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4 August 1982

USSR Report

ENGINEERING AND EQUIPMENT

(FOUO 5/82)

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AERONAUTICAL AND SPACE

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GAS GENERATORS OF ROCKET SYSTEMS

Moscow GAZOGENERATORY RAKETNYKH SISTEM in Russian 1981 (signed to press 14 Aug 81) pp 2-4

[Annotation and foreword from book "Gas Generators of Rocket Systems", by Al'bert Alekseyevich Shishkov and Boris Vasil'yevich Rumyantsev, Izdatel'stvo "Mashinostroyeniye", 1183 copies, 152 pages]

[Text] Annotation

This book gives a systematized description of the basic arrangements, characteristics and special features of the operating processes in gas generators using chemical fuels (liquid, solid and mixed) for use as power sources and gas jets aboard aircraft and in ground systems of rocket equipment. Methods of experimental finishing off of gas generators are briefly considered.

This book is intended for engineers and designers in the area of rocket technology.

Foreword

Gas generators are widely used in rocket equipment. Their main units are very similar to the main units of basic rocket engines; however, the operating processes in gas generators have essential special features which must be taken into account in designing and finishing them off.

Numerous patents and magazine articles have appeared in recent years in connection with rocket equipment, and the expanded use of gas generators, which resulted in investigations of gas generator devices [2]. Brief information on gas generators is available in manuals on the bases for designing rocket engines [2, 3]. However, as a whole, published materials on gas generators are disconnected, fragmentary and methodologically inhomogeneous.

In this book the authors attempted to systematize the description of the arrangements and special features of the operating processes in gas generators using different fuels, based on the basic principles of rocket engine theory.

The book contains five chapters. Chapter one describes the basic characteristics of gas generators and the fuel compositions used, and considers separately the methods for laboratory and test stand tests.

Chapter two describes the special features of gas flows in the gas generator, the gas conduit and exhaust nozzles, as well as methods for calculating the gas dynamic characteristics of gas generators. Questions of filtering gas generation products and of gas thermodynamic processes in the devices are elucidated.

Chapter three reviews the special features of the devices on the basis of calculating one and two-component liquid gas generators, as well as gas generators using fluidized (powdered) fuel.

Chapter four considers design arrangements, methods for internal ballistic calculations and various possible methods for regulating hard fuel gas generators (especially, by front combustion charges), including multiple connection gas generators. The problem of transition processes during the change of decisive parameters is solved.

The last chapter describes questions of developing various combination gas generators using solid (with separate components), quasihybrid and hydrid fuels in steam-gas generators and gas generators of direct-flow rocket and rocket-turbine engines; engineering methods are given for calculating the basic characteristics of a number of gas generators.

Chapters one, four and five were written together; chapter two -- by A. A. Shishkov and chapter three -- by B. V. Rumyantsev.

The authors express their deep gratitude to A. P. Tishin for his valuable recommendations and for facilitating the improvement of the manuscript in all its components; to candidate of technical sciences M. Ye. Yevgen'yev for useful advice in solving problems in several sections. They will be grateful to readers who find it possible to send their comments to Izdatel'stvo "Mashinostroyeniye" to address: 107076, Moscow, Stromynskiy per. 4.

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NUCLEAR ENERGY

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CURRENT STATE AND OUTLOOK FOR HTGR RESEARCH IN USSR

Moscow ATOMNO-VODORODNAYA ENERGETIKA I TEKHNOLOGIYA in Russian No 2, 1979 (signed to press 8 Jun 79) pp 57-66

[Report TC-109/3 at meeting of Technical Committee on HTGR's. IAEA, Vienna, 12-14 Dec 1977]

[Text] An examination is made of the major advantages of high-temperature gas-cooled thermal and fast reactors, along with the feasibility of using them for electric power production and generation of high-potential thermal energy. A survey is given of theoretical and experimental research on such reactors in the USSR.

Initial Assumptions

Electric power production accounts for about 20% of the worldwide consumption of energy resources, while 80% of energy resources (petroleum, gas and coal) are expended for industrial and household heating purposes, transportation, in the chemical, metallurgical and other areas of industry.

Among world reserves of fossil fuel, only coal is far from being exhausted (according to estimates, only 2-3% of the reserves will be used up by the end of the century). However, transportation problems and the high cost of electric power plants that use coal considerably reduce the competitiveness of coal as compared with petroleum and gas, which has led in recent decades to preferential use of these valuable chemical products for energy purposes, to their increased cost, and in future will lead to earlier depletion of their reserves as compared with coal. From this standpoint, nuclear power must cover the needs of electric energy production, and at the same time be used for producing process heat.

An important factor favoring development of nuclear power is the ecological situation. Environmental pollution may become a serious limitation on the road to further expenditure of fossil fuel, and especially coal, for power production.

Naturally, nuclear power must undergo technical changes for successful introduction in new fields. District heating and production of low-potential heat can be successfully handled by light-water reactors. On the other hand, metallurgy, the chemical industry and hydrogen production require the development of reactors with temperature level of 800-1000°C and higher. At the present stage, high-temperature helium-cooled reactors (HTGR's) can be considered the most efficient sources for combined production of electrical and high-potential thermal energy.

With extensive development of nuclear power, scales may be limited by nuclear fuel resources. The world reserves of inexpensive uranium commensurate in respect to energy resources with petroleum reserves will have already been exhausted by the beginning of the next century. The fuel problem can be solved by breeder reactors that by expanded conversion can extend the capabilities of uranium by dozens of times, putting into the cycle even the uranium dissolved in sea water. Considering the actual characteristics of energy consumption (i. e. the variable loading schedules, the necessity of producing high-potential heat and so forth), it is necessary to set up an economically feasible two-component nuclear power structure including thermal reactors (light-water reactors and high-temperature plutonium and thorium reactors) and breeders with a short doubling time (4-6 years). Such a doubling time is easier to achieve by fast helium reactors that have good physical and technological characteristics. Helium breeders will be able to accumulate secondary plutonium for their own development, as well as nuclear fuel for thermal reactors which may comprise up to 50% in the nuclear power system. In this case, when involvement of thorium is considered, an outlook is opened up for development of nuclear power on a truly enormous scale (Fig. 1-3).

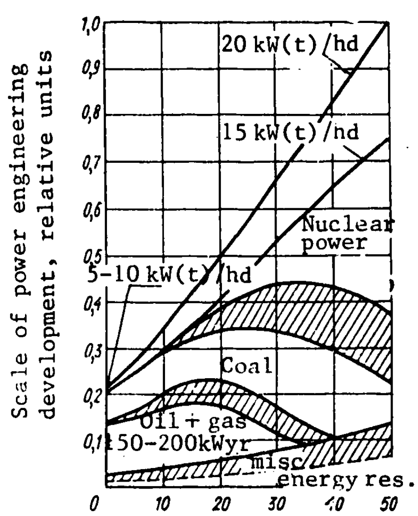


Fig. 1. Scales of development of power production (zones of undetermined use of energy resources are shaded)

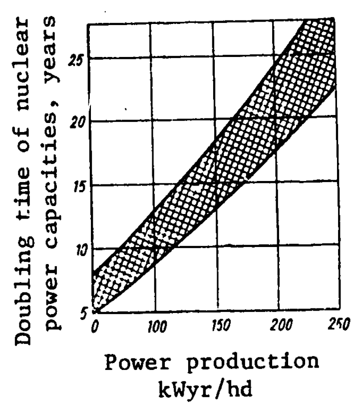


Fig. 2. Doubling time of nuclear power capabilities

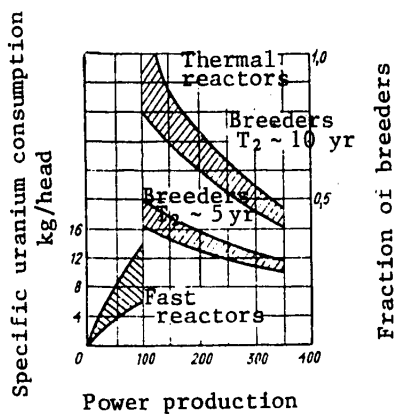


Fig. 3. Uranium consumption and necessary numbers of breeders

Peculiarities and Advantages of HTGR's

HTGR's have some distinguishing features and advantages that make them the most promising for the nuclear power industry. Principal among these are:

1) high temperature, better thermal efficiency, lower heat emissions to the environment, lower consumption of cooling water;

2) high safety due to high negative reactivity, high heat capacity of the graphite core, absence of phase transitions and chemical inertness of the coolant, and the presence of a number of safety barriers (microsphere fuel elements - element cladding - prestressed concrete vessel - emergency enclosure of the nuclear electric plant);

3) efficient fuel cycle (including Th and Pu) due to excellent neutron-physics characteristics, high accumulation factor and breeding ratio of fuel;

4) reliability in operation, simplicity of servicing, lower specific activity of the loop and leakage of radioactivity to the environment;

5) capability of high-power installations with lower capital investment, use of a gas-turbine cycle, "dry" cooling towers, simultaneous production of electric power and high-potential thermal energy, use of nuclear electric plant to cover peak loads.

HTGR Research Areas

1. Experimental facility with VGR-50 reactor of 50 MWe power. Purpose: accumulation of experience in designing and building HTGR's, working out helium technology, dynamics, safety, mass testing of fuel elements, testing components of reactor control system, equipment components, etc.

The engineering plan for the project has been worked up.

2. Prototype facilities:

with VG-400 thermal reactor of 1000 MWt power for process energy purposes; with BGR-300 fast reactor of 300 MWe power.

Purpose: accumulation of experience in making installations with HTGR's and FGR's, developing equipment (gas blowers, steam generators, heat exchangers) studying problems of making prestressed concrete vessels, industrial methods of using high-potential thermal energy, confirmation of feasibility of attaining the required conversion properties in breeders.

Design work has been done on the rough-draft and planning stage. Coordinated work is being done by scientific research and planning design agencies.

3. Industrial facilities with HTGR's and FGR's of more than three million kWt power. Purpose: production of high-potential heat, regenerators, synthetic fuel, hydrogen for industry, transportation and household use; for purposes of electric power production with the use of a direct cycle, air cooling and utilization for covering peak loads.

Studies are being done on parameters and prospects for using large HTGR's for the national economy.

State of Research on HTGR's

Theoretical and experimental research. 1. Studies are being done on analyzing areas for most efficient use of HTGR's:

a) for electric power production (here other types of reactors may be competitors), including with gas-turbine facilities and for covering peak loads; b) to produce high-potential process heat (this field of application of HTGR's is most promising, including in connection with the lack of competition at the present time). Under consideration are the processes and sectors of industry that consume the most energy, and also utilization for transportation and domestic purposes:

metallurgy, where the use of HTGR's will reduce demands for coke and natural gas, and when the technology has been successfully developed will enable transition to the process of direct reduction of iron;

chemical industry (production of ammonia, methanol, etc.);

gasification of coal;

heat supply to centralized consumers.

Particular attention is being given to hydrogen production by dissociating water, since water is an unlimited source of the most ideal energy carrier, which can be used in the power industry, metallurgy, chemistry, households, transportation, etc.

2. Physicotechnical studies are being done on different HTGR designs (physics and thermophysics of reactors, dynamics, fuel cycles, various kinds of fuel elements, safety, etc.).

3. Materials for HTGR's are being studied. Research is in progress on different kinds of graphite for fuel elements and reflector, construction materials for equipment (tubing, steam generators, heat exchangers, etc.), insulation materials.

4. Work is under way on fuel element manufacturing technology (spherical and prismatic versions) and making microsphere fuel elements.

5. Research is being done on equipment components in facilities and nuclear electric plants (prestressed concrete vessels, steam generators, heat exchangers, etc.).

6. Research is in progress on helium coolant technology, yield of fission products, monitoring instruments and helium cleaning system.

7. Facilities are being developed and made for studying patterns of movement of fuel elements, rods of the control system, materials and the like, critical stands (Astra, Grog) (Fig. 4), experimental helium loops (PG-100) (Fig. 5). Reactor ampule tests are being done on fuel elements and microspheres.

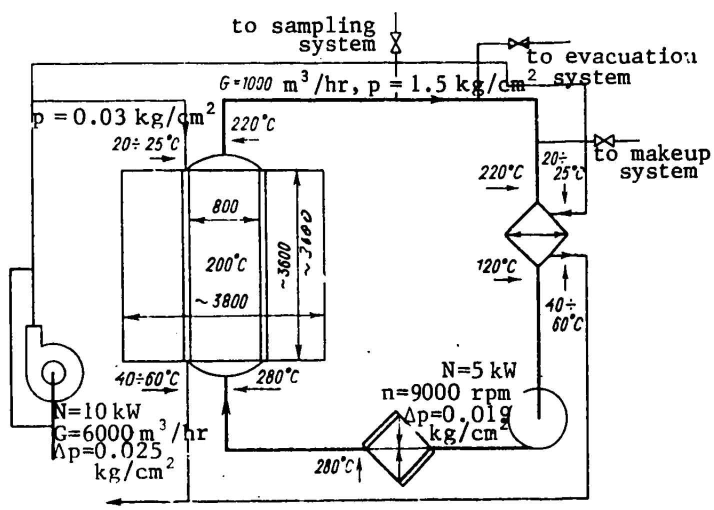


Fig. 4. Astra critical stand

8. Research is being done on helium-cooled fast reactors that have an advantage over other types of fast breeders in higher breeding gain and shorter doubling time; experiments are being done on critical assemblies (Korba).

Planning and design work. 1. Development is in progress (engineering design stage) on a two-loop experimental chemical process facility with HTGR (Fig. 6).

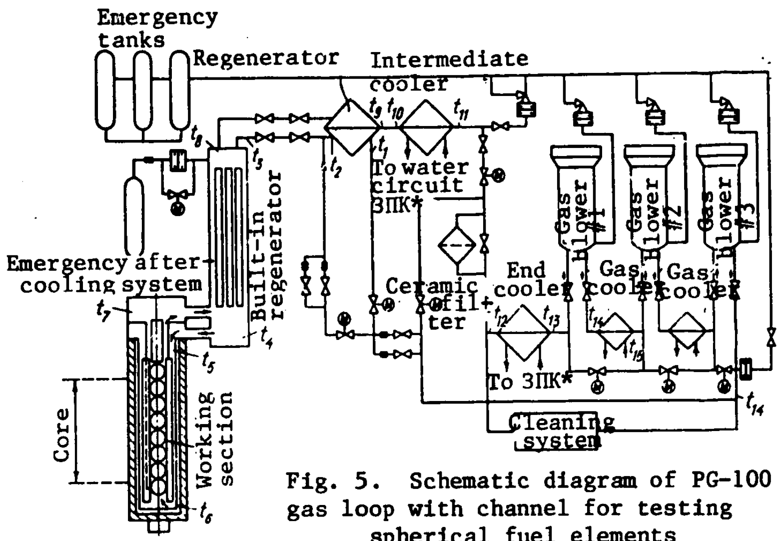


Fig. 5. Schematic diagram of PG-100 gas loop with channel for testing spherical fuel elements

*expansion of ЗПК not given

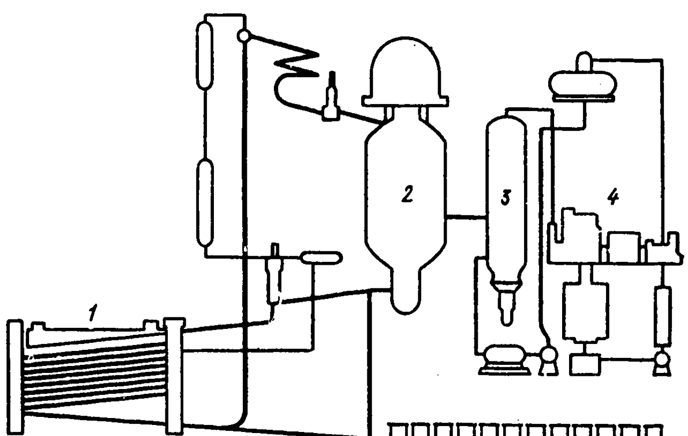


Fig. 6. Diagram of nuclear chemical processing facility: 1--irradiator; 2--reactor; 3--steam generator; 4--turbo-generator

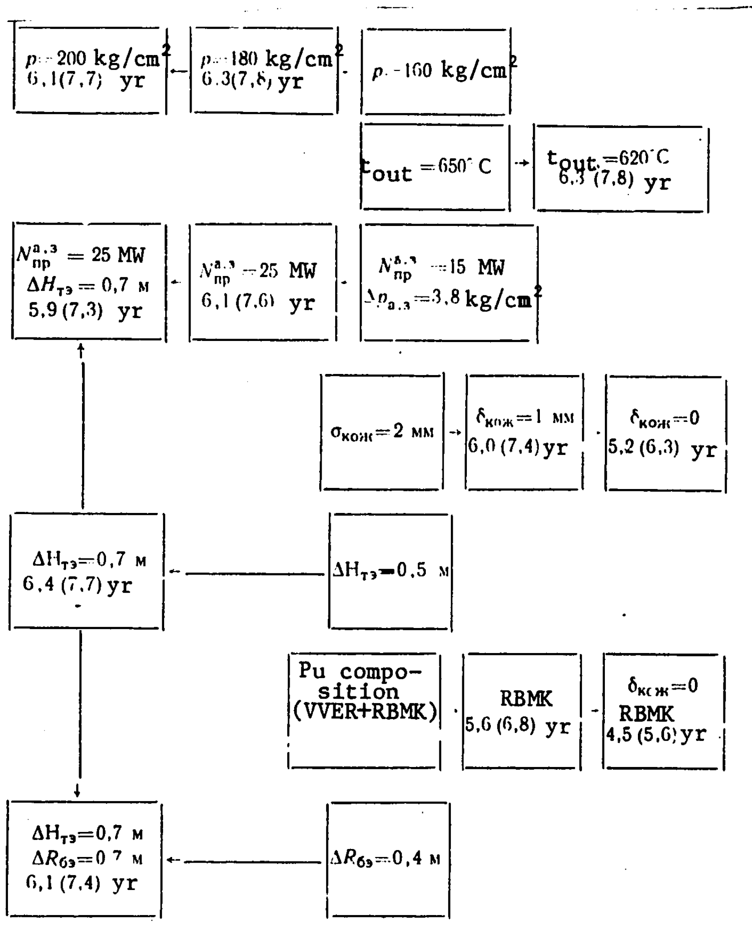
Power--50 MWe
Helium temperature--280/800°C
Pressure--40 kg/cm
Core dimensions--D/H = 2.8/4 m
Control rods:
  in reflector and pylons--24
  submerged--4-6

Fuel element--sphere (∅ = 60 mm)
Number of fuel elements:
  in facility--260,000
  in reactor--125,000
Fuel enrichment--21%
Burnup--100,000 MW·day/metric ton
Gamma power of radiation loop--300 kW

$N_e = 300$ MW; $t_{in} = 300°C$; $T_2 = 6.5(8.0)$ yr; $t_{cl}^{max} = 800°C$; $\tau_{cn} = 0.5$ (1.0) yr

$t_{fuel}^{max} = 2150°C$

Fuel $UO_2 + PuO_2$



$N_e = 300$ MW; $\delta_{кож} = 0$; $T_2 = 3.5(4.3)$ yr; $\Delta H_{тэ} = 0.7$ m;
$\tau_{пер} = 0.5(1.0)$ yr; $\Delta R = 0.6$ m; $p = 200$ kg/cm^2; $t_{in} = 300°C$
$t_{out} = 620°C$; $t_{cl}^{max} = 800°C$; $N_{пр}^{a.з} = 25$ MW; $t_{fuel} = 2150°C$;
Fuel $UO_2 + PuO_2$

Fig. 7. Influence of BGR-300 parameters on fuel doubling time

Steam parameters--90 atm, 535°C
Number of cooling loops--4

Reactor shell--steel
Proposed completion deadline--1985

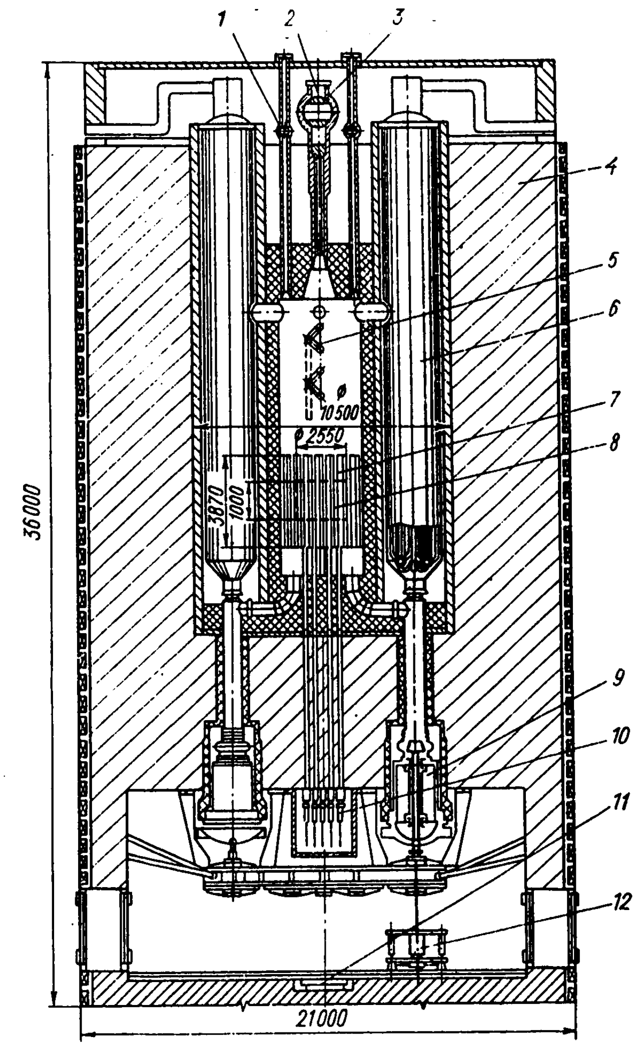


Fig. 8. Fast breeder reactor with helium cooling (integrated version): 1--passage for extracting and installing cassettes; 2--passage for reloading mechanism; 3--gate; 4--prestressed concrete vessel; 5--reloading mechanism; 6--steam generator; 7--breeding blanket; 8--core; 9--gas blower; 10--control system drive; 11--rotating device; 12--truck with telescopic hoisting crane

2. Development is in progress (rough-draft stage) on prototype facilities (different versions) for producing process heat (up to 950°C) with power of 500-1000 MWt with HTGR using spherical and block fuel elements, including the VG-400 technological power unit:

Thermal power of reactor--1000-1100 MW
Helium temperature--350/950°C
Helium pressure--50 kg/cm^2
Core dimensions--D/H = 6.4/4/8 m
Control rods in reflector and core
Fuel element--sphere (∅ = 60 mm)
Number of fuel elements--800,000
Fuel enrichment--10%
Run--3-4 yr
Number of loops--4
Electric energy production--300-400 MW
Hydrogen production (thermochemistry, methane conversion)--(20-25) 10^3 nm^3/hr per loop
Vessel--prestressed concrete
Proposed deadline--1985-1990

3. Development is in progress (rough-draft stage) on a demonstration fast helium reactor with power of 300 MWe (Fig. 7, 8):

Thermal power--800 MW
Helium temperature at reactor outlet--600-850°C
Helium pressure--160 kg/cm^2
Energy release rate--500 kW/liter
Fuel--UO_2-PuO_2
Breeding ratio--1.6-1.7
Doubling time--6-8 yr
Second loop parameters--170 atm, 540°C
Vessel--prestressed concrete
Nuclear electric plant efficiency--38%
Deadline undetermined

4. Studies are being done on parameters of facilities proposed for industrial introduction after 1990.

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SOME REQUIREMENTS FOR NUCLEAR-CHEMICAL FACILITIES WITH HIGH-TEMPERATURE REACTORS

Moscow ATOMNO-VODORODNAYA ENERGETIKA I TEKHNOLOGIYA in Russian No 2, 1979 (signed to press 8 Jun 79) pp 67-72

[Article by N. D. Zaichko, I. Ya. Yemel'yanov, A. M. Alekseyev, V. M. Panchenkov, Yu. I. Koryakin, A. A. Orlov, E. K. Nazarov, V. A Chernyayev, S. A. Mikhaylova, L. P. Dudakov and S. V. Radchenko]

[Text] The authors consider conditions of forming power-process arrangements for producing hydrogen, ammonia and other goods based on direct conversion of heat from high-temperature nuclear reactors to a technological process. Based on these conditions, major requirements are formulated for high-temperature reactors to serve industrial technology: service life, time between repairs, radiation safety, etc.

