per cm^3. As the test time increases, the strengthening of HREs decreases, but for the burn-up of $\approx 1.5 \times 10^{19}$ fissions per cm^3 achieved at the end of resource tests, the strengthening remains at the level of 20%.

The enhanced vulnerability to damage of HREs in ETCs, leading to an increase in the hydraulic resistance coefficient in HRA channels, results in the overheating and possible burnout of the heat-insulating elements and inner housings of channels. This negative situation appears because of the insufficient thermal strength of carbide–graphite HREs operating at considerable thermal stresses σ_T (the temperature drop ΔT, for example, is ≈ 300 K in the first HS). The study of defects of HIPs in ETCs after resource tests revealed that their quality deteriorated with
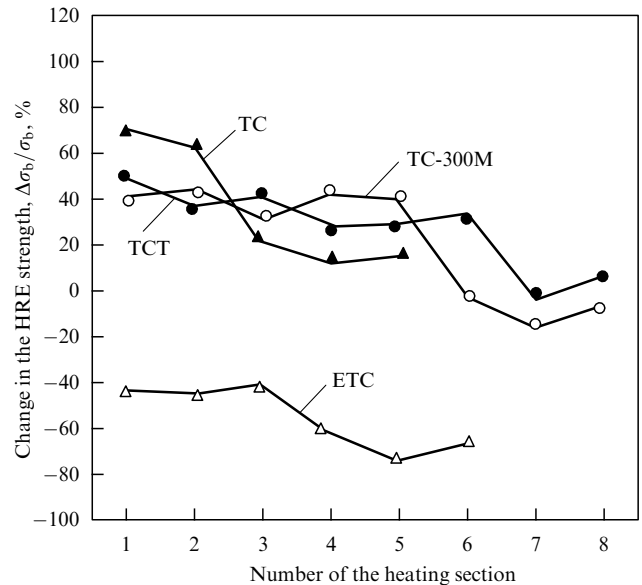

Figure 12. Changes in the strength of carbide and carbidographite HREs containing uranium from 6 to 18 mass %, along the HRA ETC of three different modifications (TC, TCT, and TC-300M) after tests in the engine NRE regime [15].

increasing the operating time. The interaction strength increases with increasing the temperature of the working substance, i.e., along the gas flow. The entrainment of material from pyrographite casings located in the region of the fourth HS achieves 25–50% of the initial mass. Damages appearing in HIPs prove to be different for the same operating times due to a large scatter in the initial properties of the heat insulation. These circumstances will be taken into account in the further development of NREs by selecting the optimal compositions of HIP materials and constructions. The prereactor thermomechanical methods for processing construction and fuel compositions have shown that the strength and thermal–strength parameters of HRA materials can be improved [10].

In a number of cases, BGs were broken after reactor tests due to the detachment of facings with the adjacent rows of rods. Although the bearing capacity of BGs was preserved in this case, the destruction indicated an uncontrollable impairment of HRA reliability. To reduce the stresses appearing in BGs and therefore the damaging drops, it was proposed to replace massive BG facings by a thin-wall cut casing with semicylindrical fillers. Model tests confirmed the tripling of the strength of the proposed construction for the same shear resistance as for grids with facings.

The efficiency of the zirconium hydrate moderator is confirmed by the fact that its chemical composition remained unchanged after long tests at increased temperatures.

The main result of the Soviet NRE program is the experimental and technological demonstration of the possibility of creating a ceramic reactor core in the NRE for heating hydrogen at the maximal values of parameters achieved in the reactor tests of different HRAs:

(i) hydrogen (H$_2$) heating temperature up to 3100 K;
(ii) specific power in HREs up to 35 MW l^{-1};
(iii) test duration 4000 s;
(iv) 12 reactor start-ups;
(v) maximum HRE heating (cooling) rates up to 400 (1000) K s^{-1}.

These results considerably exceed those obtained in the USA for graphite cores in NREs. The creation of the reactor–engine gave rise to a number of new projects and ideas.

Nevertheless, further development of the NRE were stopped in the early 1990s due to the absence of financing. The developments initiated almost half a century ago had arisen from important political problems and priorities in the cold war between the USSR and USA.

8. Outlook for nuclear rocket engine reactors

NRE reactors of different powers and NEEDs based on tested technologies have actually no alternatives in deep space investigations with the help of unmanned space probes and piloted interplanetary devices [18]. The developments of NREs was stopped only temporarily because humankind could not afford to spend a huge amount of money for large-scale cosmic studies. It is most likely that the NRE program should become an international collaboration program in the future, like programs for the development of the international thermonuclear experimental reactor (ITER), high-power accelerators, etc. The program would have a global character, in view of its legal, ecological, and other aspects. Because the program involves the use of fission materials of the highest armament quality, it should be under international control. NRE reactors for different purposes would be based on different HRE geometries with fuel compositions providing the required efficiency. To fulfill the tasks in cosmic flights, the NRE reactor should have high reliability, with the no-failure probability no less than 0.99.

The different versions of a device operating in many regimes and capable of producing, along with the reactive thrust, the electric energy for ensuring the activity of a spacecraft were extensively developed beginning from the early 1980s [4]. The NEED reactor should work not only in the basic, engine regime but also in two energy regimes at low power for a few years and high power during approximately half of the specified time resource of the engine regime. The high-power regime presents no difficulties in tests because, according to all its parameters, the reactor is loaded much more weakly than in the basic regime of the IVG-1. In the low-power regime, the heat carrier flows around the HRA only outside its housing, while the heat from HREs is transferred to the housing by radiation through heat insulation. This regime is quite different from the basic regime, when the fuel is considerably burned out (down to no less than 3–5% of the initial amount) and the chemical composition can change due to the incongruent evaporation of materials. Therefore, the efficiency of the HRA and HRE components under these conditions requires additional investigations.

It is clear that the outlook for the development and building of active cores for nuclear space energy devices will be first and foremost related to the improvement in the construction and technology of heating sections containing fuel compositions with the heat-releasing density 40 MW l^{-1} at elevated temperatures (above 3200 K) in the engine regime and to ensuring that fission products are kept in HREs for a few years at the temperature 2000 K in a deep vacuum or in hydrogen-containing working substances at pressures from 0.1 to 0.2 atm.

In 2009, the Commission of the President of Russia on the Modernization and Technological Development of Russian Economics recommended reconsidering the question of developing a spacecraft with a nuclear rocket engine. In 2010, the Government of Russia provided the initial financial support for the development of an outline for a project of a megawatt nuclear energy device, with the possible beginning of the module construction in 2018.

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