Ref. 1 reported on the feasibility and major areas of introducing high-temperature reactors for making hydrogen, ammonia and other products. It was shown that the process most ready for realization in respect to receiving thermal energy from high-temperature reactors is steam catalytic conversion of hydrocarbons. Therefore let us consider some requirements for nuclear-technological facilities that realize conversion processes.

As fossil fuel is displaced by nuclear fuel, there is a considerable reduction of labor inputs, an increase in labor productivity, and a reduction in production outlays and settling expenditures per unit of final product due to a reduction of labor inputs on extracting and transporting fuel because of the much higher "calorific value" of nuclear fuel over any kind of fossil fuel. Nonetheless, along with the overall reduction in the level of labor expenditures in the national economy, there may be some increase in the nitrogen industry. Therefore careful analysis and detailed examination of this point must be taken into consideration when studying the feasibility of introducing nuclear reactors into industrial technology.

When high-temperature heat is produced by burning natural gas, an arrangement with better technical-economic efficiency is two-stage endothermic conversion of methane, which is mainly the basis for ammonia production (Fig. 1).

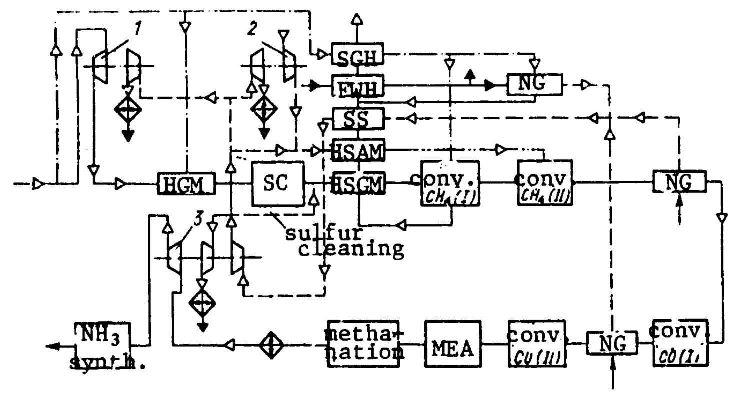


Fig. 1. Classical ammonia production scheme: 1--natural gas turbocompressor; 2--air turbocompressor; 3--nitrogen-air mixture turbocompressor; ——▷—— -- process gases; -•••-▷-••- -- air; -•-▷-•- -- natural gas (fuel); ——▶—— -- feed water; ---▷--- -- water vapor

Engineering, design and economic workups of plans for the first nuclear-chemical complexes are based on ammonia and methanol production aggregates with capacity of 2500-3000 metric tons per day. The choice of this ammonia and methanol production capacity has dictated a required power of the nuclear reactor installation of 550-600 MWt.

With respect to conditions of direct utilization of high-temperature heat from nuclear reactors in ammonia production, an arrangement with two-stage methane conversion is most preferable, although it is possible to realize a scheme with single-stage conversion of methane and additional displacement of fossil fuel even in the process channel. The advantages of the two-stage arrangement are as follows:

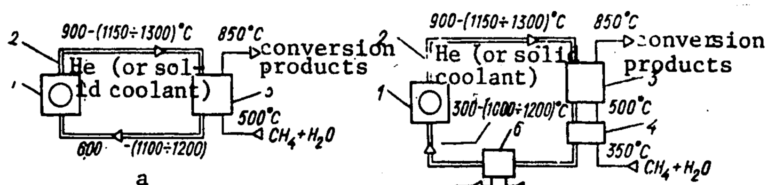
maximum capabilities for replacing fuel gas with nuclear fuel;

minimum level of working temperature of the stage of the technological process in which heat from the high-temperature nuclear reactor is to be used--less than 875°C;

the natural gas consumed in this arrangement is divided into two flows: fuel (45-50%) burned to get high-temperature heat, and process gas, facilitating conditions of replacing the fuel natural gas with nuclear fuel;

steam catalytic endothermic conversion of methane is accomplished in individual tubular reactors with diameter of less than 150 mm with external supply of high-temperature heat through a solid wall (rather than in an integrated working volume), which is more favorable for direct utilization of heat from high-temperature nuclear reactors;

the tubular reactors used in present-day production have a guaranteed service life of 100,000 hours, retain gas-tightness at a temperature of up to 950°C



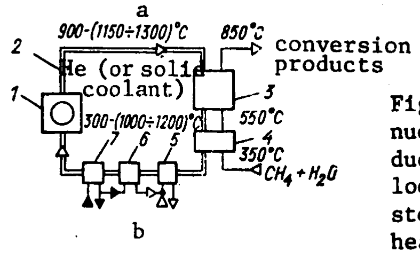


Fig. 2. Versions of utilizing nuclear reactor in ammonia production: 1--reactor; 2--coolant loop; 3--converter; 4--heater for steam-gas mixture; 5--steam superheater; 6--steam generator; 7--water heater

Structure of heat utilization (Gcal/hr) in energy scheme of ammonia production facility with capacity of 3000 metric tons per day

Index	Without using nuclear reactors (initial version)	With use of nuclear reactors: only for conversion	With use of nuclear reactors: for conversion and generating steam at pressure of 110 atm	
		Version 1	Version 2	Version 3
Conversion of steam-gas mixture	185.0	185.0	185.0	185.0
Heating steam-gas mixture	26.4	26.4	26.4	26.4
Steam generation	68.0	68.0	68.0	238.5
Steam superheating	113.1	113.1	113.1	-
Heating feed water	57.4	57.4	57.4	-
Heating steam-air mixture	12.0	12.0	12.0	12.0
Heating gas mixture	10.6	10.6	10.6	10.6
Heating fuel gas	0.2	0.2	-	-
Total power from heat source	472.7	472.7	472.5	472.5
Thermal power of reactor not counting internal needs, MWt	-	215.0	525	525

Note: Above the broken line the heat is supplied by the nuclear reactor; below -- by burning natural gas

and pressure of 30-40 atm, and may serve as an engineering base for making new tubular conversion reactors that take heat from the nuclear reactor coolant;

a considerable part of the produced hydrogen (theoretically up to 50%) is formed from water rather than from methane ($CH_4 + 2H_2O = CO_2 + 4H_2$), which means that steam catalytic conversion of methane based on nuclear reactors can be considered as a first step on the road to producing hydrogen from water.

The possible versions of using nuclear reactors, distribution of the thermal power of the reactor with respect to consumers in ammonia production based on two-stage catalytic conversion of methane, and the principal values of technological parameters and working media are given in Fig. 2 and the table.

Version 1 (see Fig. 2a) assumes utilization of heat from nuclear reactors only in the high-temperature part of production--in the first stage of methane conversion for heating reaction tubes.

Heating of the steam-gas mixture, the steam-air mixture, feed water, gas mixture, superheating of steam and generation of saturated steam in an auxiliary boiler are accomplished in this case by heating natural gas. All equipment remains unchanged other than the heat-utilizing facility, which is slightly modified. Starting conditions and transient processes are unaltered. The advantages of this version are: relative simplicity of construction of the reactor unit that heats only one flow -- the steam-gas mixture -- in the conversion process, and most complete retention of the basic technological equipment for ammonia production (excepting the tubular furnace). Its disadvantage is the small fraction (about 20%) of liberated natural gas from the total production requirement, and low reactor power.

Version 2 (see Fig. 2b) almost totally obviates the use of natural gas as a fuel. In this connection, the heat necessary for steam conversion of methane, heating the steam-gas mixture, feed water, and also for generating and superheating steam with pressure up to 110 atm is provided by a high-temperature reactor.

Version 3 (see Fig. 2c) is distinguished by the fact that the reactor facility is used only for steam conversion of methane, heating the steam-gas mixture and producing saturated steam at pressure up to 110 atm. In view of the comparatively small required total thermal power (500-600 MW), high-temperature heat and energetic steam can be produced by a single reactor even for long-range process arrangements. In practice, the area of a single chemical combine accommodates several production facilities (ammonia, methanol, higher alcohols, etc.) with various technological chains in each one, and from arguments of economy and standby capabilities it is advisable to arrange parallel connections between the individual technological chains within each facility and among facilities. This may make it possible to centralize production of hydrogen-containing gas mixtures and energetic steam in separate specialized reactor facilities.

The advantages of this arrangement are operating reliability of each technological chain with lower expenditures on standby equipment and greater economy and reliability of producing high-temperature heat and energetic steam on specialized nuclear reactors.

Successful solution of the problem of hydrogenating large amounts of carbon monoxide into methane with liberation of considerable amounts of heat may in future enable rational solution of problems of distributing the high-temperature nuclear reactors over the area of the chemical enterprise. Existing and newly planned facilities in the nitrogen industry must meet the following requirements:

prolonged accident-free operation over the established work life (up to 30 years);

high level of utilization of installed power of process equipment (up to 8000 hr/yr);

high reliability of all machines and equipment incorporated in the technological chain;

ease of control, high degree of automation;

high level of labor productivity, maximum output from each worker;

minimum necessary consumption of raw materials and energy resources;

transportability, producibility and repairability of all equipment;

high economy of operation of entire facility.

Direct utilization of the heat of high-temperature nuclear reactors in the energy-consuming industrial processes of ammonia and methanol production also involves solution of some technological problems, chief among which are:

developing and producing reliable accident-free reactors with coolant temperature of 900-1400°C at the core outlet and total working life of up to 30 years with yearly continuous-duty operation of up to 8000 hours;

development of reliable and efficient technical facilities for heat transfer from the reactor core to the working volume of process equipment;

working out engineering measures to ensure protection of final goods and technical equipment from radioactive contamination;

solution of the problem of diffusion both from the core into the process channel and in the reverse direction.

Even now when operating facilities for ammonia production with a capacity of 1360 metric tons per day, considerable difficulties arise in the matter of training operating personnel with appropriate skills. The introduction of nuclear-chemical complexes requires implementation of additional steps in this direction, since the working conditions for service personnel in the process part of the facility will evidently be on a par with those of nuclear electric plants; requirements will change with respect to the makeup by specialties and the training of service personnel.

Conclusions

1. The current state and engineering prediction of development of high-temperature reactor equipment and nuclear fuel technology, the start that has been made on research and development, and analysis of the outlook for making a nuclear-chemical facility for ammonia and methanol production based on methane conversion allow us to count on organizing an experimental industrial plant of this type in the next 10-15 years.

2. The major problems in making and using high-temperature nuclear reactors in industrial processes of methane conversion are in the area of transferring the high-temperature heat from the core to the working volume for carrying out the technological process with appropriate observance of conditions of protecting products, service personnel and the enviroment from radiation at the required level of reliability and redundancy of the nuclear power source.

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PARTICULARS OF LAYOUT AND CONSTRUCTION OF EXPERIMENTAL INDUSTRIAL HIGH-TEMPERATURE GAS-COOLED REACTOR MODEL

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[Article by F. M. Mitenkov, Yu. N. Koshkin, O. B. Samoylov and Ye. V. Komarov]

[Text] An examination is made of the layout and construction features of the reactor, and also the problems to be solved on an experimental industrial facility. The proposed plan allows development of the facility by stages with different temperature levels.

High-temperature helium-cooled reactors are a new field in nuclear power. Their distinguishing feature is the feasibility in principle of getting heat with a high temperature -- up to 1000°C or more. Such a temperature potential cannot be attained in other power reactors currently known.

Possible ways of utilizing high-potential heat have been extensively studied in the USSR and elsewhere. Research shows that raising the temperature of the heat generated in a reactor to 750-800°C enables utilization of modern turbines with high steam parameters ($t_s = 530$-580°C). It is evidently inadvisable to further increase the temperature for a steam-turbine cycle.

There is a much better outlook for using the HTGR in a gas-turbine cycle, and also as a source of thermal energy for technological processes in various sectors of the national economy in which 70-80% of all generated energy is consumed as heat, particularly in the most energy-intensive processes of the chemical and metallurgical industry. Analysis has shown that to replace fossil fuel with nuclear fuel in these processes the coolant temperature must be 950°C or more. Such a temperature is attainable in the HTGR, opening up extensive possibilities for using the reactor in this field.

The use of high-temperature helium-cooled reactors in a high-energy process facility for producing thermal energy is looked upon as the major area for reactor utilization. Design developments have revealed that combined production of electric power and high-potential heat is most advisable from the economic standpoint, enabling effective utilization of generated heat with fairly high efficiency.

Development of commercial reactor installations for combined production of high-potential thermal energy and electric power necessitates a large volume of scientific research and experimental design work, enabling resolution of some engineering problems relating to the production, conveyance and utilization of heat with very high temperature, assimilating helium technology, working out new kinds of equipment and new materials.

Considering the complexity of the problem, it seems necessary to make an experimental industrial reactor installation. The purpose of such a facility is to check and confirm all major engineering decisions, and to develop the principal equipment and control systems under conditions of industrial operation. The development of an experimental industrial facility will open up the way for producing commercial models of the facility and using them on a wide scale.

In order that experience in developing, making and using the model might subsequently to the maximum extent become a basis for making commercial installations, it is necessary first of all to make a correct and sound choice of the direction of planning and the initial technical parameters, i. e. to work out the optimum technical requirements for an experimental industrial model of the high-temperature reactor with consideration of its ultimate purpose.

The technical requirements for an experimental industrial model stem from the jobs it is to handle:

1) checking and working out the layout of the facility, including the process loop;

2) checking designs of the principal kinds of equipment and systems, and refining them from operational results, when such units are clearly to a great extent unique (gas blower, steam generator, drives in the reactor control system, heat exchanger, cleaning system, monitoring system, etc.);

3) operational check of structural components and technology of reinforced concrete vessel;

4) checking new heat-resistant structural materials under conditions of prolonged operation, etc.

The necessity for preliminary solution of the enumerated problems precludes the use of a low-power facility for this purpose. A reactor with thermal power of 1000 MW can be recommended for the experimental industrial facility. In this case the major components of the installation (core, steam generators, gas blowers, heat exchangers) will have been prototyped on a sufficient scale for future commercial facilities.

When working up the design of an experimental industrial facility, considerable attention must be given to optimizing the layout of the facility with consideration of ensuring potential capabilities of getting information when developing new commercial energy-intensive technological complexes.

As an experimental industrial model we can consider a facility intended for generating high-temperature heat that would be utilized for producing electric energy in a nuclear power plant. Realization of such a project would enable us to work out principal solutions of the plan layout, as well as the equipment in the facility, including the reinforced concrete vessel, to incorporate into operation the fundamentally new loop with helium coolant, and to elaborate the working conditions of the facility. In this case it would be much easier to solve the problem of choosing structural materials since steam parameters (t_s = 530-550°C) can be ensured at a temperature of 750°C in the first circuit. However, this version would lack capabilities for checking the plan of the technological complex using high-potential heat and developing equipment at a temperature necessary for the commercial technological complex.

The second way is to develop a direct prototype of the energy complex in full scale, and hence with working temperature needed for supporting the given process cycle (t = 950°C). This assumes development of new heat-resistant materials, thereby pushing back the real deadline for making the experimental industrial facility. Furthermore, it should be taken into consideration that startup and alignment on this facility will undoubtedly take a long time, and bringing the temperature up to working level will be gradual. Most of the time on startup and alignment is taken up by the reactor installation proper since it is the most complex and important part.

However, the disadvantages of the second version can in large measure be eliminated if the design of the experimental industrial model allows development of the prototype by stages. For this purpose, the facility diagrammed in Fig. 1 can be suggested as an experimental industrial model of the installation. The heat produced in the energy unit can be used to generate electric power in a turbogenerator, and also for producing hydrogen in a chemical process complex.

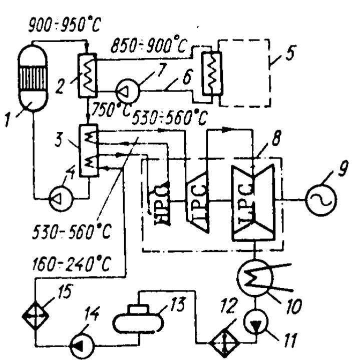

Fig. 1. Schematic diagram of experimental industrial nuclear power-producing and process facility (NPPF): 1--reactor; 2--high-temperature intermediate heat exchanger; 3--steam generator; 4--main gas blower; 5--chemical process circuit; 6--intermediate circuit; 7--gas blower for intermediate circuit; 8--turbine; 9--generator; 10--condenser; 11--condensate pump; 12--low-pressure water heater; 13--deaerator; 14--feed pump; 15--high-pressure water heater

Realization of the chemical technological process of hydrogen production requires a first-loop coolant temperature of 900-950°C at the reactor outlet. High-parameter steam is generated in the steam generator at temperature of 750°C at the inlet to the first loop. Such a facility can be manufactured and developed in three stages.

On the first stage the facility can be worked out on a temperature level up to 750°C with generation of electric energy in a steam-turbine cycle (Fig. 2)

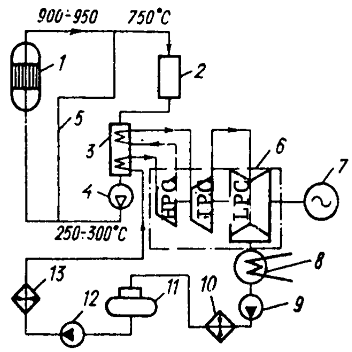

Fig. 2. Schematic diagram of NPPF for first and second stages of operation: 1--reactor; 2--high-temperature intermediate heat exchanger loop; 3--steam generator; 4--main gas blower; 5--bypass; 6--turbine; 7--generator; 8--condenser; 9--condensate pump; 10--low-pressure water heater; 11--deaerator; 12--feed pump; 13--high-pressure water heater

without completing development and manufacture of the heat exchanger, developing high-temperature fuel or installing the equipment of the chemical complex, by installing bypass pipes in place of the heat exchanger. Maximum reactor power in this mode is 70% of W_{nom}. The flowrate of coolant in the first loop, and all parameters of the steam generator and gas blower will be nominal.

On the second stage, with the same makeup of equipment as on the first, the temperature at the outlet of the core can be raised to 950°C, the former temperature level being maintained in the steam generators by diluting the hot coolant coming from the core with cool gas fed from the pressure side of the gas blower through bypass 5 (see Fig. 2).

On the third stage after making and installing the intermediate heat exchanger and all chemical process equipment, as well as completing startup and alignment work on the reactor facility, the entire facility shown in Fig. 1 can be developed and brought up to nominal power.

The plan for an installation with combined production of heat and electric energy is the most optimum solution in choosing an experimental industrial model of a facility with high-temperature helium reactor using thermal neutrons. This model provides an excellent prototype for the most promising power-producing and process facilities, and the design of the equipment and layout of the instllation allow the necessary multistage manufacture and operation of the model.

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CHOOSING DESIGN CONCEPT AND PHYSICAL FEATURES OF HTGR CORE FOR ENERGY FACILITIES

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[Article by G. P. Goroshkin, A. S. Kaminskiy, V. D. Kolganov, Ye. M. Kuz'min, M. D. Segal' and V. P. Smetannikov]

[Text] The authors consider the design of a high-temperature channel reactor with spherical fuel elements with thermal power of 540 MW with helium temperature of 950°C at the outlet of the core. Physical and hydraulic profiling of the core reduces the maximum temperature of the fuel elements. The advantages of such a reactor over other designs are indicated for use as part of a power-producing facility with combined supply of energy to chemical, metallurgical and other energy-intensive facilities.

Two directions of development of HTGR's are known in world practice: with a stationary core and with moving fuel elements in the core.

The first direction is characterized by the use of large graphite blocks in the form of hexagonal prisms in the core (reactors of the HTR type) with numerous openings for accommodating the fuel and passage of the cooling gas. This type of core is stationary, and recharging requires the use of loading machines that operate relatively rarely when replacing individual depleted blocks of the core or replacing the core in its entirety.

In the second direction, the core consists of a charge of spherical fuel elements that contain both fuel and moderator. In a reactor with such a core (type AVR and THTR) fresh elements are loaded and depleted elements are unloaded continuously during operation at power for a prolonged period.

In our view, disadvantages of such directions in reactor construction are:

a) for the first type of reactor: shutdown of the reactor during reloading of core blocks; variation of energy release distributions during reactor operation; comparatively long time for reloading core; high labor-intensiveness and technological complexity of fabricating the graphite core blocks; considerable thermal stresses that arise in graphite blocks under high heat loads;

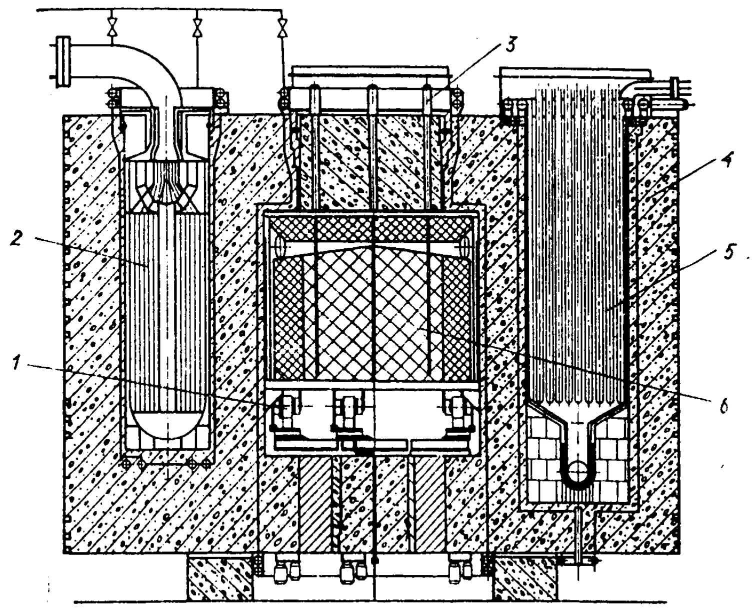

Fig. 1. Agat reactor facility: 1--loading machine; 2--intermediate heat exchanger; 3--actuating mechanism of reactor control system; 4--prestressed concrete reactor vessel; 5--conversion furnace; 6--core

b) for the second type of reactor: nonuniformity of spherical fuel element movement in the core; no capability for precise profiling of energy release with respect to core radius; necessity for accommodating the rods of the reactor control system in the charge of spherical fuel elements in the core in graphite pylons specially provided in the body of the core; possible fluctuations of porosity in the charge of spherical fuel elements of the core over the entire period of reactor operation; graphite moderator in the fuel elements, leading to additional expenditures when reprocessing depleted elements.

For industrial facilities (e. g. chemical, metallurgical and other sectors of the national economy), uninterrupted operation of the reactor throughout the technological production cycle is of decisive importance. This condition is met to a greater extent by reactors with continuous fuel recharging during operation at power. Reactors with spherical fuel elements can be put into this category. The Agat reactor (Fig. 1), designed to produce high-potential heat for the needs of chemical production, represents the first attempt to develop a facility that would not have the disadvantages of the above-mentioned reactors while retaining their positive features. The following design features have been incorporated into the facility: channel type core; regular geometry of core channels and control rods; partial separation of moderator and fuel; use of principle of one-time passage of fuel elements through the core; continuous reloading of spherical elements during reactor operation at power; capability for rearranging physical channels.

The core of the Agat reactor is made up of graphite components with the exception of the upper spacing plate and the lower support plate. The fuel elements are microspheres in a graphite matrix enclosed in a graphite cladding of spherical shape 60 mm in diameter. The moderator of the core is a set of vertically arranged prisms in which the fuel elements move (Fig. 2). The prisms are held in the lower support plate by metal sleeves that are hinged to the plate. Concomitant movement of fuel elements and coolant is necessary to maximize the coolant temperature at the outlet from the reactor at the permissible temperature in the center of the fuel element with the highest heat release rate (for example we can have a coolant temperature of 1200°C at the reactor outlet when the temperature inside the fuel element is 1300-1350°C).

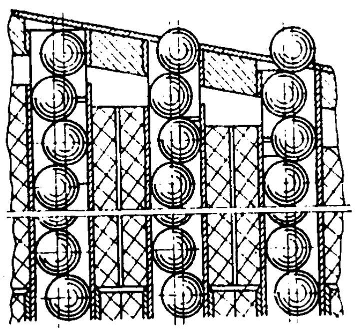

Fig. 2. Core fragment

The core is surrounded by a graphite reflector made of hexagonal prisms. Above it is an upper heat shield made of graphite blocks. The upper face of the core is conical; this is necessary so that the depleted fuel elements can roll down past the boundaries of the core. The thickness of the side reflector in the radial direction averages 1200 mm, and that of the upper reflector in the axial direction averages 1000 mm.

The reactor control system consists of 61 rods; these move in the same channels as the fuel elements and have a working section with absorber 5 m long. The drive mechanisms are situated on the cover of the reactor vessel.

The equipment is configured in the following way.

The prestressed reactor vessel is a monolithic block with recesses to accommodate the major equipment of the facility, emergency aftercooling equipment, and the channels of the reactor circuit (see Fig. 1). In the central part of the vessel is a cylindrical space for accommodating the core, reflectors, heat insulation of the vessel and lower support plate for the core. Above the central cavity is a passage to accommodate the reactor cover. In the lower part of the vessel under the core are seven vertical passages for installing the loading mechanisms for the spherical fuel elements. To accommodate the gas blowers of the reactor loop and the emergency aftercooling system, horizontal passages are provided in the reactor vessel in which the blowers are placed together with their drives. A hermetically sealed carbon steel facing (liner) fills the inside of the reactor vessel. To ensure the necessary temperature conditions for operation of the vessel, the liner is protected by heat insulation with a gas layer -- a so-called gas wall -- and tubes of a water-cooling system are buried in the concrete of the vessel at a certain distance from the liner. The cylindrical cavity of the housing is divided into two sections by the lower support plate, which has a passage for the fuel elements under each channel of the core, and openings for passage of the coolant that serves the moderator and reflector. A device for feeding fresh fuel elements into the channel is placed in each channel opening of the plate.

Seven reloading mechanisms provide continuous reloading of fuel elements during reactor operation. The spherical elements are loaded into each channel, each serving its own part of the core. When one of these mechanisms fails, the reactor is capable of operation at somewhat reduced power (about 15% below nominal) right up to shutdown for routine maintenance.

The design with lower placement of reloading mechanisms is chosen for the following reasons: the supporting structures of the core are situated in the zone of "cool" coolant; operation of the reloading mechanisms is facilitated by the absence of control rods under the core; the force from the pressure differential in the core is directed opposite to the force of gravity of the fuel elements and side reflector; coolant circulation in the reactor circuit coincides with the direction of motion of the coolant with natural circulation in the reactor in case the gas blowers stop; the principle of one-time passage of fuel elements through the core requires concomitant movement of fuel elements and coolant.

The proposed design has typical physical features of the HTGR, among which we note the following: 1) use of graphite, a weak absorber of neutrons, as the moderator, which ensures neutron economy, improves the breeding properties of the core and reduces the charge of uranium compared with other types of thermal reactors; 2) burnup is much higher than in other reactors: about 10^5 MW·days per metric ton; 3) the negative temperature coefficient of reactivity and large heat capacity of the core ensure a high degree of safety.

At the same time, the proposed design successfully combines the advantages and avoids the disadvantages of the spherical and prismatic forms of HTGR fuel elements.

Regularity of the passage of fuel elements through the core in the proposed channel reactor enables the use of a variety of effective methods of profiling the field of energy release. The necessary profiling through the core body can be achieved by: varying the fuel enrichment with ^{235}U in profiling zones; changing the rate of passage of the fuel elements in profiling zones; varying the density of the graphite moderator.

Temperature fields in the core body can also be equalized by hydraulic profiling.

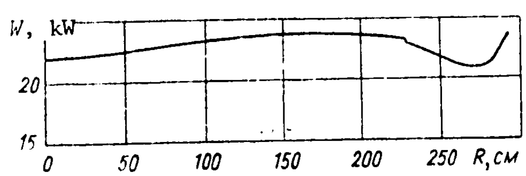

Fig. 3. Channel power distribution with respect to core radius

In the proposed reactor, three-zone profiling of the core is provided by using two types of fuel elements differing with respect to ^{235}U enrichment and moving at different velocities. Enrichment of fuel elements in the central (I) and peripheral (III) zones is 6.5%, and in the intermediate zone (II) -- 10%. This reduces the coefficient of nonuniformity of channel power along the radius of the reactor to 1.05 (Fig. 3).

The proposed design extends capabilitiss for controlling the process of bringing the core up to steady-state operation. This is done by providing controllable placement of absorbing elements specially introduced into the channels, and corresponding configuration of the control rods.

The proposed channel reactor design facilitates physical monitoring of core parameters at the necessary number of points to get reliable information, enabling on-the-spot correction of the coefficient of nonuniformity of energy release, raising the specific and thermal load on the fuel, and increasing the average burnup. The configuration of the control rods in the channels can also be optimized, which raises their effectiveness. In this way, the design has advantages over the AVR, where the control rods are situated around the periphery of the core in individual pylons.

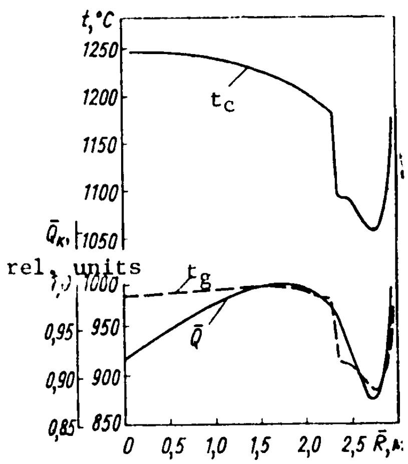

Fig. 4. Distribution of relative heat release $\bar{Q}_k$, gas temperature t_g and temperature in the center of the fuel core t_c along reactor radius $\bar{R}$

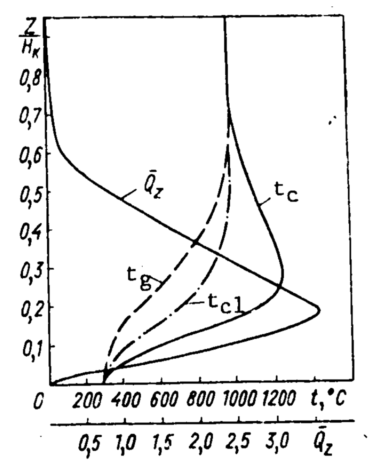

Fig. 5. Distribution of relative heat release $\bar{Q}_z$, gas temperature t_g, cladding temperature t_{cl} and temperature in the center of the fuel core t_c over the height of the core Z/H_k

Programmed motion of the fuel elements in each channel assumes stable distribution of energy release heightwise of the core throughout a run, and concomitant motion of fuel elements and coolant maximizes the gas temperature at the core outlet at the permissible fuel temperature. Thermohydraulic calculations for steady-state operation have shown that the temperature distribution can be kept fairly uniform through the core body (Fig. 4, 5).

Studies have shown that nonuniformity of the coefficient of heat transfer over the surface of a sphere from maximum to minimum is 2.2-3.0, and as a result, heightwise the maximum fuel temperature may be 10°C higher.

The feasibility of hydraulic profiling was checked for the selected version of physical profiling to determine the effectiveness of equalizing temperature fields along the radius of the core. For a channel diameter of 74 mm in physical profiling zone II and 75 mm in the other zones, the gas temperature at the outlet from the channel cores can be equalized and maximum fuel temperature can be reduced by 20°C compared with the hydraulically unprofiled version. When the channel diameter is 72 mm in physical profiling zone II, a reduction in maximum fuel temperature by 50°C is achieved, but nonuniformity of gas temperature at the core outlet is increased to 130°C as compared with the 110°C nonuniformity for the unprofiled version. Of course, hydraulic profiling somewhat increases the hydraulic drag of the core: for the unprofiled version, hydraulic drag is 0.39 kgf/cm^2; with channel diameter of 74 mm, drag is 0.41 kgf/cm^2, and for 72 mm -- 0.45 kgf/cm^2.

Based on thermohydraulic calculation, we can conclude that physical profiling enables attainment of the necessary equalization of temperature fields, while hydraulic profiling in the given case is less effective and requires at least two sizes of channels in the core.

As a result of design analysis, neutron-physics and thermohydraulic calculations of the reactor, the following characteristics are obtained:

Thermal power of reactor, MW	538
Dimensions of core, m:	
diameter	6
height	5
Number of channels	3481
Fuel element diameter, mm	60
Charge of uranium, kg	6570
Enrichment, %:	
in profiling zones I and III	6.5
in profiling zone II	10
Run, days:	
for fuel elements of profiling zones I and III	860
for fuel elements of profiling zone II	800
Reactor coolant	helium
Coolant flowrate in reactor circuit, kg/s	160
Coolant temperature, °C:	
at inlet to reactor	306
at outlet from reactor	950
Coolant pressure in reactor circuit, kgf/cm^2	40

In summary, we can conclude that engineering and design calculations have demonstrated the feasibility of developing a high-temperature gas-cooled reactor combining the advantages of cores of channel and microsphere types. Such a reactor can be used to produce high-potential heat in the chemical, metallurgical and other energy-intensive sectors of the national economy.

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MOLTEN-SALT REACTOR WITH NATURAL CONVECTION OF FUEL MIXTURE AND OPEN GAS-TURBINE AIR CYCLE

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[Article by V. A. Legasov, I. G. Belousov, N. K. Yerokhin and A. S. Doronin]

[Text] The authors consider some problems of using a high-temperature molten-salt reactor with natural convection of the fuel mixture in the primary circuit. Radiation provides the thermal coupling between the primary circuit and the energy (or process) circuit. Reactor heat can be used at a temperature near maximum. Combining a reactor of this type with a gas-turbine facility operating on an open cycle gives efficient conversion of heat to electricity.

Nuclear reactors with molten salt fuel mixture are in many respects an instructive phenomenon in nuclear power. Interest in these reactors arose in the 1950's in the United States in connection with development of a nuclear aircraft [Ref. 1]. An experimental reactor with power of 8 MW (MSRE) [Ref. 2] was operated at Oak Ridge National Laboratory from 1966 to the spring of 1968. During this period, 70,000 MWh of electricity was generated, and extensive experimental material was accumulated on many aspects of scientific and design developments of molten-salt reactors, which was the basis of project MSBR -- a one-fluid breeder reactor with thermal power of 2250 MW [Ref. 3, 4].

Project MSBR was shelved, although the anticipated properties of a nuclear power plant of this type opened up unique prospects both from the standpoint of utilizing [Ref. 5] and reprocessing [Ref. 6, 7] nuclear fuel, and from the standpoint of capital expenditures [Ref. 4]. There was no more really serious work on the problem of the molten-salt reactor, and poorly advised attempts to revive interest in the idea have led to considerable discreditation.

There are two reasons why it was quite natural to stop work on project MSBR. First of all, the power industry was not yet feeling any scarcity of nuclear fuel, and with the comparatively low fuel component in the cost of nuclear electricity, extra efforts to develop technology for processing salt fuel seem economically superfluous even in an ideal fuel cycle like that of the MSBR. In the second place, the coolant temperature attained in the primary circuit (700°C) is lower than in the HTGR, and further upward movement on the temperature scale is impeded by the particulars of interaction of salt with structural materials based on metals. On the other hand, the low capital component of the MSBR is obtained by calculation and cannot be taken as a conclusive argument.

The situation is considerably altered if metal-based structural materials are eliminated from the molten-salt energy circuit. An isothermal high-temperature molten-salt reactor design (VTRS) has been proposed in which the only metallic structural materials in the salt circuit are in the pump group. The purpose of our research is to examine the peculiarities of a VTRS in which the only structural material in contact with the molten-salt fuel mixture is isotropic pyrolytically precipitated graphite. The thermophysical layout of a power plant with such a reactor is exceptionally simple, and the attainable level of the coolant temperature in the primary loop, and also the thermodynamic quality [Ref. 8] of the reactor may be anomalously high. Heat from the core is transferred to a radiant heat exchanger by natural convection of the fuel mixture in graphite coaxial fuel elements. The resultant efficiency of a nuclear power plant with VTRS may reach 50-60%, and the thermodynamic quality of the reactor may be 0.95-0.98. Thus the way is opened up for considerable improvement of high-temperature nuclear heat sources for future power and process applications.

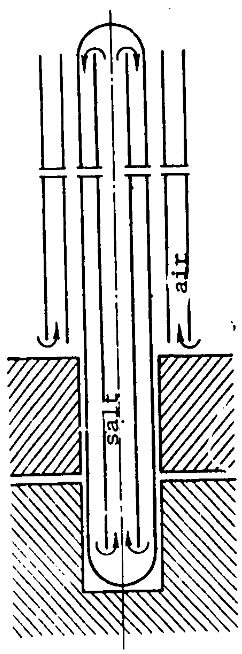


Fig. 1. Design of coaxial fuel element with natural convection of salt fuel mixture (LiF --0.75, ThF_4--0.24, UF_4 --0.01)

A temperature difference between the inner and outer columns of liquid (Fig. 1) is obtained by external heat removal in a radiant heat exchanger from the upper part of the fuel element, and volumetric nuclear heating of the lower part. Parameters of flow of the molten salt in the circuit of the fuel element are:

$$\left.\begin{aligned} &\mathrm{Gr} = \left(gd^2L\rho/\mu^2\right)\beta\Delta t_1\cdot D/(D+d) \sim 10^9 \div 10^{10};\\ &\mathrm{Re} = \rho w d/\mu \sim 5\cdot 10^3 \div 5\cdot 10^4;\\ &\mathrm{Nu} = \alpha d/\lambda \sim 50 \div 100;\\ &\mathrm{St} = \mathrm{Nu}/(\mathrm{Re}\cdot\mathrm{Pr}) \sim 10^{-3} \div 10^{-2}, \end{aligned}\right\} \quad (1)$$

where Gr, Re, Nu, St are the Grashof, Reynolds, nusselt and Stanton numbers. Conventional symbols are used to denote the parameters. The law of circulation is approximately described by the dimensionless equation [Ref. 9]

$$\mathrm{Gr} = 2{,}5\mathrm{Re}^2\left\{1 + \left(\frac{D-d}{d}\right)^3\left(\frac{D+d}{d}\right)^{1,75} + \frac{D-d}{L+l}\left[1 + \left(\frac{D^2-d^2}{d^2}\right)^2\right]\frac{\mathrm{Re}^{0,25}}{0{,}316}\right. . \quad (2)$$

We can see from equations (1) and (2) that a change in temperature head Δt_1 by a factor of nearly 100 is possible between the salt and the outer wall of the graphite channel in the vicinity of the radiative heat exchanger without changing the turbulent flow state (Blasius interval). In other words, at a fixed average temperature of the salt fuel mixture the external load can be reduced by two orders of magnitude while maintaining stable circulation.

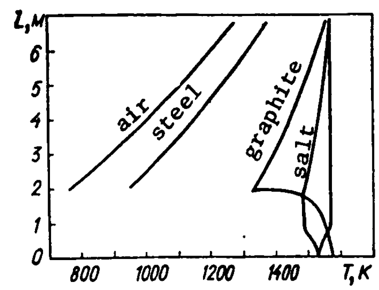


Fig. 2. Typical diagram of temperature distribution in the salt circuit, the outer jacket of a fuel element, the heat exchanger tubes and air heated therein

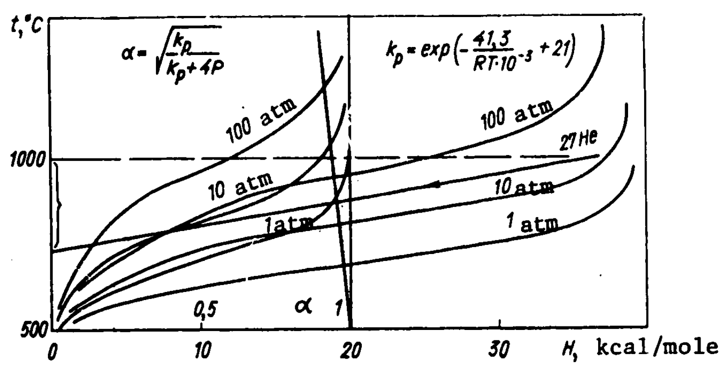


Fig. 3. Example of process consumption of heat from the nuclear reactor (conversion of coal to carbon monoxide)

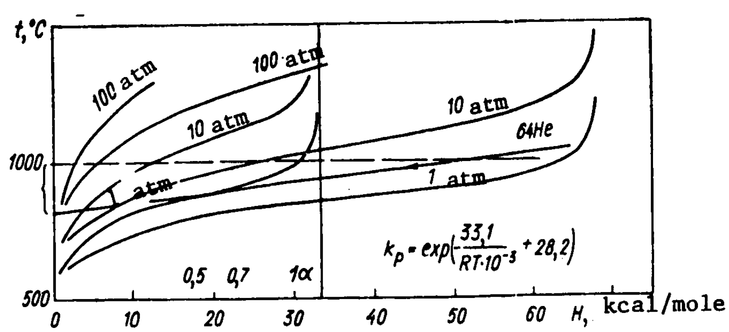


Fig. 4. t-H diagram of heat consumption on the first stage of a two-stage water thermolysis cycle

The nuclear reactor is made up of a series of fuel elements. The temperature differential lengthwise of the fuel element cladding (Fig. 2) in the zone of heat removal is about 100-150°C. Consequently, all high-temperature reactor heat can be transferred to the heat exchanger at a temperature little different from maximum. This explains the high thermodynamic quality of the VTRS as a heat source. Fig. 3 and 4 show examples of possible process consumption of nuclear heat of comparatively high quality. For example, when coal is converted to carbon monoxide (Fig. 3) according to the Boudoir reaction

$$\left.\begin{aligned} &2CO + 2H_2O \rightarrow 2CO_2 + 4H_2; \\ &\Delta G_2 = -9,55 + 1,9\,T/300 \text{ kcal/mole} \end{aligned}\right\} \quad (4)$$

with subsequent exothermal generation of carbon dioxide

$$\left.\begin{aligned} &CO_2 + C \rightarrow 2CO; \\ &\Delta G_1 = 41,3 - 12,6\,T/300 \text{ kcal/mole} \end{aligned}\right\} \quad (3)$$

It can be seen that carrying out reaction (3) at pressure of 10 atm involves compensation of the reaction energy in the temperature range of 750-1050°C.

Fig. 4 shows the t-H diagram of heat consumption in the temperature range of 820-1000°C associated with the first stage of the two-stage cycle of water thermolysis:

$$\left.\begin{aligned} &\text{I: } 2MnCO_3 + H_2O \rightarrow Mn_2O_3 + 2CO_2 + H_2; \\ &\Delta G_3 = 65,5 - 22,1\,T/300 \text{ kcal/mole } H_2O; \end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned} &\text{II: } Mn_2O_3 + 2CO_2 \rightarrow 2MnCO_3 + 1/2O_2; \\ &\Delta G_4 = -8,1 + 12,6\,T/300 \text{ kcal/mole} \end{aligned}\right\} \quad (6)$$

Obviously high-efficiency thermolysis cycles can be realized only in the case where an external heat source is capable of compensating the reaction energy in a narrow range of temperatures close to maximum. An example of a cycle of water dissociation with low-quality heat from the source is the sulfuric acid cycle:

$$\left.\begin{aligned} &\text{I: } H_2SO_4 \rightarrow SO_3 + H_2O; \\ &\text{II: } SO_3 \rightarrow SO_2 + 1/2O_2; \\ &\text{III: } 2H_2O + SO_2 \xrightarrow{\text{эл.}} H_2SO_4 + H_2 \end{aligned}\right\} \quad (7)$$

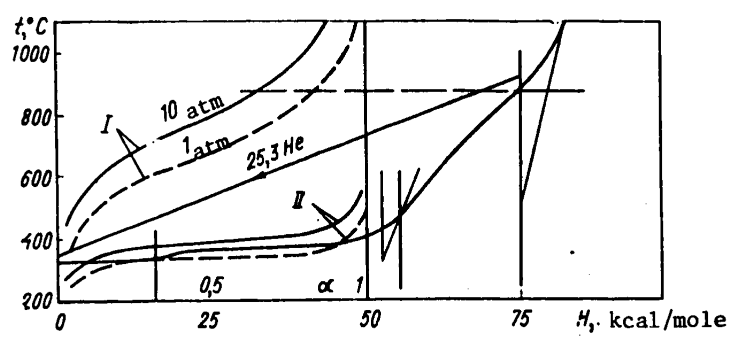
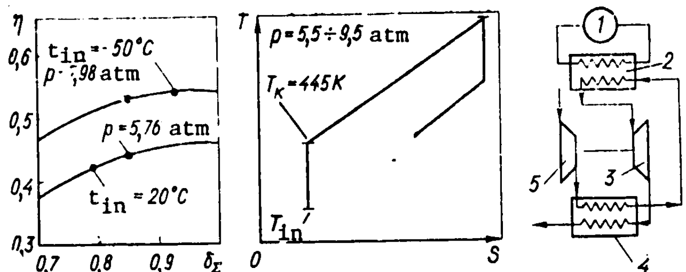


Fig. 5. t-H diagram of heat consumption on two stages of sulfuric acid dissociation: I--$SO_3 \rightarrow SO_2 + \frac{1}{2}O_2$; II--$H_2SO_4 \rightarrow SO_3 + H_2O$

The t-H diagram of the first two stages is shown on Fig. 5. The reaction energy is compensated in a temperature range of 370-900°C, and in this case we cannot count on high energy efficiency of the cycle corresponding to the maximum temperature of the heat source. It is known [Ref. 10] that the limiting thermodynamic efficiency of a cycle of dissociation of a substance into components does not depend on the use of either exceptionally high-temperature heat or electricity obtained from the Carnot-cycle machine. The limiting efficiency of the dissociation cycle is uniquely determined by the nature of the substance being decomposed and the extremum temperatures of the heat source and drain. In this sense the process utilization of high-temperature nuclear heat in the thermolysis cycle does not automatically give any advantages over the traditional method of generating electric energy and subsequent electrolysis (or plasma-chemical reaction [Ref. 11]). High-productivity electrolyzers or plasma-chemical reactors combined with a good electric power plant may be preferable to thermolysis process facilities. Therefore the method described below for converting high-temperature and high-quality nuclear heat to electricity by using a gas-turbine installation with open air cycle may be taken as a component in development of one of the important elements of process utilization of nuclear energy.



a b c

Fig. 6. Simple thermodynamic cycle (b) of gas turbine power plant with open air cycle ($\eta_t = 0.95$; $\eta_c = 0.9$; $\varepsilon = 0.8$; $t_g =$ 1273 K; $\delta_\Sigma = \prod_{i=1}^{n} \delta_i$); dependence of efficiency on total hydraulic losses in the air channel and air temperature at the compressor inlet (a) and schematic diagram of realization of this cycle based on VTRS heat (c): 1--reactor; 2--heat exchanger; 3--turbine; 4--regenerator; 5--compressor

A comparison of temperature curves for salt coolant and air in a radiative heat exchanger (Fig. 2) shows the possibility of a further appreciable increase in efficiency of utilizing high-temperature heat of the VTRS. However, some open gas-turbine cycles even on the given stage of optimization enable us to get quite high characteristics (Fig. 6). The air temperature at the inlet to the turbine is taken as 1000°C. The degree of regeneration of 0.8 is near optimum; the total relative hydraulic losses through the channel $1 - \delta_\Sigma$ are equal to ~0.14. The resultant efficiency of the power plant is 0.44 for air temperature of +20°C at the inlet to the compressor, and 0.53 for air temperature of -50°C. We should also take note of the low maximum pressure in the air circuit for temperatures of +20 and -50°C: about 6 and 8 atm respectively. This factor is quite significant for getting a reliable design of a high-temperature radiant heat exchanger. It is proposed that grade KhN45Yu steel be used as the construction material. The wall thickness of the hot tubes of the heat exchanger is 3 mm. At a temperature of 1100°C and pressure differential of 1 atm, the long-term (10,000 hr) strength reserve is 2.

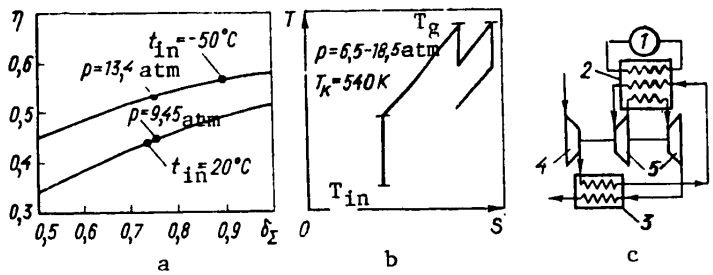


Fig. 7. Characteristics of open gas turbine cycle with one intermediate heater (conditions and notation same as on Fig. 6)

More complicated cycles enable us to improve the efficiency of the power plant (Fig. 7). The schematic of the power plant is a little more complex, but there is an appreciable gain in efficiency. For example at ambient air temperatures of +20 and -50°C the efficiency of a gas-turbine unit with two-stage heating is 0.48 and 0.56 respectively. The next step in improving the

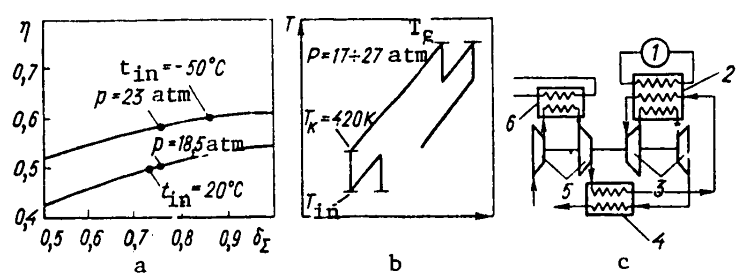
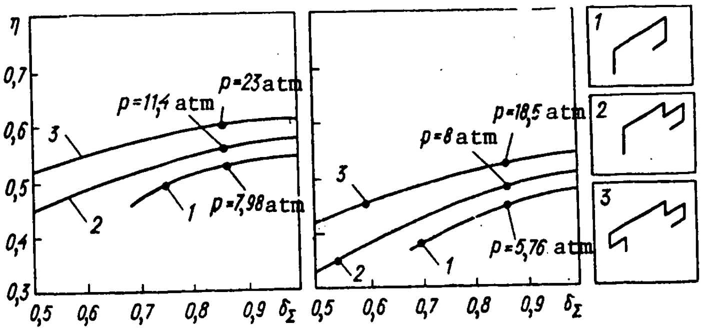


Fig. 8. Characteristics of open gas turbine cycle with intermediate cooling of air in the compressor (conditions and symbols the same as on Fig. 6; b--intermediate cooler)

cycle involves adding an intermediate stage of air cooling in the compressor (Fig. 8). The efficiency of the facility increases to 0.52 and 0.60 for air temperature at the inlet to the gas turbine unit of +20 and -50°C respectively. Optimum pressure in the air channel is 18.5 and 23 atm. Fig. 9 shows a clear comparison of efficiency of complex gas-turbine cycles for different air temperatures at the inlet to the compressor. As these data imply, it makes practical sense to develop complex cycles although pressure increase is a constraint.



a b c

Fig. 9. Comparison of efficiency of complex gas-turbine cycles at different air temperatures at the inlet to the compressor: a--$\eta_t = 0.95$; $\eta_c = 0.9$; $\varepsilon = 0.8$; $t_{in} = -50°C$; $T_g = 1273$ K; b--$\eta_t = 0.95$; $\eta_c = 0.9$; $\varepsilon = 0.8$; $t_{in} = 20°C$; $T_g = 1273$ K

We must emphasize a number of factors that are organically related to direct process utilization of VTRS's, or to their use in combination with a gas turbine power plant.

1. The attainable level of working temperatures of structural components based on graphite-salt opens up wide vistas for conquest of the high-temperature region.

2. The use of natural circulation of the fuel mixture in the primary circuit obviates the need for developing a high-temperature pump group, and enables transition to nuclear sources of high-temperature, high-quality heat.

3. The fuel cycle of molten-salt reactor systems is among the most promising both from the standpoint of complete utilization of fissionable materials (uranium, thorium, plutonium) in accordance with the sequence

$$\begin{array}{l} {}^{233}U \longrightarrow \downarrow \\ {}^{235}U \rightarrow {}^{232}Th \rightarrow {}^{233}U \rightarrow {}^{238}U \rightarrow {}^{239}Pu, \\ {}^{239}Pu \longrightarrow \uparrow \end{array}$$

and from the standpoint of reprocessing and disposal of fission products.

4. Absence of a water-cooling energy cycle makes nuclear power plants of the proposed type independent of a source of cooling water and more ecological compared with conventional plants.

5. The attainable efficiencies in the VTRS give access to new possibilities in technology of converting heat to electricity.

6. The fact that industry is prepared to produce air gas-turbine plants of the required class gives important economic advantages to development of

high-temperature nuclear power in the direction of the VTRS. Research organizations, design offices, metallurgists and machine builders have accumulated adequate experience for formulating and solving the problem of making gas-turbine power plants of the required class.

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PHYSICAL FEATURES OF HTGR WITH CIRCULATING FUEL

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[Article by N. N. Ponomarev-Stepnoy, A. N. Protsenko, Ye. S. Glushkov, V. N. Grebennik, V. Ye. Demin, V. S. Malkov, L. K. Malkova, O. N. Smirnov, D. F. Tsurikov and L. A. Bogatova]

[Text] An investigation is made of the characteristics of a high-temperature gas-cooled thermal reactor with graphite moderator for combined utilization of high-temperature heat and gamma radiation of spherical fuel elements circulating in the system made up of the reactor and irradiator. A curve is given for the way that the power of gamma radiation of the irradiator depends on the multiplicity of fuel circulation in the system. An examination is made of the particulars of fuel burnup effects compensated by absorbing elements that circulate concomitantly in the system made up of the reactor and irradiator.

The main tendency in the development of nuclear power at the present time is expansion of limits of application not only in electric power production, but also for producing high-temperature heat, energy supply to the metallurgical industry and production of reducing agents for metallurgy, power and heat supply to many sectors of the chemical industry, stimulation of chemical processes, etc. [Ref. 1-3]. Research has shown [Ref. 3] that these problems can best be solved by using high-temperature reactors with helium coolant. In particular there is a certain interest in the use of a nuclear reactor as a source of radiation for radiation-chemical processes. In this connection, use is made of gamma radiation of fissuion products in the radiation circuits as fuel is circulated in the reactor-irradiator system [Ref. 5, 6].

A diagram of fuel circulation is shown on Fig. 1. The reactor is the high-temperature VGR-50 with graphite moderator, helium coolant and spherical graphite fuel elements based on microspheres with multilayer coating [Ref. 4]. The reactor permits combined use of high-temperature heat that is removed by the helium coolant from the packed spherical fuel elements, and transportation to the irradiator of gamma-emitting fission products in the makeup of the irradiated fuel elements due to their circulation. It is desirable that the

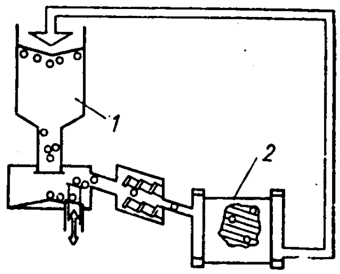

Fig. 1. Diagram of fuel circulation in facility with combined use of energy and gamma radiation: 1--reactor; 2--irradiator

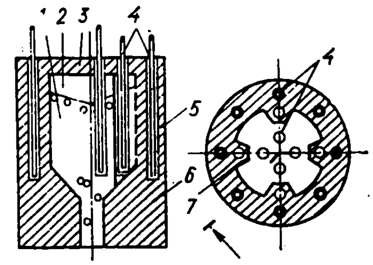

Fig. 2. Diagram of nuclear reactor: 1--core (packing of spherical fuel elements and absorbers); 2--gap; 3--top end reflector (graphite); 4--control rods; 5--radial reflector (graphite); 6--bottom end reflector (graphite); 7--pylons (graphite projections) for control rods

time of delivery of the irradiated fuel and its stay in the irradiator be short (a few hours) so as to use the radiation of short-lived isotopes of fission products.

A physical diagram of the nuclear reactor is shown in Fig. 2. The radial graphite reflector forms a cylindrical cavity that tapers into a cone in the lower part. In the bottom end reflector is an opening for unloading the contents of the core. The reactor is covered by the top end graphite reflector. The inner cavity is filled with spherical fuel elements and absorbers. Provisions are made for changing the number of absorbers in the circuit during circulation to compensate for fuel burnup during a run, the amount of absorbers not exceeding 15% of the amount of fuel elements. Between the top end reflector and the spherical packing of the core is a gap that can be varied over a wide range during reactor operation. The nominal size of the gap is about 0.5 m. The main parameters of the reactor are as follows:

Reactor power, MW	140	Spherical fuel element diameter, mm	60
Coolant	helium	Content of U in one fuel element, g	2-5
Helium pressure, atm	40	Fuel enrichment, %	10-30
Helium temperature, input/output, °C	270/800	Power of gamma radiation in irradiator, kW	400
Core dimensions, D/H, cm	280/450		

To study the influence that multiplicity of fuel circulation has on the power of gamma radiation in the irradiator, an analysis was made of experimental data on power and the spectral makeup of fission products [Ref. 7-10]. As a result of the analysis, an approximation formula is recommended for the time dependence of power of gamma radiation of fission products after fission:

$$\Gamma(t) = 1.5t^{-1.2} + 3.4t^{-1.4} \text{ MeV/(s·fission)},$$

where $t \geq 10^3$ s. The change in spectral makeup of gamma radiation is illustrated by the data of Table 1 [Ref. 10]

TABLE 1

Spectral makeup of gamma radiation of ^{235}U fission products at different times after fission, relative units

Time after fission, s	Energy range, MeV					
	0,1–0,5	0,5–1,0	1–2	2–3	3–4	4–5
900	0,125	0,266	0,381	0,172	0,040	0,016
$7{,}2\cdot10^3$	0,088	0,345	0,372	0,169	0,018	0,008
$1{,}8\cdot10^4$	0,070	0,342	0,407	0,160	0,014	0,007
$3{,}6\cdot10^4$	0,103	0,376	0,410	0,096	0,008	0,007
$8{,}6\cdot10^4$	0,196	0,515	0,259	0,018	0,005	0,007
$2{,}6\cdot10^5$	0,249	0,520	0,203	0,015	0,005	0,008

Theoretical studies have shown strong dependence of the power of gamma radiation of an irradiator on multiplicity of circulation in the system. Fig. 3 shows the way that the power of gamma radiation in the irradiator depends on the multiplicity of fuel circulation. It can be seen that an increase in the multiplicity of fuel circulation can raise the power of gamma radiation by a factor of approximately 10 as compared with the case without fuel circulation. A further increase in the power of gamma radiation is limited by the hold of the fuel following the irradiator that is necessary for de-excitation of delayed neutrons ($t_{del} \cong$ 10–20 min). The high core temperature leads to a strong temperature effect of reactivity. The change in effective breeding ratio as temperature increases is due to a number of factors:

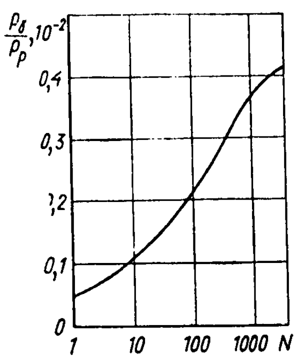

Fig. 3. Dependence of power of gamma radiation in the irradiator on multiplicity of fuel circulation (P_γ--power of gamma radiation; P_p--reactor power; N--multiplicity of circulation (run of 1-2 years)

Doppler broadening of resonant levels of ^{238}U as fuel temperature is increased;

a change in the spectrum of low-energy neutrons, which leads to a reduction in the yield of secondary neutrons per absorption in the fuel, a change in the ratio of absorption of the neutrons in the fuel and in other elements of the reactor, and an increase in the square of the diffusion path of thermal neutrons;

the temperature change in the density of reactor materials and the dimensions of its components, which primarily affects neutron leakage.

When studying reactor dynamics, it is important to break down the temperature effect of the reactor into individual components, which we took as follows:

the temperature effect of the fuel; this is the fastest-acting effect and is due mainly to Dopper broadening of resonant levels of ^{238}U;

temperature effect of the moderator associated with effects of thermalization of slow neutrons, change in density of the moderator in the core and change of dimensions;

temperature effect of the reflector associated with the change in the spectrum of low-energy neutrons and the dimensions and density of the reflector.

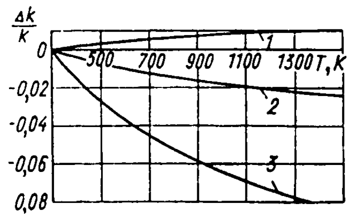

Fig. 4. Components of reactor temperature effect: 1--reflector effect; 2--fuel effect; 3--moderator effect

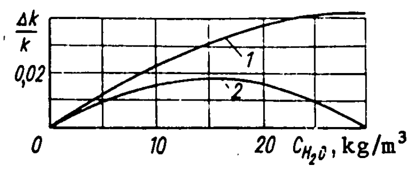

Fig. 5. Influence that water in the core has on reactivity (C_{H_2O} is the amount of water per m^3 of the core with submerged (1) and extracted (2) compensating control rods)

The overall temperature effect is negative (Fig. 4), and the reduction in the effective breeding ratio as temperature increases may reach ~10%.

Fluctuation of the level of sphere stacking in the core influences reactivity as a result of change in core height and the shooting effect in the cavity between the top end reflector and the core. Dependence of reactivity on the relative width of the gap between the top end reflector and the core stacking (Fig. 5) near the nominal stacking level has a rather flat slope, which is due to the large height of the core compared with its diameter.

As the reactor operates, certain changes in the density of spherical packing can be observed. In this connection, an estimate was made of the effect that a change in the porosity of spherical packing of the core has on the effective breeding ratio; this effect is characterized by the quantity $dk/d\varepsilon \cong -0.33$. The high porosity of the core makes such a reactor quite sensitive to hydrogen-containing substances in the core (water, water vapor, etc.). The following factors may influence the breeding ratio:

an increase in the moderating power of the core, leading to an increase in the probability of avoiding resonant absorption of neutrons by ^{238}U (positive effect);

a reduction in the length of migration of neutrons in the reactor, leading to a reduction of neutron leakage from the reactor (positive effect);

Absorption of neutrons in hydrogen (negative effect).

A typical maximum can be observed on the curve for reactivity as a function of the content of water (water vapor) in the core (Fig. 6).

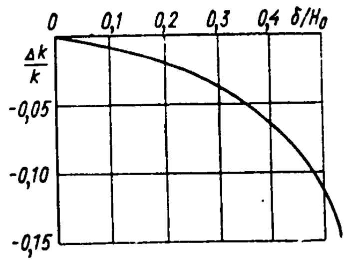

Fig. 6. Reactivity as a function of gap between top end reflector and spherical stacking of the core (δ--gap; H_0--distance between top and bottom end reflectors)

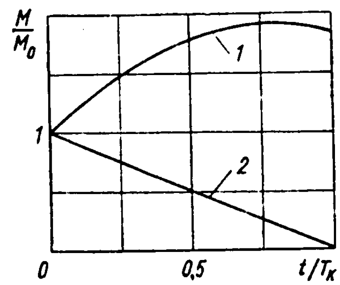

Fig. 7. Number of absorbers in core to compensate burnup effects: 1--units with burnable absorber ^{10}B; 2--units with unburnable absorber; M--number of absorbers located in the core stacking; t/T_K--ratio of elapsed time to run time

To compensate for effects of burnup with rapid circulation of fuel in the reactor, special absorbers of spherical shape (like the fuel elements) are added to the fuel charge of the core. As the reactor operates with circulating fuel, provision is made for the capability of changing the number of absorbers in the spherical packing to maintain criticality.

Fig. 7 shows the change in the necessary number of absorbers during a reactor run for two cases -- for burnable absorber (based on ^{10}B) and for nonburnable absorber.

The use of a "burnable" absorber, which does not necessitate a change in the number of absorbers during a run increases the negative temperature effect of the moderator due to blocking of the absorber as temperature is increased. Fast circulation of fuel in the reactor determines the particulars of ^{135}Xe poisoning due to entrainment of the irradiated fuel from the reactor with a large flux of thermal neutrons to the irradiator, where the thermal neutron flux is near zero with multiple repetition of the process.

A peculiarity of ^{135}Xe poisoning of the reactor during fuel circulation can be discovered by solving the following system of equations:

$$\partial\rho_I/\partial t + v\partial\rho_I/\partial z = \Phi_T\Sigma_{fT}W_I - \lambda_I\rho_I;$$
$$\partial\rho_{Xe}/\partial t + v\partial\rho_{Xe}/\partial z = \Phi_T\Sigma_{fT}W_{Xe} + \lambda_I\rho_I - \lambda_{Xe}\rho_{Xe} - \Phi_T\rho_{Xe}\sigma_{Xe},$$

where $\rho_I=\rho_I(t, z)$; $\rho_{Xe}=\rho_{Xe}(t, z)$ are the concentrations of ^{135}I and ^{135}Xe at time t at point z of the circuit; it is convenient to take as coordinate z the distance from the upper level of the core to the given point of the circuit in the direction of fuel movement; $\Phi_T(t, z)$ is thermal neutron flux density, $\Sigma_{jT}(t, z)$ is the macroscopic thermal-neutron fission cross section of the core, λ_I, λ_{Xe} are the constants of radioactive decay of ^{135}I and ^{135}Xe; W_I, W_{Xe} are the yields of the corresponding products upon fission of ^{235}U;

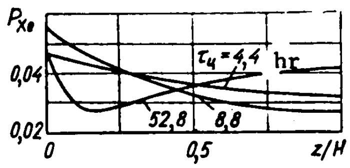

Fig. 8. Distribution of ^{135}Xe concentration heightwise of reactor with circulating fuel for different circulation times:

where ρ_{Xe}, ρ_5 are concentrations, σ_{cXe}, σ_{c_5} are the microscopic thermal-enutron absorption cross sections for ^{135}Xe and ^{235}U respectively

σ_{Xe} is the macroscopic thermal-neutron absorption cross section of ^{135}Xe; v is the velocity of fuel displacement during circulation.

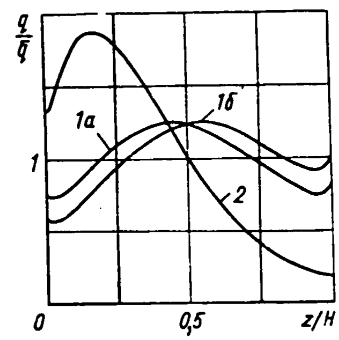

Fig. 9. Distribution of heat release heightwise of the core: 1a--considering (1б--disregarding) nonuniformity of temperature distribution heightwise of the core in the presence of fuel circulation ($\tau_ц$ = 4.4 hr); 2--using the principle of one-time passage of fuel elements through the core

At any time t, the solution of the system of equations should be periodic with respect to z with period l_K equal to the length of the fuel circulation loop. Let us note that instead of z we can introduce the variable

$$\tau = \int_0^z dz'/v,$$

where $\tau_K = \int_0^{l_K} dz'/v$ is the time taken by the fuel to complete one cycle.

In the case where the time of circulation is close to the period of decay of ^{135}Xe, strong nonuniformity is observed in the distribution of xenon concentration heightwise of the core (Ref. 8); however, there is little change in the average xenon concentration.

It is clear from the distribution of heat release heightwise of the core (Fig. 9) that when fuel is circulated the distribution of heat release is not very nonuniform (curves 1a and 1б), whereas with one-time passage of fuel through the core in the equilibrium state one observes strong distortion of the distribution of heat release heightwise of the core toward an increase at the beginning of the zone (curve 2), which is conducive to equalizing the temperature of the core material.

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SOME PROBLEMS OF HEAT EXCHANGE AND HYDRODYNAMICS IN HTGR CORE COMPONENTS (SURVEY)

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[Article by Yu. N. Kuznetsov and V. L. Lel'chuk]

[Text] The paper gives some results of theoretical and experimental studies of heat exchange and hydrodynamics in the annular channels, rod bundles, and in channels with permeable walls as applied to helium-cooled high-temperature reactors.

An examination is made of methods of calculating thermohydraulic processes in the primary circuit of HTGR's and GCFR's.

Mathematical Modeling of Processes of Convective Heat Exchange in Rod Bundles and Annular Channels. One of the authors (Kuznetsov) has been doing theoretical research on convective heat exchange in HTGR cores with rod fuel elements, in which the peculiarities are associated with comparatively low heat transfer coefficient, complicated geometry of the channel, variability of thermophysical properties of the coolant and large volumetric flowrate.

A theoretical study has been done on patterns of convective heat exchange in rod bundles and annular channels for arbitrary laws of change in the thermal load lengthwise of the channel. Yu. N. Kuznetsov has developed a technique that enables reconstruction of local values of heat exchange characteristics in any channel cross sections and for any law of heat supply based on studying the stabilized heat exchange far from the inlet with some specially selected law of heat supply. First for annual channels under conditions of constant thermophysical properties of the coolant and constant change in the heat load on both surfaces lengthwise of the channel (with constant heat load on the perimeter), the author examined the principles of stabilizing heat exchange with increasing disatance from the channel inlet, introducing a criterion that characterizes the influence of heat load variability, and is proportional to the logarithmic derivative of the function describing the change in heat load lengthwise of the channel.

As the heat load described by functions of exponential type changes with increasing length, the temperature field of the coolant is stabilized, but differs from the temperature field on the section of the heat exchanger stabilized with respect to length for the case of a constant load. These differences increase with increasing relative rate of change in the load, and they characterize the thermal inertia of the flow. This enables us to reconstruct the influence function for the given heat exchange process, which also characterizes the thermal inertia of the coolant flow. Mathematically, the process of finding the influence function reduces to solving an ordinary differential equation with unit boundary conditions in the complex plane, and to subsequent determination of some integral of the real part of the solution.

The major difficulties arise in description of the velocity field and transport coefficients of the turbulent flow of coolant. A model of turbulent coolant flow in annular channels is proposed. Results of calculations of the characteristics of turbulent flows and heat exchange by this model are compared with experimental data of various authors.

Values and generalizing formulas for the influence function G_1 are obtained for the temperature difference between wall and coolant over a wide range of working parameters and geometric dimensions. It is shown that the problem of local heat exchange characteristics in the case of longitudinal flow around infinite bundles of rods that are not too close can be reduced to investigation of heat exchange in the inner zone (between the rod surface and the line of maximum velocity) of such an annular channel for which the line of maximum velocity in some sense coincides with the line of maximum velocity of the given rod bundle. This has enabled us to use the above described results for studying annular channels, giving relations for the influence function with heat exchange in rod bundles.

The resultant formulas can be used for fairly exact calculations of local characteristics of heat exchange in any channel cross section with any law of variation in heat load lengthwise over a wide range of geometric and flow parameters: for annular channel $0 \leqslant r_1/r_2 \leqslant 1$; $10^4 \leqslant Re \leqslant 10^6$; $0.7 \leqslant Pr \leqslant 100$; for triangular or sqare bundle arrays $1.5 \leqslant \rho/d \leqslant 2.2$; $10^4 \leqslant Re \leqslant 10^6$; $Pr = 0.7$. Reliability of results is confirmed by comparison with experimental data of a number of authors.

It should be noted that experimental data on heat exchange in bundles, and especially on local characteristics of heat exchange, are rather scarce and often contradictory. Therefore experimental research has been done at the All-Union Heat Engineering Institute on local coefficients of heat exchange in bundles in the region of relative spacings of 1.2-1.7, which is of greatest interest for gas-cooled reactors.

Some Results of Experimental Studies of Thermohydraulic Characteristics of Turbulent Gas Flow Along Heated Surfaces. Some results for a turbulent air flow washing over a bundle of seven tubes with relative spacing of 1.2 located in a hexagonal unheated shell have been obtained by V. L. Lel'chuk et al. The diameter of the tubes was 10 mm, and minimum spacing between the walls of the peripheral tubes and the shell was the same as between the tubes, i. e. 2 mm; the equivalent diameter of the bundle was the same as for a bundle with an infinite number of tubes, $d_{eq} = d_{eq\infty} = 5.86$ mm; total length of the bundle between the end centering sleeves was 1200 mm; centering spacers were placed at distances of 300, 600 and 900 mm from the inlet. All tubes are heated by electric current of the same power flowing through them in parallel. Nineteen thermocouples are welded to each tube with different distances between them; to check uniformity of wall temperature around the periphery, the ten odd-numbered thermocouples are situated on a single generatrix facing toward the inside of the bundle on the peripheral tubes, and the other nine are placed in the spaces between the odd-numbered thermocouples, but on the opposite generatrix. In one control section near the outlet, special probes were used to measure the dynamic and static pressures and temperature of the flow in each peripheral and central cell of the flow. In addition, the temperature and pressure of the flow were measured in the stagnation chambers preceding the inlet and following the outlet of the tube bundle. The heat balance was computed from the difference between the total increment of entropy of the air in the tube bundle and the supplied electric energy with consideration of heat losses; the latter were determined from preliminary calibration; they came to 1-2%; divergence of the heat balance did not exceed 3%.

It was found that the wall temperatures of the central tube on both generatrices agree and are joined by a single smooth curve, with the exception of cross sections where the spacers are installed. In these cross sections the wall temperatures were systematically somewhat lowere than the overall curve, which is evidence of a stepwise change in the coefficient of heat transfer at the spacers. On the peripheral tubes, the temperature on the generatrices facing the center of the bundle was close to the temperature of the central tube (but higher than the temperature on the generatrices facing the unheated shell; the difference was about 10% of the temperature head). This gave the authors a basis for calculating the coefficient of heat transfer from the central tube to the air flowing along it in the region bounded from within by the wall of the central tube, and on the outside by the boundary passing over 1/3 of each peripheral tube and over the shortest distance between them.

Generalizing the results of their experiments, the authors obtained the following empirical relation for calculating local values of the Nusselt number for the initial thermal section of the investigated tube bundle under condition of constant thermophysical properties of the gas

$$(Nu/Nu_{40}) - 1 = 1.82(x/d_{eq})^{-0.728}, \quad (1)$$

where $Nu_{40} = 0.0184Re^{0.8}Pr^{0.4}$ are the values of the Nusselt number at $x/d_{eq} = 40$. In a first approximation it is assumed that heat exchange is stabilized at $x/d_{eq} = 40$.

The authors are still gathering experimental data to explain the influence of certain factors on heat exchange in tube bundles, and in particular the variability of physical properties of the coolant. The authors are also doing research on intensifying heat exchange in the fuel elements of the overheated part of BWCR's and GCFR's. Optimum geometric parameters are being determined for the artificial microroughness applied to the outer surface of rod fuel elements. Experiments are being done with annular channels that have a rough inside surface, and with rod bundles.

Experimental Study of Hydrodynamics of Cassettes With Microsphere Fuel Elements for GCFR's. L. L. Kalishevskiy and others are doing research in hydrodynamics of GCFR's on cylindrical and conical simulators of a microsphere fuel element bed using various configurations of porous tubes. They are determining the effect that a change in geometric characteristics has on the distribution of local values of flowrate through the wall of a porous tube with respect to length.

Analysis of experimental data has shown the following:

a) in cylindrical models, the distribution of local values of flowrate through the porous wall over the length of the cassette depends weakly on the ratio of cross sectional areas of the distributing and collecting channels F_p/F_c. In models of cassettes with conical porous inserts, due to the taper and to the corresponding change with respect to area of the distributing and collecting channels, there is a better opportunity for action on redistribution of the velocity of blow-in through the layer lengthwise of the cassette. On the other hand, if in addition to changing the flow sections of the distributing and collecting channels we also increase wall thickness, the flowrate of coolant through the porous wall reaches maximum values at $x/L \sim 0.5$;

b) static pressure changes insignificantly in the distributing channel, but in the collecting channel it falls off sharply toward the outlet end. Thus for constant drag and thickness of the porous layer, which determine the distribution of blow-in velocity lengthwise of the model, there is a change of static pressure in the collecting channel;

c) total hydraulic losses in models of cassettes with a cylindrical porous layer increase sharply with decreasing F_p/F_c. Minimum losses are observed at $F_p/F_c \cong 0.8$. Models of cassettes with conical porous layer also show an increase in losses with decreasing area of the distributing channel as compared with the output cross section. The total drag of the cassette depends on the Reynolds number to a power of 0.6-0.63, and is practically the same for different versions of cassette design. Such a power exponent corresponds to relations typical of spherical packing and porous materials.

Thus the required law of distribution lengthwise of the channel for values of flowrate of the coolant passing through a layer of microsphere fuel elements can be obtained by simultaneously varying the geometry of the channels and the drag of the microsphere fuel element layer; the preferable hydrodynamic arrangement of the cassette is one in which the distributing channel is located inside the layer of microspheres, while the collecting channel is on the outside.

Calculating Three-Dimensional Temperature Fields in Bundles of Fuel Elements of Rod Type. Determination of the temperqture field of the coolant in a bundle of fuel elements of rod type for known values of the coefficient of heat transfer and drag, and a known law of heat release is considered in Ref. 1. The physical model that is used is one of a homogeneized two-phase flow with stationary solid phase. The author considers hydrodynamically stabilized flow of an ideal gas with volumetric source of energy release, assuming that there is no transverse pressure gradient.

The initial system of equations takes the form

$$\rho u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho\,(\nu + D_T \mathrm{Pr}_T)\,\frac{\partial u}{\partial r}\right] + \frac{1}{r^2}\frac{\partial}{\partial s}\left[\rho\,(\nu + D_T \mathrm{Pr}_T)\,\frac{\partial u}{\partial s}\right] - \zeta\,\frac{\rho u^2}{2d_\Gamma}; \tag{2}$$

$$\rho u c_p \frac{\partial T}{\partial x} = q_v\,\frac{1-\varepsilon}{\varepsilon} + \frac{1}{r}\frac{\partial}{\partial r}\left[r\,(\lambda + \rho c_p D_T)\,\frac{\partial T}{\partial r}\right] + \frac{1}{r^2}\frac{\partial}{\partial s}\left[(\lambda + \rho c_p D_T)\,\frac{\partial T}{\partial s}\right]; \tag{3}$$

$$G = \varepsilon \int_0^{2\pi}\int_0^{R_0} \rho u r\,dr\,ds; \quad p = \rho RT; \quad T_w = T + \frac{d_\Gamma(1-\varepsilon)}{4\varepsilon\alpha}\,q_v. \tag{4}$$

where ε is the gas porosity of the bundle; d_Γ is the hydraulic diameter; Pr_T is the turbulent Prandtl number; α is the heat transfer coefficient; D_T is the turbulent transfer coefficient determined from experiments on heat or mass transfer and represented as $D_T \cong \kappa u d_\Pi$ (κ is the dimensionless effective transport coefficient); c_p is the specific heat of the coolant. All thermophysical properties of the coolant are assumed to depend on temperature. The given system can be solved only by numerical methods. To solve it, a synthetic method was developed that combines the method of matrix factorization with iteration cycles over nonlinearties.

The numerical analog of the system was written in an implicit finite-difference scheme having absolute stability. The equation of motion was split into two equations. The author of Ref. 1 devised a computational algorithm by using a vector-matrix form for recording the numerical analogs of the equations, boundary conditions of periodicity of the sought functions with respect to azimuth and conditions of the second and third kind for the equation of motion and energy. This algorithm was realized as a program in FORTRAN written for the BESM-6 computer. The algorithm has fairly high speed, and enables solution at 6000 points of a three-dimensional grid with dimensions of radius, azimuth and height. The error of integration of the finite-difference analogs of the initial equations does not exceed 0.5%. Convergence and stability of the solution were verified by numerical experiment.

Unfortunately, nothing is said in Ref. 1 about what relations were used or should be used for calculating the values entering into the algorithm: transport coefficients, Prandtl number Pr_T of the turbulent gas flow, heat transfer coefficient and drag in the bundle. There are no examples of calculations and estimation of the reliability of theoretical results. There are doubts about the form of recording the last term in the right-hand member of equation of motion (2).

Program of Thermohydraulic Calculation of Axisymmetric Channel. Ref. 2 gives a general description of a program for engineering thermal and hydraulic calculation of a multiflow cylindrical heat exchange channel of complex configuration. The given channel may consist of 1-5 lines separated by walls with up to ten heat-insulating layers in each wall. The direction of flow of coolants in the individual lines may be arbitrary. The central line contains the fuel elements. The geometry and material composition of the fuel elements and heat insulation may vary with respect to height. Some of the lines may be terminated with constricting flowmeter devices--a nozzle or diaphragm.

Solution of the problem can be based on a system of equations that define axial distribution of mean-mass temperature, coolant pressure, flow in the constricting devices, and also leakage of heat between lines through the thermal insulation.

In the program the principal equations of coolant flow in the channels are equations of heat balance, pressure differential and discharge from the nozzle. The process of heat exchange between coolant and thermal insulation is described by Newton-Riechmann law, and the process of heat transfer for cylindrical thermal insulation is described by a heat conduction equation.

In calculating heat leaks between lines, use is made of the condition that ideal contact exists between layers of heat insulation, and that there are uniformly distributed heat sources within each heat insulating layer. The coefficients of heat conduction of each layer of heat insulation are taken as constant and corresponding to the average temperature of the layer.

The problem is solved by an iteration method.

All thermophysical properties of heat insulating and construction materials depend on temperature, while the corresponding properties of the coolants depend on temperature and pressure.

There is a library of thermophysical constants for coolants, heat-insulating and construction materials.

The basic initial data for calculation in the program are:

a) geometric characteristics (channel height, geometry of fuel elements, structural dimensions of heat insulation, diameters of critical cross sections of nozzles or diaphragms);

b) parameters of coolants (flowrate in lines, temperature and pressure at the inlet or at the outlet from the lines);

c) energy characteristics (distribution of energy release with respect to channel height and in heat insulation);

d) characteristics of coolants and heat insulation (for each coolant, heat insulating material and structural material a number is introduced that corresponds to its number in the library of constants).

Upon completion of the calculation by the program, values are printed out for the pressure and temperature of the coolant heightwise of the channel, and also for the temperature field in the heat insulation.

All printout entries are labeled. The program is written in FORTRAN for application to the BESM-6 computer with Dubna operating system.

Unfortunately, this paper also lacks any specific application of the problem to a particular object.

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SOME RESULTS OF EXPERIMENTAL RESEARCH ON HTGR EQUIPMENT COMPONENTS

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[Article by R. G. Bogoyavlenskiy, Yu. D. Nikiforov, A. B. Anapol'skiy, L. M. Minkin and O. I. Kunakhovich]

[Text] The paper gives experimental data on wear of graphite models of spherical fuel elements moving at different velocities based on various components of the helium circulation loop at different temperatures, and also on the intensity of wear in life service tests of a plain bearing coated with molybdenum disulfide.

The main difference between the dual-purpose power-chemical facility and nuclear power plants with HTGR's is the presence of a process irradiator that consists of rows of ball guides through which spherical graphite fuel elements are moved by continuous-action mechanisms.

The entire circulation loop including the gamma irradiator is under a helium pressure of 40 kgf/cm^2. The helium temperature ranges from 300 to 1000°C along the line of fuel element circulation.

Each spherical graphite fuel element travels a distance of 150 km through the circulation loop during a run. In doing so, it moves at different velocities and experiences different loads.

As a result of friction between the sphere and the surfaces of the steel ball guides, and striking against the edges of joints and other components of the circulation loop, the graphite shell of the fuel element becomes worn. Therefore it is necessary to do experimental research on the wear of spherical graphite elements in helium under different loads and at different temperatures.

Another problem that arises in making the power-producing chemical facility is determination of materials for the bearings in mechanisms of the plant.

Mechanisms that transport fuel elements operate in helium at temperature of 300°C, pressure of 40 kgf/cm^2, and under the action of gamma radiation. It is not admissible to use liquid and plastic lubricants in the bearings of the bearings of mechanisms in the circulation loop. It is known that the coefficient of friction of unlubricated materials rises sharply in a pure helium atmosphere, which may lead to seizing and failure of the bearing. Thus it is necessary to select materials for bearings that would have a low coefficient of friction and high durability with "dry" friction, and to do life service tests on bearings under stand conditions.

The intensity of wear of spherical graphite fuel elements depends to a great extent on the nature of contact of the interacting bodies. For example in the case of elastic contact, which evidently occurs when a graphite ball moves in a metal ball guide, the intensity of wear depends on geometric and microgeometric characteristics, mechanical properties, the coefficient of friction, the fatigue characteristic of the material, contact pressure and other factors. The modulus of elasticity of the material also has an appreciable influence on intensity of wear. For example, the dependence of wear intensity on the modulus of elasticity takes the following form [Ref. 1]:

$$J_R \sim E^{t--\beta t-1},$$

where J_R is intensity of wear, E is the modulus of elasticity, t is the index of the fatigue curve, which varies from 3 to 14, $\beta = (2\nu + 1)^{-1}$, ν is the constant of microgeometry of the surface.

The influence of the specific contact stress on intensity of wear is expressed by the power law

$$J_R \sim q^{1+\beta t},$$

where q is specific contact stress, and the influence of the coefficient of friction is expressed by the dependence

$$J_R \sim f^t,$$

where f is the coefficient of friction.

When simulating the process of wear of spherical fuel elements, the influence of the modulus of elasticity, specific contact stress and microgeometry can be eliminated by making the geometric, mechanical and velocity characteristics of the model analogous to full-scale conditions in the facility; therefore the influence of the atmosphere shows up largely through the coefficient of friction. For this reason, we should know the change in the coefficient of friction in helium atmosphere at different temperatures.

Graphite in air at elevated temperatures has good antifriction properties. However, it has been observed that in vacuum and in some gas atmospheres its coefficient of friction increases and the wear of graphite materials becomes high. For example, the coefficient of friction of graphite after outgassing in vacuum becomes an order of magnitude higher, and elevated "pulverized" wear begins. Such wear is observed in air under severe friction conditions. The high antifriction properties of graphite in air can be attributed to its complex structure and easy slip over the most densely packed planes. In deep vacuum and in a helium atmosphere, graphite does not show the oriented layers on friction surfaces that are usual of friction in air and in an atmosphere of gases that contain oxygen, water vapor and other substances, which is evidently what explains the considerable increase in the coefficient of friction of graphite materials.

As a result of numerous studies on the coefficient of friction of graphite in vacuum at room temperature, and the way that it is affected by various gases and vapors, the absorption theory of friction of graphite materials has been formulated and widely accepted [Ref. 2]. In accordance with this theory chemosorption or physical adsorption reduces the energy of atoms of a crystal of the surface layer of graphite, which in turn leads to weakening of the forces between surface planes, facilitating displacement between them.

Usually, in order to satisfy the requirement of reducing the coefficient of friction and wear, graphite must have condensed moisture vapor; in some cases, the presence of oxygen alone may be sufficient.

Ref. 3 gives the results of a study of the way that the coefficient of friction of graphite depends on the depth of vacuum and temperature. A study of the influence of temperature from 20 to 800°C on the friction of graphite material grade E (AG-1500) against grade 1Kh18N10T steel has shown that in the case where the pressure of the ambient medium changes from atmospheric to $5 \cdot 10^{-4}$ mm Hg, the friction coefficient increases by a factor of 1.5-2 at all except room temperatures.

A study of the wear of spherical fuel elements made of grade MPG-6 graphite was done at VNIIAM [expansion not given] on three experimental sections of the Iznos stand. Experimental section #1 was a straight 12Kh18N10T stainless steel pipe with cross section of 76 x 4.5 mm, 6500 mm long. The pipe was heated by an electric coil, and the ends were covered with spherical graphite inserts. When the pipe is inclined at an angle of 10°, the ball moves under the force of gravity and strikes the insert.

Experimental section #2 is a pipe in the shape of a torus with radius of 1 m that is made up of two halves joined by flanges. The pipe was vibrated by an electromechanical drive, moving the ball under the action of the force of gravity and centrifugal force.

Some results of the study of wear of graphite balls on these two sections are given in Ref. 4.

Experimental section #3 was the same torus as section #2, but rotating in the vertical plane. The section also consisted of two halves joined by flanges. The pipe material was grade 12Kh18N10T stainless steel. Inside the pipe was a ball 65 mm in diameter or several balls that moved under the action of gravity and forces of friction in the rotating torus. The electromechanical drive permitted continuous variation of the speed of rotation of the torus from 5 to 30 rpm, and of the velocity of motion of the ball from 0.5 to 3 m/s. The section was heated by an electric coil wound over the entire length of the pipe.

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TABLE 1

Results of experiments on wear of graphite balls on the experimental sections

Experimental section	Number of experiment	Length of travel, km	Ball velocity, m/s	Atmosphere	Temperature of atmosphere, °C	Ball density, g/cm³	Mass of ball before experiment, g	Mass of ball after experiment, g	Loss of mass, g	Intensity of wear, mg/km
№ 1	1	32,2	1,0	Air	300	1,7490	250,44	250,18	0,26	8,08
	2	30,0	1,0			1,7490	250,18	244,99	0,19	6,33
	3	30	1,0			1,7490	249,99	249,78	0,21	7,00
	4	30	1,0			1,7490	249,78	249,53	0,25	8,33
	5	30	1,0	»	20	1,7490	249,53	249,39	0,14	4,66
	6	30	1,0			1,7490	249,39	249,58	0,11	3,66
№ 2	7	30	1,62	»	300	1,7094	245,58	245,34	0,24	8,00
	8	30	1,62			1,7094	245,34	245,08	0,23	8,61
	9	30	1,62			1,7094	245,08	244,80	0,28	9,33
	10	30	1,62			1,7094	244,80	244,57	0,23	7,66
	11	30	1,62	»	20	1,7094	244,57	244,40	0,17	5,66
	12	30	1,62			1,7094	244,40	244,23	0,17	5,66
	13	30	1,62			1,7094	244,23	244,09	0,14	4,66
	14	30	1,62			1,7094	244,09	243,95	0,14	4,66
№ 2	15	30	1,62	Helium	300	1,7094	250,0	249,70	0,30	10,00
	16	30	1,62			1,7094	249,70	249,35	0,35	11,65
	17	30	1,62			1,7094	249,35	249,06	0,30	10,00
	18	30	1,62	»	20	1,7094	249,05	248,70	0,35	11,66
	19	30	1,62			1,7094	247,17	246,82	0,35	11,65
	20	30	1,62			1,7094	246,35	246,09	0,26	8,67
	21	30	1,62			1,7094	246,09	245,84	0,25	8,28
	22	30	1,62			1,7094	244,84	245,58	0,26	8,52
№ 3	23	150	19,7	»	300	1,7915	241,50	238,22	3,28	21,83
	24	150	20,0			1,7915	236,09	232,61	3,48	23,19
	25	150	18,2			1,7015	232,61	230,20	2,41	16,07
	26	150,1	2,100	»	20	1,7691	246,25	243,51	2,74	18,27
	27	150	2,093			1,7691	243,51	241,15	2,36	15,72
	28	150	2,093	»	400	1,7094	243,82	239,45	4,37	19,10
	29	143,99	1,780		375	1,7915	225,81	223,29	2,52	17,51

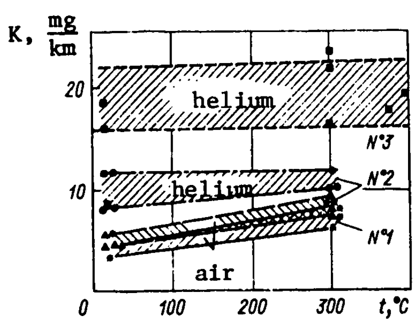

Fig. 1. Mass intensity of wear of graphite ball as a function of temperature on experimental sections: #1: *--air; v_{av} = 1.14 m/s; v_{max} = 2.5 m/s; #2: ●--helium; ▲--air; v = 1.8 m/s; #3: ■--helium; v = 2.0-2.1 m/s

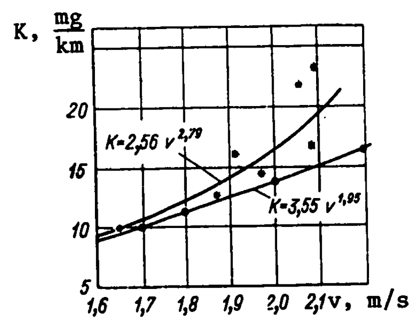

Fig. 2. Mass intensity of ball wear as a function of velocity: ● --experimental section #2; *--experimental section #3; atmosphere--helium; t = 300°C

Wear of an isolated graphite ball was studied for a helium atmosphere and air at a temperature of 20, 300 and 400°C. In each experiment, the ball travelec 150 km through the pipe, undergoing about 25,000 impacts against the graphite insert in section #1, and about 50,000 impacts against the edges of the flange connections in sections #2 and #3.

The results of some experiments are summarized in Table 1. The graphs show the way that wear intensity depends on the temperature of the medium (Fig. 1) and linear velocity of motion of the ball (Fig. 2). The intensity of wear of the ball was determined by the formula

$$K = \Delta G/L,$$

where ΔG is the loss of mass of the sphere in mg, and L is the length of travel of the sphere through the pipe in km.

The influence of temperature on wear of a graphite ball in air was studied in sections #1 and #2. As temperature increases from 20 to 300°C, wear intensity increases (see Fig. 1) from 4 to 7 mg/km in section #1, and from 5 to 9 mg/km in section #2. This is explained by the fact that as temperature increases, there is a reduction in the amount of water in surface layers of the graphite ball; in this connection, in accordance with the adsorption theory of lubrication there is an increase in the energy of atoms of a crystal of the surface layer, and displacement between surface planes is impeded.

The greater wear in section #2 than in section #1 can be attributed to the fact that the ball was moving at a slower velocity in section #1.

The influence of temperature on wear of a graphite ball in helium was studied in section #2 at a ball speed of v = 1.6 m/s, and in section #3 at ball speed of v = 2 m/s. As helium temperature was changed in section #2 from 20 to 300°C and in section #3 from 20 to 400°C, ball wear intensity in each section remained unchanged (see Fig. 1). Besides, wear intensity in section #2 with testing in helium was somewhat higher (~10-20 mg/km) than in air. This is also satisfactorily explained by the absorption theory of lubrication since in high-purity helium the amount of water vapor and oxygen is nearly independent of temperature, and is considerably lower than in air. The higher intensity of ball wear in helium in section #3 (18-22 mg/km) than in #2 (9-12 mg/km) is attributed to higher speed of the ball.

The intensities of ball wear in helium in section #3 for speed of 1.6-2.1 m/s are shown on Fig. 2 as a curve $K = 2.56v^{2.79}$.

Wear with motion of a chain of five balls in helium at a temperature of 20°C and speeds from 0.35 to 0.85 m/s was studied on section #3. The results are summarized in Table 2 and Fig. 3.

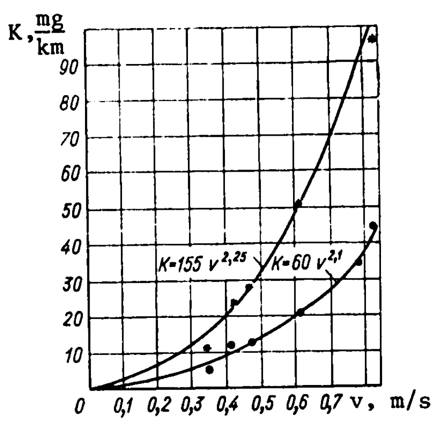

Fig. 3. Mass intensity of wear of a chain of balls in experimental section #3: *--for the middle ball of the chain; •--average for balls in the chain; atmosphere--helium; t = 20°C

The experimental curves show the mass intensity of wear of the middle ball of the chain as a function of speed $K_{av} = 155v^{2.25}$ and the average intensity of wear of balls in the chain (per ball) $K = 60v^{2.1}$.

From the graphs (Fig. 2, 3) we can see that the middle balls in the chain show greater wear than those on the ends, and also are worn more than an isolated ball. This can be attributed to the fact that in experimental section #3 the chain of balls moves over a concave surface, and the middle balls are worn not only by friction against the steel pipe and by impacts against projections, but also due to friction of sliding against adjacent balls.

Analysis of the quantitative data shown in Table 2 demonstrates that the sliding friction between adjacent balls in a chain has a very great influence on their wear since the inside balls that have two points of graphite-graphite contact are worn two-three times more than the end balls that have a single point of contact, and five times more than an isolated ball.

The experimental data found for the wear of isolated balls and for a chain of balls in different sections of the helium stand enabled estimation of the wear of a spherical fuel element in an irradiator tube.

As a result of work on studying the influence of helium temperature on friction and wear of spherical graphite elements, the following conclusions were drawn:

TABLE 2

Results of wear of a chain of five graphite balls in helium on experimental section #3

Experiment number	Ball number	Length of travel, km	Velocity of ball, m/s	Temperature of atmosphere, °C	Density of ball, g/cm³	Mass of ball before experiment, g	Mass of ball after experiment, g	Loss of mass, g	Average loss of mass, g	Intensity of wear, mg/km	Average wear intensity, mg/km
1	4	72,3	0,83	300	1,7690	250,435	248,280	2,155	2,93	29,8	40.11
	13				1,6924	239,605	235,625	3,98		55,0	
	16				1,6361	230,480	223,520	6,96		96,2	
	6				1,8190	238,270	237,390	0,91		12,5	
	7				1,7915	220,390	219,760	0,63		8,7	
2	4	24,4	0,42	100	1,7690	248,88	248,110	0,17	0,295	6,96	12,10
	13				1,6924	235,625	235,160	0,465		19,1	
	16				1,6361	223,520	222,903	0,590		24,2	
	6				1,8190	237,390	237,200	0,160		6,55	
	7				1,7915	219,760	219,670	0,090		3,7	
3	4	28	0,47	20	1,7690	248,11	247,90	0,21	0,384	7,5	12,778
	13				1,6924	235,16	234,67	0,49		17,5	
	16				1,6361	222,93	222,14	0,79		28,2	
	6				1,8190	237,20	236,99	0,21		0,4	
	7				1,7915	219,670	219,55	0,12		1,29	
4	4	38,1	0,61	20	1,7690	247,90	247,44	0,46	0,810	12,07	21,28
	13				1,6924	234,67	233,67	1,00		26,25	
	16				1,6361	222,14	222,20	1,94		50,92	
	6				1,8190	236,99	238,62	0,37		9,71	
	7				1,7915	219,55	219,27	0,27		7,35	
5	4	81,6	0,35	20	1,7690	247,44	247,20	0,22	0,492	2,69	5,906
	13				1,6924	233,67	232,98	0,69		8,456	
	16				1,6361	220,20	219,3	0,90		11,03	
	6				1,8190	235,62	236,19	0,43		3,677	
	7				1,7915	219,27	219,05	0,22		3,677	
6	4	48,5	0,79	20	1,7690	247,20	246,25	0,92	1,81	19,59	37,32
	13				1,6924	232,98	230,73	2,25		46,39	
	16				1,6361	219,3	214,34	4,96		102,3	
	6				1,8190	236,10	235,66	0,53		10,92	
	7				1,7915	219,05	218,60	0,36		7,12	

1) with a temperature change from 20 to 400°C the intensity of wear of graphite balls in helium changes insignificantly; it can be assumed that wear is independent of temperature in this range;

2) an increase is observed in the wear of the inside balls moving in a chain; this shows the possibility of a considerable increase in wear when balls move in a chain through the circulating system;

3) a power-law relation is confirmed for the way that wear of graphite balls depends on speed up to 2 m/s when moving as isolated spheres, and also as a group of spheres in a 12Kh18N10T steel pipe in helium.

The expected wear of fuel elements in irradiator tubes is calculated on the basis of the resultant data: 0.5% of the mass of the fuel element over the course of a run.

As we have already noted, the conditions of operation of bearings in mechanisms of the circulation system are characterized by comparatively high temperature (up to 300°C) and a highly pure helium atmosphere, which precludes the use of liquid and plastic lubricants, and raises the problem of selecting self-lubricating materials and coatings with consideration of the type of contacting rubbing surfaces of components, friction conditions and permissible wear.

Analysis of published data [Ref. 5-9] has shown that friction and wear of materials in a highly pure helium atmosphere at elevated temperature has been practically unstudied, and specific recommendations can be made on the basis of general ideas about the mechanism of friction and wear of solids. For example, contacting of solids under these conditions is characterized by absence of oxidation processes that play an important and frequently positive role with friction in air. Since helium is an inert gas and does not interact with contacting surfaces, it can be simulated by a high vacuum with adequate reliability as the external medium for friction under temperature conditions up to 300°C. In this case, selection of the necessary materials becomes more sound since friction of known solid lubricants and coatings in vacuum has been extensively studied.

At the present time, especially with the development of space technology, materials have been studied and used with physical and mechanical properties that enable them to be utilized in friction couples under conditions of vacuum or oxygen-free media. One of them is molybdenite or molybdenum disulfide MoS_2; its principal advantage is the capability of improving friction characteristics with increasing temperature and decreasing amount of oxygen and water impurities in the gas atmosphere. Molybdenum disulfide MoS_2 shows almost no vaporization in vacuum. Besides, this material is radiation resistant.

Molybdenum disulfide has a hexagonal structure; in its elementary cell, six sulfur atoms are arranged around a molybdenum atom at the vertices of a regular trigonal prism ($A = 3.26$ Å, $C = 12.30$ Å) [Ref. 5]. Thus, an elementary layer with thickness of 6.25 Å consists of molybdenum atoms with sulfur atoms on both sides. Bonding between molybdenum and sulfur atoms is covalent, and the sulfur-sulfur bond between elementary layers is by van der Waals forces.

Therefore, these elementary layers can slide freely relative to each other along cleavage planes. According to many researchers [Ref. 5, 6], the mechanism of lubricating action looks like this: with friction in a couple with metal, a high-temperature film is transferred to the metal that is partly oriented by basis plane (0001) in parallel with the slip plane. The bonding forces between this film and the metal considerably exceed the bonding forces of layers of MoS_2. During motion, friction is produced by displacement within the MoS_2 layer rather than by displacement relative to the metal.

Molybdenum disulfide as a solid lubricant for plain bearings is used in the form of a ground of solid lubricant coating, or an isotropic composite whose wearability and durability depend appreciably on composition and manufacturing techniques.

Most promising for a helium atmosphere are MoS_2 coatings of diffusion type formed on molybdenum components as a result of chemical heat treatment in an atmosphere containing sulfur. They have considerable thickness (60-100 μm), durability and temperature stability in vacuum and inert atmospheres (up to 800°C) with prolonged operation.

Laboratory appraisals have been done in a shaft-sleeve arrangement on solid lubricant coatings and isotropic materials based on MoS_2 in different combinations with friction in a medium of highly pure helium at 300°C at different speeds and loads, which have been the basis for selection of promising couples: M-801—M-802-1 and M-801—M-802-2.

M-801 material is a combination of a heat-resistant molybdenum base with solid lubricant molybdenum disulfide coating up to 60 μm thick that is formed as a result of chemical heat treatment of the component in a sulfur medium.

Materials M-801-1 and M-801-2 are similar to M-801, but the MoS_2 layer is produced by chemical heat treatment of molybdenum in a ZnS medium at different temperatures.

Service life tests of the bearing unit of an injection-ejection mechanism were done at VNIIAM [expansion not given] on the Rabotosposobnost' stand in helium at normal pressure and temperature of 300°C.

The major equipment of the stand consists of a working section, loading devices, an electric drive, an electromagnetic clutch, electric heater, evacuating and charging system, monitoring and measurement instrumentation. The working section is a hermetically sealed chamber of cylindrical shape made of grade Kh18N10T stainless steel in which a shaft is installed on roller bearings along with the bearing unit to be tested. Torque is applied by a hermetically sealed electromagnetic clutch.

A radial-thrust sliding bearing of the injection-ejection mechanism was made for the purpose of the tests. M-801 material was used for the inner sleeve of the bearing, and the outer sleeve was made of M-802-1 material. The axial load on the bearings was 40 kgf, radial load was 10 kgf, and speed of rotation was 200 rpm.

Every so often, the working section was opened, the sleeves of the bearing were weighed, and the intensity of wear was determined.

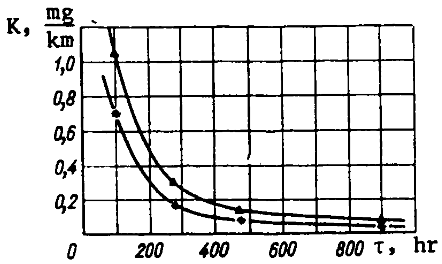

Fig. 4. Mass intensity of wear of sliding bearings: *--outside sleeve of bearing; ▲--inner sleeve of bearing; atmosphere--helium; t = 300°C

The results of plain bearing tests (Fig. 4) showed that run-in of bearings takes place in about the first 300-400 hours, after which wear stabilizes at about 0.1 mg/km. The bearing operated more than 5000 hours without seizing. The working surface has a metallic shine without scoring.

In addition to the plain bearing, tests were done on this same stand on roller bearings: standard units and with separators made of self-lubricating materials. After ~100 hours of operation, the roller bearing with brass separator showed appreciable separator wear (~100 μm) and adhesion transfer of brass to the ball bearings and to the raceways. The ball diameter increased by 15-20 μm.

A similar pattern was observed after 100 hours of operation of a bearing with S-820 material; there was a considerable increase in separator wear (~150 μm), the diameter of the balls increased by ~10 μm. S-820 material is a porous steel matrix impregnated with copper-lead alloy.

The bearing with separator of M801-1 material ran in after ~300 hours; transfer of MoS_2 to the balls was insignificant, but the coating of the separator material was completely worn off.

Based on the studies that were done and analysis of Soviet and non-Soviet experience with operation of bearing units in non-oxidative gas atmospheres at high temperature, as well as laboratory and stand tests, it is recommended that M-801 and M-802 materials be used for bearing units in mechanisms of the circulation system of a power-producing chemical facility.

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FABRICATION AND QUALITY CONTROL OF COATED FUEL PARTICLES, FUEL ELEMENTS AND FUEL ASSEMBLIES FOR HTGR's

Moscow ATOMNO-VODORODNAYA ENERGETIKA I TEKHNOLOGIYA in Russian No 2, 1979 (signed to press 8 Jun 79) pp 160-177

[Article by A. S. Chernikov, Yu. V. Koshelev, Z. A. Shokina, V. I. Stolyarov and G. N. Nikanorova]

[Text] In the course of studying and analyzing various methods, a process layout is proposed for fabrication and operation-by-operation quality control of components of monolithic prismatic fuel assemblies and spherical fuel elements for HTGR's. Process and control operations of the arrangement are considered, beginning with spheroidization of the fuel, and the interrelation between these operations is examined.

Introduction

The design of high-temperature gas-cooled reactors (HTGR's) as prospective nuclear facilities intended for combined production of high-temperature process heat and electric power has become possible thanks to advances in development of uranium-graphite fuel elements that hold fission products at a temperature of 1200-1400°C and burnup of $(1.0\text{-}1.5)\cdot10^5$ MW-days per metric ton on a level of $R/B = 10^{-4}\text{-}10^{-5}$ (where R and B are the yield rate and formation rate of fission products). In selecting the design of the fuel element we should be guided by considerations of minimum fuel temperature, technological feasibility and minimum cost of fuel element fabrication. Operational requirements of the energy-producing process HTGR are most completely met by spherical fuel elements, although in some instances they may face competition from other types of fuel elements as well (e. g. prismatic for large HTGR's, and block type for HTGR's with radiant heat exchange).

Typical of a fuel element of any type is imbedding of coated fuel particles in a graphite matrix, since graphite has good nuclear and technological properties, and because of its inherent porosity cannot provide a reliable barrier to fission fragments. In this connection, when making HTGR fuel elements the basis has been the condition that coated fuel particles should perform the function of containment of fission products.

Extensive non-Soviet experience in developing HTGR fuel elements has shown that:

the most widely used fuel kernel is oxide fuel, and the most widely used coating is layers of pyrocarbon (PyC) of various densities and silicon carbide;

the buffer layer of the coating immediately adjacent to the nuclear fuel must be porous and have a low Young modulus to relieve internal pressure on the rest of the coating;

reactor tests of fuel particles in the free-piled state cause frequent occurrence of cracks in the coating, and it is difficult to judge the efficacy of fuel particles as part of fuel elements because of the difference in the nature of the stressed state (the graphite matrix has a favorable effect on the behavior of fuel particles under irradiation [Ref. 1]);

at a maximum temperature of fuel up to 1250°C, BISO pyrocarbon coatings can be used as evidenced by the construction of the spherical fuel element for the THTR-300 reactor (West Germany). Operating temperature can be increased to 1400°C for fuel particles with coating including silicon carbide (TRISO coating) [Ref. 2, 3];

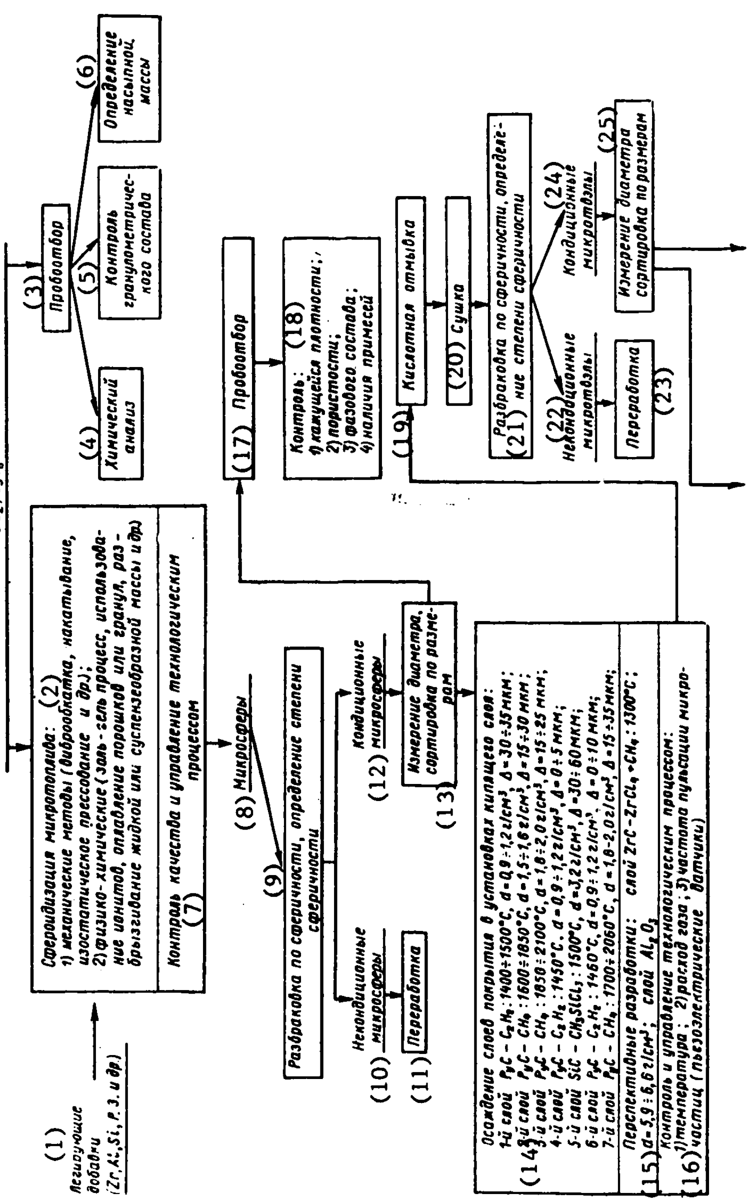
irradiated fuel elements of the AVR reactor show practically no straight-through fracture of the fuel particle coating [Ref. 4]. The yield of fission products from AVR fuel elements on level $R/B = 10^{-4}-10^{-5}$ can be attributed to damage of fuel particles on the operation of fuel element fabrication, and to technological uranium "contamination" of the fuel particle coating and graphite matrix;

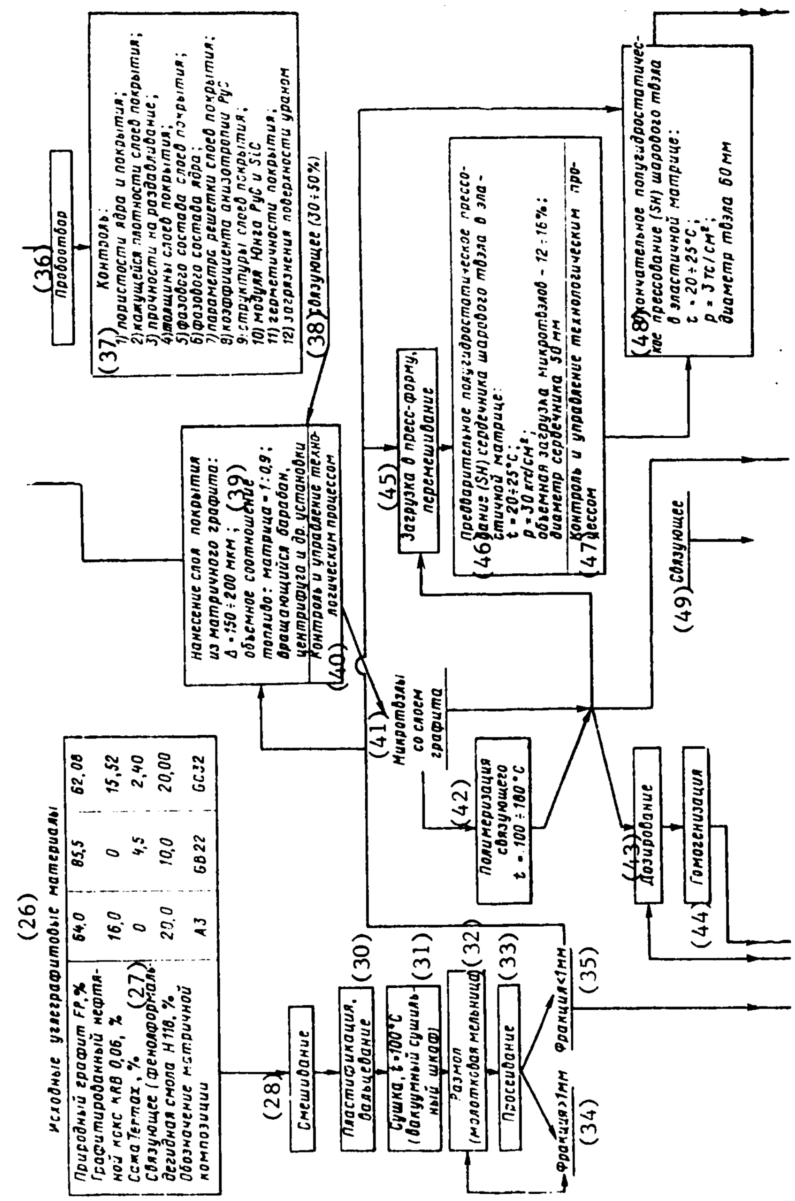
one of the possible methods of reducing R/B or increasing fuel particle operating temperature is to optimize the design and material composition of the fuel particles. For example, the nuclear fuel could be based on uranium nitride or carbonitride. It is advisable to dope the fuel material with trace amounts of a getter that binds metallic fragments (for oxide fuel -- 3-5% by mass of oxides of zirconium, silicon and aluminum [Ref. 5]). In this case, the coatings of the fuel particles contain in addition to pyrocarbon layers, carbide layers of more refractory compounds than SiC, e. g. ZrC [Ref. 6, 7].

Outside the Soviet Union, uranium-graphite fuel elements are being successfully used in HTGR's, enabling maintenance of the helium temperature at the core outlet at about 950°C [Ref. 4, 8]. In the near future, engineering and design features may be realized relating mainly to fuel particles that will enable a further increase in this temperature by 200-250°C without any appreciable increase of radioactivity in the primary circuit.

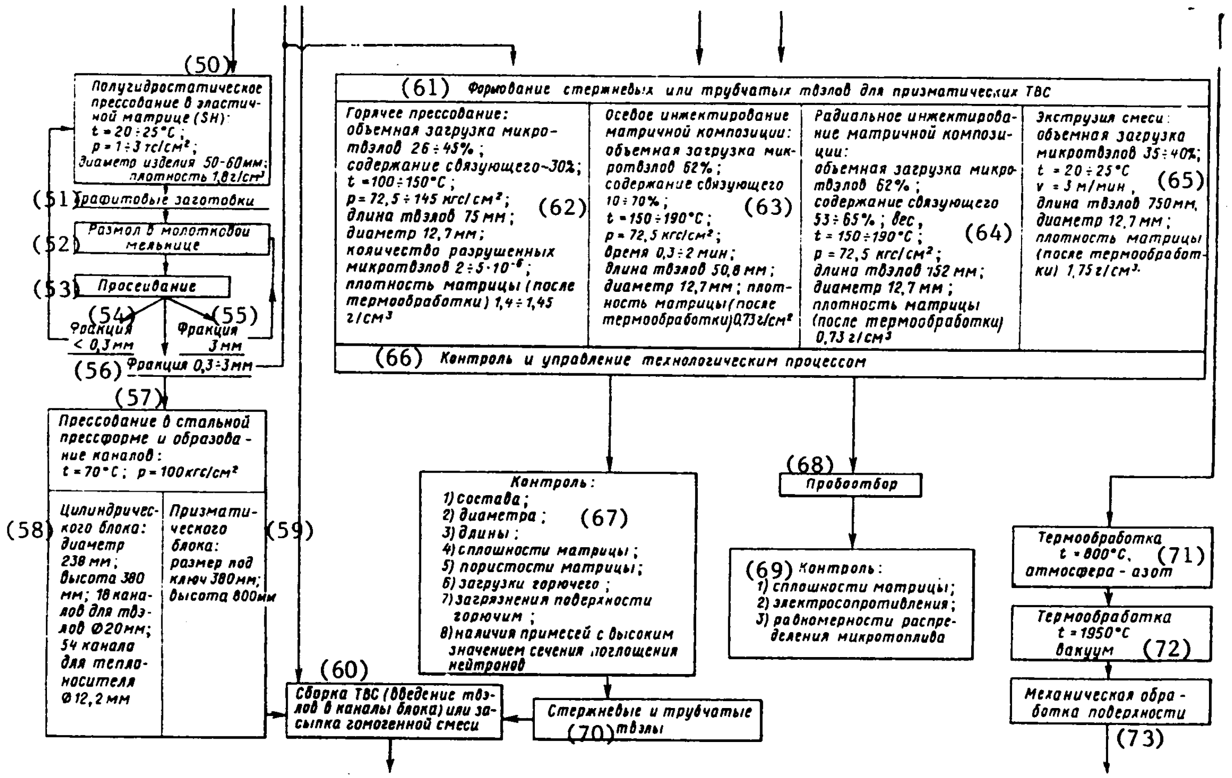
Of interest from this standpoint is non-Soviet experience in developing technology for fabricating uranium-graphite fuel elements for HTGR's.

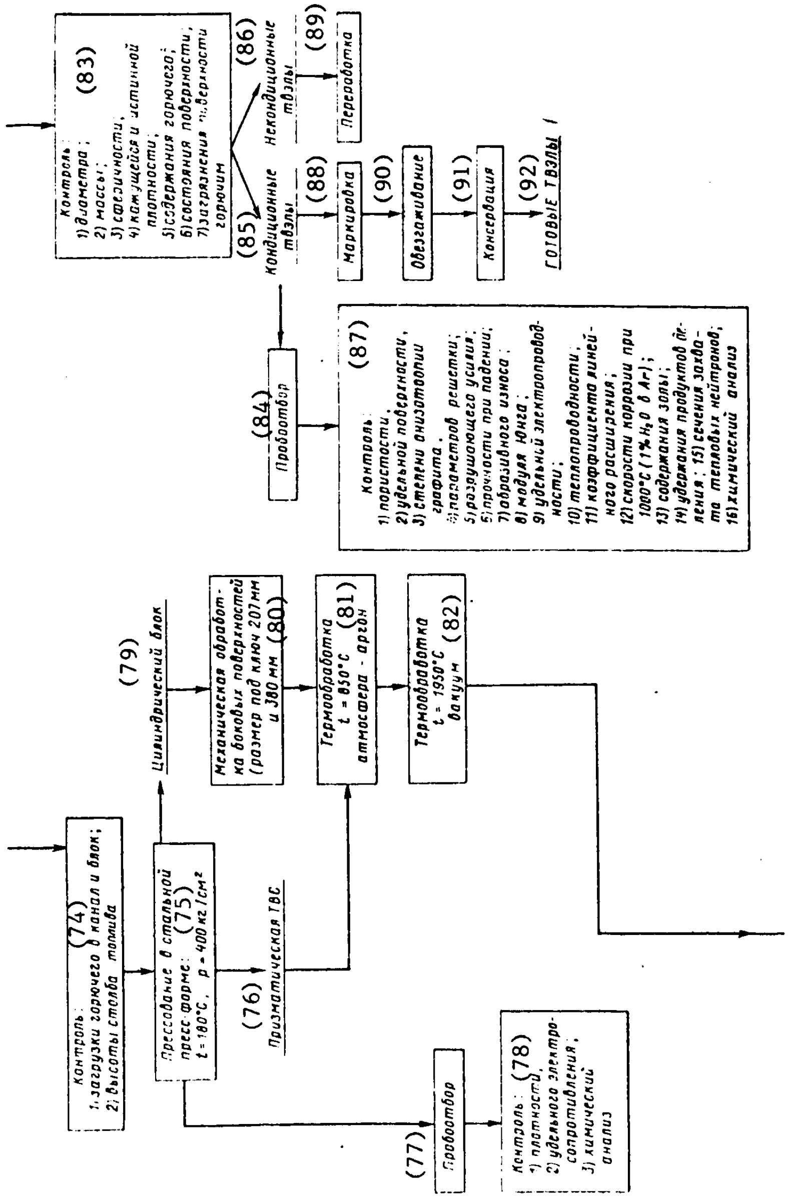
Questions of fabrication and quality control of fuel particles and fuel elements and also the management of technological processes as applied to HTGR fuel elements are covered in considerable detail in informative publications of the United States, West Germany, the United Kingdom, France, Japan and other nations [Ref. 9, 10].


UO2; U3O8
(1) Легирующие добавки (Zr, Al, Si, Р.З. и др.)
(2) Сфероидизация микротоплива:
1) механические методы (виброобкатка, накатывание, изостатическое прессование и др.);
2) физико-химические (золь-гель процесс, использование ионитов, оплавление порошков или гранул, разбрызгивание жидкой или суспензеобразной массы и др.)
(7) Контроль качества и управление технологическим процессом
(3) Пробоотбор
(4) Химический анализ
(5) Контроль гранулометрического состава
(6) Определение насыпной массы
(8) Микросферы
(9) Разбраковка по сферичности, определение степени сферичности
(10) Некондиционные микросферы
(11) Переработка
(12) Кондиционные микросферы
(13) Измерение диаметра, сортировка по размерам
(14) Осаждение слоев покрытия в установках кипящего слоя:
1-й слой PyC – C2H2: 1400÷1500°C, d = 0,9÷1,2 г/см³, Δ = 30÷35 мкм;
2-й слой PyC – CH4: 1600÷1850°C, d = 1,5÷1,6 г/см³, Δ = 15÷30 мкм;
3-й слой PyC – CH4: 1850÷2100°C, d = 1,8÷2,0 г/см³, Δ = 15÷25 мкм;
4-й слой PyC – C2H2: 1450°C, d = 0,9÷1,2 г/см³, Δ = 0÷5 мкм;
5-й слой SiC – CH3SiCl3: 1500°C, d = 3,2 г/см³, Δ = 30÷60 мкм;
6-й слой PyC – C2H2: 1460°C, d = 0,9÷1,2 г/см³, Δ = 0÷10 мкм;
7-й слой PyC – CH4: 1700÷2060°C, d = 1,8–2,0 г/см³, Δ = 15÷35 мкм;
(15) Перспективные разработки: слой ZrC – ZrCl4 + CH4: 1300°C; d = 5,9÷6,6 г/см³; слой Al2O3
(16) Контроль и управление технологическим процессом: 1) температура; 2) расход газа; 3) частота пульсации микрочастиц (пьезоэлектрические датчики)
(17) Пробоотбор
(18) Контроль: 1) кажущейся плотности; 2) пористости; 3) фазового состава; 4) наличия примесей
(19) Кислотная отмывка
(20) Сушка
(21) Разбраковка по сферичности, определение степени сферичности
(22) Некондиционные микротвэлы
(23) Переработка
(24) Кондиционные микротвэлы
(25) Измерение диаметра сортировка по размерам


(26)
Исходные углеграфитовые материалы
Природный графит FP, % 64,0 85,5 62,08
Графитированный нефтяной кокс KRB 0,06, % 16,0 0 15,52
Сажа Termax, % (27) 0 4,5 2,40
Связующее (фенолформальдегидная смола H118, % 20,0 10,0 20,00
Обозначение матричной композиции A3 GB22 GC32
(28) Смешивание
Пластификация, вальцевание (30)
Сушка, t = 100°C (вакуумный сушильный шкаф) (31)
Размол (молотковая мельница) (32)
Просеивание (33)
Фракция>1мм (34)
Фракция<1мм (35)
(36) Пробоотбор
(37) Контроль:
1) пористости ядра и покрытия;
2) кажущейся плотности слоев покрытия;
3) прочности на раздавливание;
4) толщины слоев покрытия;
5) фазового состава слоев покрытия;
6) фазового состава ядра;
7) параметра решетки слоев покрытия;
8) коэффициента анизотропии PyC
9) структуры слоев покрытия;
10) модуля Юнга PyC и SiC
11) герметичности покрытия;
12) загрязнения поверхности ураном
(38) Связующее (30÷50%)
Нанесение слоя покрытия из матричного графита:
Δ = 150 ÷ 200 мкм; (39)
объемное соотношение топливо: матрица = 1:0,9;
вращающийся барабан, центрифуга и др. установки
(40) Контроль и управление технологическим процессом
(41) Микротвэлы со слоем графита
(42) Полимеризация связующего t = 100 ÷ 180°C
(43) Дозирование
(44) Гомогенизация
(45) Загрузка в пресс-форму, перемешивание
(46) Предварительное полугидростатическое прессование (SH) сердечника шарового твэла в эластичной матрице:
t = 20÷25°C;
p = 30 кгс/см²;
объемная загрузка микротвэлов - 12÷16%;
диаметр сердечника 50 мм
(47) Контроль и управление технологическим процессом
(48) Окончательное полугидростатическое прессование (SH) шарового твэла в эластичной матрице:
t = 20÷25°C;
p = 3 тс/см²;
диаметр твэла 60 мм
(49) Связующее

64


(50) Полугидростатическое прессование в эластичной матрице (SH): t = 20 ÷ 25°C; p = 1 ÷ 3 тс/см²; диаметр изделия 50-60мм; плотность 1,8 г/см³
(51) Графитовые заготовки
(52) Размол в молотковой мельнице
(53) Просеивание
(54) Фракция < 0,3 мм
(55) Фракция 3 мм
(56) Фракция 0,3÷3мм
(57)
Прессование в стальной прессформе и образование каналов: t = 70°C; p = 100 кгс/см²
(58) Цилиндрического блока: диаметр 238 мм; высота 380 мм; 18 каналов для твэлов Ø20мм; 54 канала для теплоносителя Ø12,2 мм
(59) Призматического блока: размер под ключ 380мм; высота 800мм
(60) Сборка ТВС (введение твэлов в каналы блока) или засыпка гомогенной смеси
(61) Формование стержневых или трубчатых твэлов для призматических ТВС
(62) Горячее прессование: объемная загрузка микротвэлов 26 ÷ 45%; содержание связующего ~30%; t = 100 ÷ 150°C; p = 72,5 ÷ 145 кгс/см²; длина твэлов 75 мм; диаметр 12,7 мм; количество разрушенных микротвэлов 2 ÷ 5·10⁻⁶; плотность матрицы (после термообработки) 1,4 ÷ 1,45 г/см³
(63) Осевое инжектирование матричной композиции: объемная загрузка микротвэлов 62%; содержание связующего 10 ÷ 70%; t = 150 ÷ 190°C; p = 72,5 кгс/см²; время 0,3 ÷ 2 мин; длина твэлов 50,8 мм; диаметр 12,7мм; плотность матрицы (после термообработки) 0,73 г/см³
(64) Радиальное инжектирование матричной композиции: объемная загрузка микротвэлов 62%; содержание связующего 53 ÷ 65%, вес; t = 150 ÷ 190°C; p = 72,5 кгс/см²; длина твэлов 152 мм; диаметр 12,7 мм; плотность матрицы (после термообработки) 0,73 г/см³
(65) Экструзия смеси: объемная загрузка микротвэлов 35 ÷ 40%; t = 20 ÷ 25°C; v = 3 м/мин, длина твэлов 750мм, диаметр 12,7 мм; плотность матрицы (после термообработки) 1,75 г/см³.
(66) Контроль и управление технологическим процессом
(67) Контроль: 1) состава; 2) диаметра; 3) длины; 4) сплошности матрицы; 5) пористости матрицы; 6) загрузки горючего; 7) загрязнения поверхности горючим; 8) наличия примесей с высоким значением сечения поглощения нейтронов
(68) Пробоотбор
(69) Контроль: 1) сплошности матрицы; 2) электросопротивления; 3) равномерности распределения микротоплива
(70) Стержневые и трубчатые твэлы
(71) Термообработка t = 800°C, атмосфера - азот
(72) Термообработка t = 1950°C вакуум
(73) Механическая обработка поверхности


Контроль: (74)
1) загрузки горючего в канал и блок;
2) высоты столба топлива
Прессование в стальной пресс-форме: (75)
t = 180°C, p = 400 кг/см²
(76) Призматическая ТВС
(77) Пробоотбор
Контроль: (78)
1) плотности,
2) удельного электросопротивления;
3) химический анализ
(79) Цилиндрический блок
Механическая обработка боковых поверхностей (размер под ключ 207 мм и 380 мм (80)
Термообработка t = 850°C атмосфера - аргон (81)
Термообработка t = 1950°C вакуум (82)
Контроль: (83)
1) диаметра;
2) массы;
3) сферичности,
4) кажущейся и истинной плотности;
5) содержания горючего;
6) состояния поверхности;
7) загрязнения поверхности горючим
(85) Кондиционные твэлы
(86) Некондиционные твэлы
(84) Пробоотбор
Контроль: (87)
1) пористости,
2) удельной поверхности,
3) степени анизотропии графита,
4) параметров решетки;
5) разрушающего усилия;
6) прочности при падении;
7) абразивного износа;
8) модуля Юнга;
9) удельный электропроводности;
10) теплопроводности,
11) коэффициента линейного расширения;
12) скорости коррозии при 1000°C (1% H₂O в Ar);
13) содержания золы;
14) удержания продуктов деления; 15) сечения захвата тепловых нейтронов;
16) химический анализ
(88) Маркировка
(89) Переработка
(90) Обезгаживание
(91) Консервация
(92) Готовые твэлы

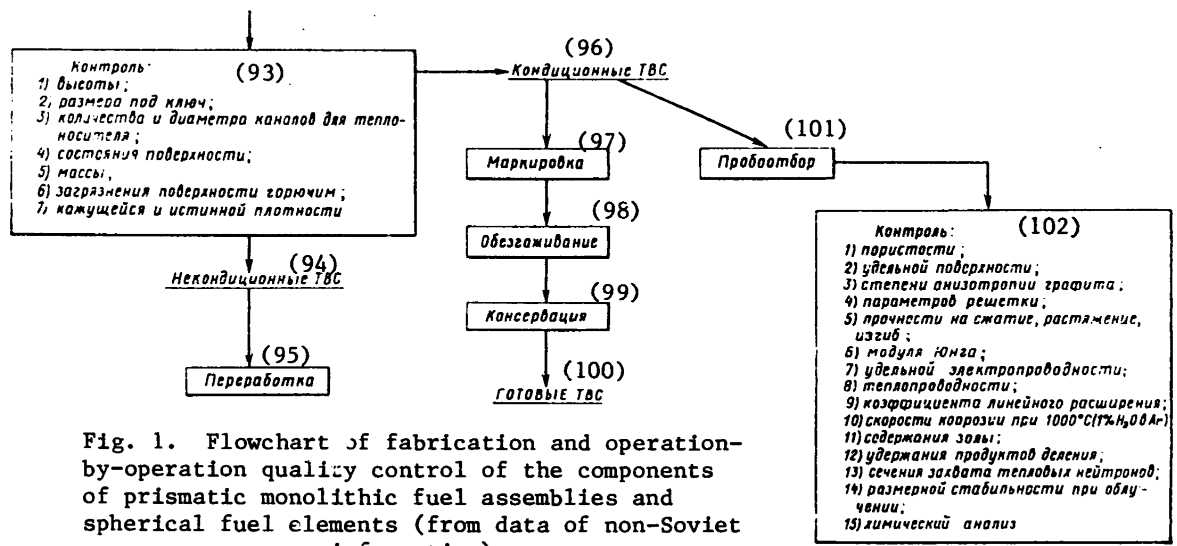


Fig. 1. Flowchart of fabrication and operation-by-operation quality control of the components of prismatic monolithic fuel assemblies and spherical fuel elements (from data of non-Soviet information)

[see the key on following pages]

Key to Fig. 1:

1--Dopants (Zr, Al, Si, rare earths, etc.)
2--Spheroidization of fuel particle:
 1) mechanical methods (vibration treatment, rolling, isostatic pressing, and so on);
 2) physicochemical methods (sol-gel process, use of ion exchange resins, melting powders or granules, spraying liquid or suspension-like mass, and so on);
3--Sampling
4--Chemical analysis
5--Checking granulometric compoeition
6--Determining bulk mass
7--Quality control and management of technological process
8--Microspheres
9--Sphericity treatment, determining degree of sphericity
10--Unconditioned microspheres
11--Reprocessing
12--Conditioned microspheres
13--Measurement of diameter, sorting by sizes
14--Deposition of coating layers in fluidized bed facilities:
 1-st layer PyC-C_2H_2: 1400-1500°C, d = 0.9-1.2 g/cm^3, Δ = 30-35 μm;
 2-nd layer PyC-CH_4: 1600-1850°C, d = 1.5-1.6 g/cm^3, Δ = 15-30 μm;
 3-rd layer PyC-CH_4: 1850-2100°C, d = 1.8-2.0 g/cm^3, Δ = 15-25 μm;
 4-th layer PyC-C_2H_2: 1450°C, d = 0.9-1.2 g/cm^3, Δ = 0-5 μm;
 5-th layer SiC-CH_3SiCl_3: 1500°C, d = 3.2 g/cm^3, Δ = 30-60 μm;
 6-th layer PyC-C_2H_2: 1460°C, d = 0.9-1.2 g/cm^3, Δ = 0-10 μm;
 7-th layer PyC-CH_4: 1700-2060°C, d = 1.8-2.0 g/cm^3, Δ = 15-35 μm;
15--Future developments: layer of ZrC-$ZrCl_4 + CH_4$: 1300°C; d = 5.9-6.6 g/cm^3; layer of Al_2O_3
16--Control and management of technological process:
 1) temperature; 2) gas flowrate; 3) microparticle pulsation frequency (piezoelectric sensors)
17--Sampling
18--Checking:
 1) apparent density;
 2) porosity;
 3) phase composition;
 4) presence of impurities
19--Acid rinsing
20--Drying
21--Sphericity treatment, determining degree of sphericity
22--Unconditioned fuel particles
23--Reprocessing
24--Conditioned fuel particles
25--Measurement of diameter, sorting by sizes
26--Initial graphitized carbon materials
27--Natural graphite FP, %
 Graphitized petroleum coke KRB 0.06, %
 Termax carbon black, %
 Binder (H118 phenolformaldehyde resin), %
 Grade of matrix composition

28--Mixing
30--Plasticizing, rolling
31--Drying, t = 100°C (vacuum drying cabinet)
32--Grinding (hammermill)
33--Screening
34--Fraction >1 mm
35--Fraction <1 mm
36--Sampling
37--Checking:
1) porosity of nuclear fuel and coating;
2) apparent density of coating layers;
3) crushing strength;
4) thickness of coating layers;
5) phase composition of coating layers;
6) phase composition of nuclear fuel
7) lattice parameter of coating layers;
8) coefficient of anisotropy of PyC;
9) structure of coating layers;
10) Young modulus of PyC and SiC;
11) gas-tightness of coating;
12) uranium contamination of surface
38--Binder (30-50%)
39--Application of graphite matrix coating layer: Δ = 150-200 μm; volumetric fuel:matrix ratio = 1:0.9; rotating drum, centrifuge and other facilities
40--Control and management of technological process
41--Fuel particles with graphite layer
42--Polymerization of binder, t = 100-180°C
43--Batching
44--Homogenization
45--Charging into mold, mixing
46--Preliminary semihydrostatic pressing (SH) of spherical fuel element core in elastic matrix:
t = 20-25°C;
p = 30 kgf/cm^2
volumetric charge of fuel particles -- 12-16%;
core diameter 50 mm
47--Control and management of technological process
48--Final semihydrostatic pressing (SH) of spherical fuel element in elastic matrix:
t = 20-25°C;
p = 3 metric tons per sq. cm;
fuel element diameter 60 mm
49--Binder
50--Semihydrostatic pressing in elastic matrix (SH):
t = 20-25°C;
p = 1-3 metric tons per sq. cm;
finished diameter 50-60 mm;
density 1.8 g/cm^3
51--Graphite blanks
52--Grinding in hammermill
53--Screening

54--Fraction <0.3 mm
55--3 mm fraction
56--Fraction 0.3 - 3 mm
57--Pressing in steel mold and formation of channels:
  t = 70°C;
  p = 100 kgf/cm^2
58--Cylindrical block: diameter 238 mm; height 380 mm; 18 channels for fuel elements Ø20 mm; 54 coolant channels Ø12.2 mm
59--Prismatic block: wrench size 380 mm; height 800 mm
60--Putting together the fuel assembly (inserting fuel elements into channels of the block) or pouring in homogeneized mixture
61--Forming tubular or rod fuel elements for prismatic fuel assemblies
62--Hot pressing:
  volumetric charge of fuel particles 26-45%;
  binder content ~30%;
  t = 100-150°C;
  p = 72.5-145 kgf/cm^2;
  length of fuel elements 75 mm;
  diameter 12.7 mm;
  quantity of damaged fuel particles $2\text{-}5 \cdot 10^{-6}$;
  density of matrix (after heat treatment) 1.4-1.45 g/cm^3
63--Axial injection of matrix composition:
  volumetric charge of fuel particles 62%;
  binder content 10-70%;
  t = 150-190°C;
  p = 72.5 kgf/cm^2
  time 0.3-2 minutes;
  length of fuel elements 50.8 mm;
  diameter 12.7 mm;
  matrix density (after heat treatment) 0.73 g/cm^3
64--Radial injection of matrix composition:
  volumetric charge of fuel particles 62%;
  binder content 53-65 wt.%;
  t = 150-190°C;
  p = 72.5 kgf/cm^2;
  length of fuel elements 152 mm;
  diameter 12.7 mm;
  matrix density (after heat treatment) 0.73 g/cm^3
65--Extrusion of mixture:
  volumetric charge of fuel particles 35-40%;
  t = 20-25°C;
  v = 3 m/min;
  length of fuel elements 750 mm;
  diameter 12.7 mm;
  matrix density (after heat treatment) 1.75 g/cm^3
66--Control and management of technological process
67--Checking:
  1) composition;
  2) diameter;
  3) length;
  4) integrity of matrix;
  5) matrix density;

6) fuel charge;
7) fuel contamination of surface;
8) presence of impurities with large neutron absorption cross section

68--Sampling

69--Checking:
1) matrix integrity;
2) resistivity;
3) uniformity of fuel particle distribution

70--Tubular and rod fuel elements

71--Heat treatment:
t = 800°C,
atmosphere--nitrogen

72--Heat treatment:
t = 1950°C,
vacuum

73--Mechanical surface treatment

74--Checking:
1) fuel charge in channel and block;
2) height of fuel column

75--Pressing in steel mold:
t = 180°C; p = 400 kg/cm^2

76--Prismatic fuel assembly

77--Sampling

78--Checking:
1) density
2) resistivity;
3) chemical analysis

79--Cylindrical block

80--Mechanical treatment of side surfaces (wrench size 207 and 380 mm)

81--Heat treatment:
t = 850°C,
atmosphere--argon

82--Heat treatment:
t = 1950°C,
vacuum

83--Checking:
1) diameter;
2) mass;
3) sphericity;
4) apparent and true density;
5) fuel content;
6) surface state;
7) fuel contamination of surface

84--Sampling

85--Conditioned fuel elements

86--Unconditioned fuel elements

87--Checking:
1) porosity;
2) specific surface;
3) degree of anisotropy of graphite;
4) lattice parameters;
5) breaking force;

6) falling strength;
7) abrasive wear;
8) Young modulus;
9) resistivity;
10) thermal conductivity;
11) coefficient of linear expansion;
12) corrosion rate at 1000°C (1% H_2O in Ar);
13) ash content;
14) retention of fission products;
15) thermal-neutron capture cross section;
16) chemical analysis

88--Marking
89--Reprocessing
90--Outgassing
91--Canning
92--FINISHED FUEL ELEMENTS
93--Checking:
1) height;
2) wrench size;
3) number and diameter of coolant channels;
4) surface state;
5) mass;
6) fuel contamination of surface;
7) apparent and true density

94--Unconditioned fuel assemblies
95--Reprocessing
96--Conditioned fuel assemblies
97--Marking
98--Outgassing
99--Canning
100--FINISHED FUEL ASSEMBLIES
101--Sampling
102--Checking:
1) porosity;
2) specific surface;
3) degree of anisotropy of graphite;
4) lattice parameters;
5) compression, tensile and bending strength;
6) Young modulus;
7) resistivity;
8) thermal conductivity;
9) coefficient of linear expansion;
10) corrosion rate at 1000°C (1% H_2O in Ar);
11) ash content;
12) retention of fission products;
13) thermal-neutron capture cross section;
14) dimensional stability under irradiation;
15) chemical analysis

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Fig. 1 shows a possible version of a flowchart for fabrication and operation-by-operation quality control of fuel microspheres, coating layers, graphite matrix, and also spherical fuel elements and fuel assemblies. This flowchart is derived from a study and analysis of published information.

The optional nature of some of the process operations considered and methods of control is due to the particulars of national policy. The absence of information of an economic nature on these sections of the chart makes it difficult to evaluate the optimum version. Despite limitations of this kind, the given diagram is logically complete, as it reflects the state of the art in non-Soviet development. Let us consider the individual technological operations of this arrangement.

With consideration of requirements to be met, the fuel for HTGR's must be spherical fuel particles dispersed in a graphite matrix. Such fuel particles consist of the nuclear fuel and several layers of protective coatings (Fig. 2).

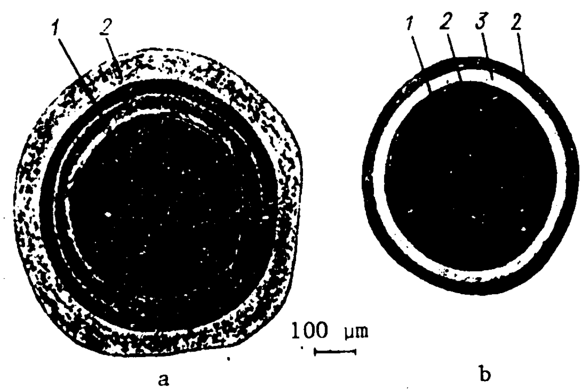


Fig. 2. Fuel particles with coatings of type BISO (a) and sandwich-type TRISO (b) [Ref. 19]: 1--porous pyrocarbon layer; 2--high-density pyrocarbon layer; 3--silicon carbide layer

There are many methods of fabricating spherical fuel particles from uranium dioxide, carbide or nitride, thorium, plutonium, and also solid solutions based on them. All methods can be arbitrarily divided into two groups: 1) mechanical (vibration treatment, rolling, isostatic pressing, etc. [Ref. 12-14]); 2) physicochemical (sol-gel process, use of ion exchange resins, melting powders or granules, spraying liquid or suspension-like mass, etc. [Ref. 15-19]). Comparison of the possibilities of these methods shows that physicochemical methods are most promising, in particular the sol-gel and sorption processes for oxide and carbide fuel.

Let us consider the capabilities of physicochemical methods of making fuel microspheres in somewhat more detail.

Depending on the conditions of the sol-gel process, microspheres can be produced with diameters from 0.2 to 2 mm with high uniformity of dimensions from a variety of fuel materials with controllable density (80-99% of the theoretical value) [Ref. 15]. By using ion exchange resins with granules of known sphericity (d_{max}/d_{min}) and size, it is also possible to produce a variety of fuel microspheres of monofractional composition with satisfactory sphericity and volumetric distribution of fuel [Ref. 16, 17].

Semi-industrial and laboratory facilities for producing microspheres of nuclear fuel by physicochemical methods are currently in operation in the United States, the United Kingdom, West Germany, Italy, the Netherlands and Switzerland. These facilities have a capacity of 2-10 kg of uranium (thorium) per hour [Ref. 15].

The next technological operation is deposition of protective coatings on the microspheres. In view of the fact that the quality of the deposited layers depends on the degree of sphericity of the nuclear fuel grain, subsequent technological operations must be done on particles that have passed quality control for sphericity ($d_{max}/d_{min} \leq 1.05$).

Conventional methods of separating the spherical fuel grains from aspherical ones are based on the way that the coefficient of friction depends on particle shape, and assume the use of a rotating disk or inclined plane in reciprocating motion [Ref. 20-22]. Quantitative evaluation of the degree of sphericity is usually done by an automatic image analyzer of the Quantimet-720 type [Ref. 23, 24]. It is important to separate conglomerates of several particles from the general mass. This operation is done by stereoscopic microscope [Ref. 23].

An optical analyzer [Ref. 11] is used for rapid and accurate measurements of the diameter of grains (at a rate of up to 1500 min^{-1}). The instrument works on the principle of light blockage, i. e. as the particle intersects a light beam, the current of a photocell decreases in proportion to the cross sectional area of the particle. Measurement accuracy is ensured by a batcher that synchronizes the feed of unit particles into the measurement space.

After mass quality control for sphericity and determination of diameter, sampling takes place for quality control of the ›llowing parameters: apparent density, porosity, phase composition, presence of impurities.

The apparent density of fuel grains can be de ermined by dividing the mass of a batch of particles by their volume. The method of mercury pycnometry [Ref. 29] is conventionally used for measuring volume.

The total porosity of the fuel grains is calculated on the basis of the values of the apparent and theoretical density; open porosity is determined by impregnating with liquids that wet the nuclear fuel in vacuum [Ref. 25].

Size distribution of pores can be found by methods of mercury porometry and metallography [Ref. 25]. In the latter technique, the number and volume of the pores are determined simultaneously. Monitoring is done automatically by an image analyzer of the Quantimet-720 type [Ref. 23, 24].

Phase composition and contamination with impurities are determined by physicochemical methods [Ref. 11, 23].

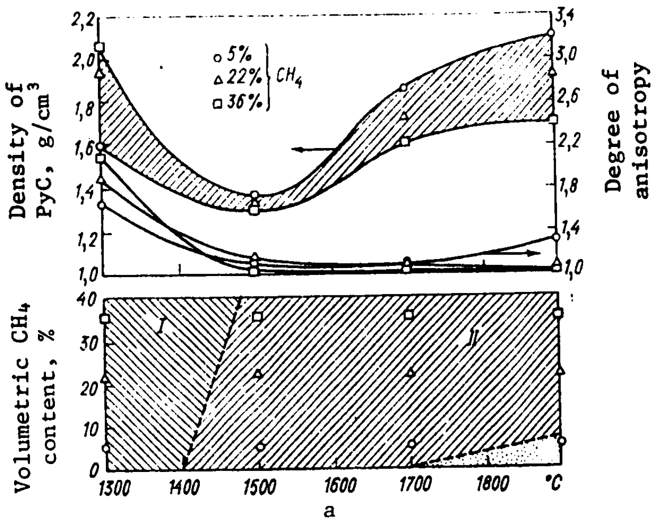
In measuring the enumerated parameters, considerable attention is given to proper taking of the control sample. To do this, special multistage samples have been designed that guarantee separation of 10% or less of the initial batch on each checking stage. For example, a three-stage conical sampler [Ref. 18] separates out down to 0.1% of a batch of microparticles. A considerable advantage of this sampler is that it has no rotating parts.

After measurement of parameters, protective coatings are applied to the certified fuel grains. The main purpose of protective pyrocarbon layers is to contain gaseous and partly solid fission products, and also to ensure compatibility of the nuclear fuel material with the graphite matrix. Layers of coatings of silicon carbide, zirconium carbide, niobium carbide and carbides of other elements are used for reliable containment of highly radioactive solid fission products.

According to computational data [Ref. 26], fuel particles with oxide nuclear fuel may have 5-7 layers of coatings (see Fig. 1). Usually the number of coating layers does not exceed four. As a rule, the missing layers are the transition layer (second from the nuclear fuel) of pyrocarbon with density of 1.5 g/cm^3, and the two buffer layers of low-density pyrocarbon to either side of the carbide coating with density of 0.9-1.2 g/cm^3.

The layers of pyrocarbon and carbide coatings are deposited in "fluidized beds" by the reaction of hydrocarbon pyrolysis or by pyrolysis of halide compounds of silicon, zirconium and so on [Ref. 27-30]. The source of carbon is a hydrocarbon that when heated splits into radicals with release of free carbon. Amorphous carbon black or crystalline pyrocarbon of various modifications may be produced, depending on the conditions of pyrolysis. Of greatest interest is the modification of isotropic pyrocarbon that has maximum stability of properties under irradiation. Isotropic pyrocarbon with the necessary characteristics is formed under strictly defined conditions of pyrolysis of such hydrocarbons as methane and propylene (Fig. 3, data of Ref. 31). High-density isotropic pyrocarbon (density of 1.8-2 g/cm^3) is produced in the process of pyrolyzing methane at a temperature above 1750°C, and with volumetric concentration of methane in the gas mixture of 5-40%. This is so-called high-temperature isotropic HTI pyrocarbon. In addition, pyrocarbon with analogous characteristics is precipitated in the process of pyrolyzing propylene at a temperature of 1250-1280°C and volumetric concentration of propylene of 10-15%--low-temperature isotropic LTI pyrocarbon. Intermediate layers of pyrocarbon with density of 1.4-1.6 g/cm^3 are formed when methane is pyrolyzed with a lower temperature (1550-1700°C) than the high-density layers in the same range of concentrations. Use of propylene precludes formation of single-phase isotropic hydrocarbon with density of 1.4-1.6 g/cm^3, since the deposited material contains inclusions of soot. Loose buffer deposits of pyrocarbon with density of 0.9-1.2 g/cm^3 are produced by pyrolyzing acetylene with temperature of 1400-1500°C [Ref. 39].

Thus, in contrast to deposits of pyrocarbon with moderate and low density, high-density isotropic pyrocarbon can be deposited from either methane or



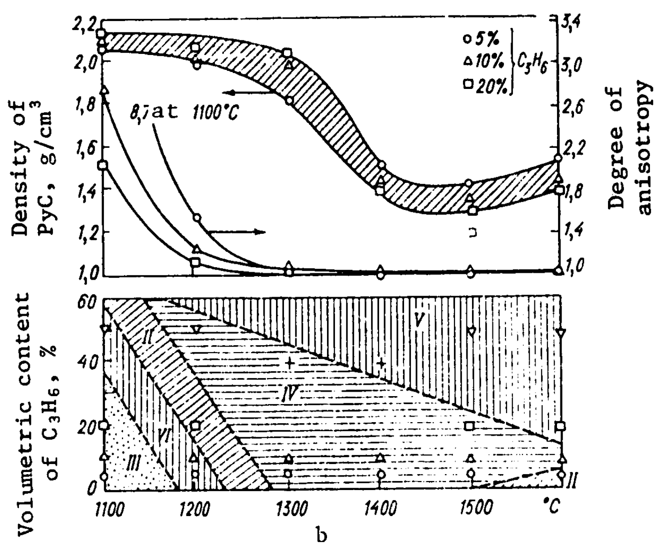


Fig. 3. Density, degree of anisotropy and structure (I--laminar; II--isotropic; III--acicular; IV--isotropic with inclusions of soot; V--porous isotropic with soot inclusions; VI--grainy) of pyrocarbon as functions of temperature and concentration of methane (a) and propylene (b) in the gas mixture [Ref. 26]

propylene. The advantage of the latter is the lower pyrolysis temperature, which reduces interaction of PyC with the fuel and "contamination" of the surface.

Pyrolytic silicon carbide is precipitated from a mixture of methyl chlorosilane (MTS) with a carrier gas [Ref. 28]. The carrier gas is usually hydrogen, which reduces the silicon halide and pyrolyzes the CH_3 radical to free carbon.

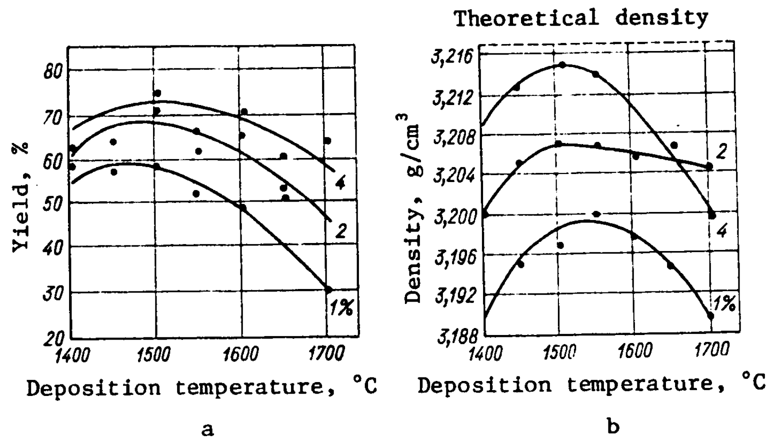


Fig. 4. Effect of volumetric concentration of methyl chlorosilane in hydrogen and pyrolysis temperature on coefficient of utilization of MTS (a) and density (b) of silicon carbide [Ref. 23]

The influence that hydrogen additives have on silicon carbide density can be judged from the data of Fig. 4. Optimum conditions of the process of deposition of the silicon carbide layer are: temperature 1500-1550°C, volumetric concentration of methyl chlorosilane in hydrogen 4%.

Conditions of depositing zirconium carbide on microfuel are described in Ref. 6, 29, 30. To produce it, a hydrocarbon is added to an initial mixture consisting of a zirconium halide and hydrogen. By varying conditions, layers of pure zirconium carbide and mixtures with pyrocarbon are produced with a stepwise change in zirconium concentration. Coating with zirconium carbide or its mixture with pyrocarbon is usually done at a temperature of 1100-1300°C. Photographs of a ground section of a fuel particle with such a coating are shown on Fig. 5.

It should be noted that during deposition of protective coatings, they accumulate a certain amount of fuel. An acid rinsing operation is done to prevent surface contamination of fuel particles [Ref. 33].

There is a relation between the outer shape of fuel particles and the properties of the coating [Ref. 34]. Since fuel particles may acquire a polygonal shape during the deposition of protective coatings, repeated mass quality control for sphericity is required, as well as checking the diameter of the fuel particles and sorting by sizes, using auxiliary methods of microradiography and roentgenography [Ref. 35]. X-ray equipment can produce a radiograph of a fuel particle with magnification of 100x and automatic measurement of the

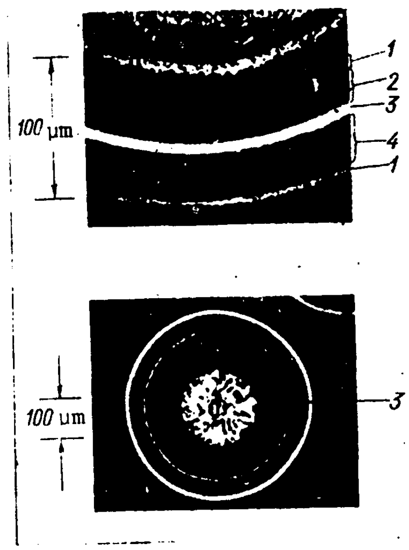


Fig. 5. Photographs of a ground section of ZrC-PyC composite [Ref. 28]: 1--dense PyC; 2--C-ZrC composite; 3--ZrC; 4--ZrC-C composite

diameter and thickness of individual layers of the coating. Measurement results are printed out after computer processing.

After mass quality control for the given parameters, the fuel particles are sampled to determine certain characteristics that reveal the extremum and average values that limit operability of fuel elements. The range of control methods that are used is rather broad since the layers of protective coatings as well as the nuclear fuel particles differ in properties. Besides, when coatings are deposited there may be changes in the fuel that are detrimental to the properties of the fuel particle. Most extensively used in sampling control are optical, metallographic, radiographic and other physicochemical methods of analysis. For example, to study the size distribution of pores in a pyrocarbon layer, the following methods are used: metallography, mercury porometry, and scattering of x-rays at small angles [Ref. 25, 36].

The apparent density of pyrocarbon and silicon carbide are usually determined by a gradient column [Ref. 35]. This is a cylindrical graduate about 70 cm high filled with a mixture of isobutyl alcohol and bromoform so that the density of the mixture increases linearly with height from 0.8 to 2.8 g/cm^3 for pyrocarbon, and from 0.88 to 3.3 g/cm^3 for silicon carbide. Part of the pyrocarbon or carbide coating (without fuel) is placed in the gradient column and balanced at a certain depth. The density of the coating material corresponds to the density of the flotation material at this depth.

The mechanical characteristics of fuel particles (crushing strength, diametric compression strength and also Young modulus) are determined by special methods described in Ref. 25, 35. For example, crushing strength is determined from smashing fuel particles between two flat surfaces. The breaking load is fixed by dynamometers of various designs. The principal disadvantage of these tests is the difficulty of establishing a relation between the breaking load and the breaking stress in the coating [Ref. 35].

The breaking strength and Young modulus of individual layers of a coating are calculated from the results of tests on diametric compression of a ring or half-ring (Ref. 25].

An important characteristic of pyrocarbon is the degree of anisotropy of crystal orientation, which can be measured by an x-ray (so-called Bacon anisotropy factor -- BAF) or optical (optical anisotropy factor -- OPTAF or OAF) method [Ref. 37, 38]. Most widely used is an optical method in which a comparison is made of the intensity of polarized light beams reflected from two mutually perpendicular planes of pyrocarbon crystals.

To determine the structure of pyrocarbon, ground sections are etched with ionized oxygen ("plasma" oxidation) or a solution of oxidant ("wet" oxidation) [Ref. 25, 36]. The following are used in etching silicon carbide ground sections: thermal etching in argon atmosphere at a temperature of 1550°C for 30 minutes; electric etching with a solution of potassium bichromate in phosphoric acid at current density of 4-5 A/cm^2 for 1.5 minutes; chemical etching with a mixture of equal volumes of saturated solutions of caustic soda and potassium ferrocyanide.

Due to strict limitations on the yield of fission products from fuel particles, the need arises for inspection and rejection of particles with a defective coating. A simple method of determining the gas-tightness of the coating is treating the fuel particles for 8 hours [Ref. 39] at a temperature of 95°C with Thorex reagent that consists of a mixture of nitric and hydrofluoric acids. Methods have also been developed for high-temperature oxidation of the nuclear fuel grain with respect to defects in coatings [sic] [Ref. 40]. For microfuel elements with type BISO coating, a method has been developed to determine gas-tightness of pyrocarbon by high-temperature chlorine treatment [Ref. 41].

As already noted above, in the process of depositing protective coatings the layers may be contaminated with uranium, which may lead to inadmissible release of fission products into the coolant. Therefore it is necessary to monitor volumetric and surface contamination of microspheres with fuel before doing the operations of fuel element fabrication. There are several methods of checking the degree of contamination of fuel particles, the most promising being measurement of the alpha-radioactivity of uranium, and also the use of mica foils [Ref. 42, 43].

It should be noted that agreement is good between the realized and required values of parameters of fuel particles in fabrication and quality control. The table summarizes actual data for an industrial batch of fuel particles. As we can see, the standard deviation of all investigated parameters from the average value does not exceed 5%.

Comparison of requirements for fuel particle parameters with attainable data [Ref. 44]

Parameter	Required value	Attainable value		
		Average	Standard deviation	
			within batch	between batches
Nuclear fuel UO_2:				
density, % of theoretical	82-93	90	4	2
diameter, μm	780	780	19	60
O/U	2000	2003	-	0.005
d_{max}/d_{min}	1.10	1.03	0.024	0.020
Layers of pyrocarbon coating (in direction from nuclear fuel to surface):				
porous layer				
density, g/cm^3	1.05	1.00	-	0.05
thickness, μm	33	30	-	3
intermediate layer				
density, g/cm^3	1.5	1.6	-	0.05
thickness, μm	30	30	-	5
dense layer				
density, g/cm^3	1.8	1.8	-	0.05
thickness, μm	27	29	-	5
Total thickness of inside pyrocarbon layers, μm:	90	89	-	13
SiC layer				
density, g/cm^3	3.2	3.2	-	0.02
thickness, μm	35	35	2.4	3.4
outside pyrocarbon layer				
density, g/cm^3	1.8	1.8	-	0.05
thickness, μm	30	30	2.7	5.0
Total thickness of coating, μm	155	154	8	10
Mass content of uranium in fuel particles, %	64	63	-	0.6

Fuel particles are certified with consideration of the results of sampling quality control, after which they can be used for fabricating fuel elements of the required configuration.

The United States, West Germany and other nations have developed industrial technological methods for making microspheres and precipitating protective pyrocarbon and carbide coatings on them. The availability of reliable methods for mass and sampling quality control enables fabrication of conditioned fuel particles for making graphite fuel elements capable of providing a helium temperature of about 950°C at the outlet of the HTGR core.

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TRANSPOSING FUEL ASSEMBLIES TO EQUALIZE ENERGY DISTRIBUTION AND IMPROVE FUEL CYCLE IN RBMK REACTORS

Moscow ATOMNAYA ENERGIYA in Russian Vol 52, No 4, Apr 82 (manuscript received 24 Apr 81) pp 231-235

[Article by Yu. I. Mityayev and V. K. Vikulov]

[Text] To reduce capital outlays on construction of nuclear electric plants, provisions are made for balancing the power of fuel channels in power reactors. In this way the required power is produced with fewer fuel channels, and there is less variance in burnup of the discharged uranium. The average power of a fuel channel is increased by balancing, which also reduces the fuel component of adjusted expenditures.

The fuel channel power is equalized by profiling multiplication and diffusion properties over the reactor core area. As demonstrated in Ref. 1, two-zone profiling is optimum. In this case the average neutron multiplication factors of the central k_∞^c and peripheral k_∞^p regions of the reactor must be no less than the necessary values $k_\infty^c \geqslant k_\infty^{nc}$ and $k_\infty^p \geqslant k_\infty^{np}$ ensuring the required equalization of fuel channel power and predetermined effective neutron multiplication factor $k_{ef} \geqslant 1$ (without considering the action of the reactor control rods).

In large channel reactors, $(k_\infty^{np} - 1)$ is 2-5 times greater than $(k_\infty^{nc} - 1)$ [Ref. 2]. This leads to considerable underburning of uranium in the discharged peripheral fuel assemblies (PFA), which must be extracted from the reactor at a burnup that is lower than that of the extracted central fuel assemblies (CFA). To increase the burnup of uranium in the PFA's, the peripheral region of the reactor can be charged with uranium of higher enrichment. This is economically advantageous since it reduces the fuel component of the cost of electric energy by several percent; however, it entails production of fuel assemblies with differing uranium enrichment, and the burnup of the discharged uranium is still less than could be realized by using these fuel assemblies in the center.

Let us try to define the conditions under which the burnup of discharged uranium could be increased by transposing PFA's with completion of burnup in the central region of the reactor core. We will consider a two-zone channel reactor in which fuel channel power is equalized by profiling multiplication properties, i. e. $k_\infty^{np} > k_\infty^{nc}$. Let us assume that the law of change in k_∞ as a function of uranium burnup P, i. e. $k_\infty(P)$, is linear and the same for CFA's and PFA's [Ref. 3].

In the simplest mode of continuous recharging, the central and peripheral regions of the reactor are supplied independently with the same kinds of fuel assemblies (Fig. 1, I), the uranium burnup in the discharged CFA's and PFA's being P_0 and P respectively, where $P_0 > P$. This mode does not provide for transpositions and additional burnup of the fuel assemblies, and is the generally accepted mode of operation for channel reactors.

Another reloading mode can be imagined in which all fresh fuel assemblies are loaded into the peripheral region of the reactor, operated there up to the same uranium burnup as in the first mode, and then transposed and additionally burned in the center (see Fig. 1, II). If operation of the reactor in

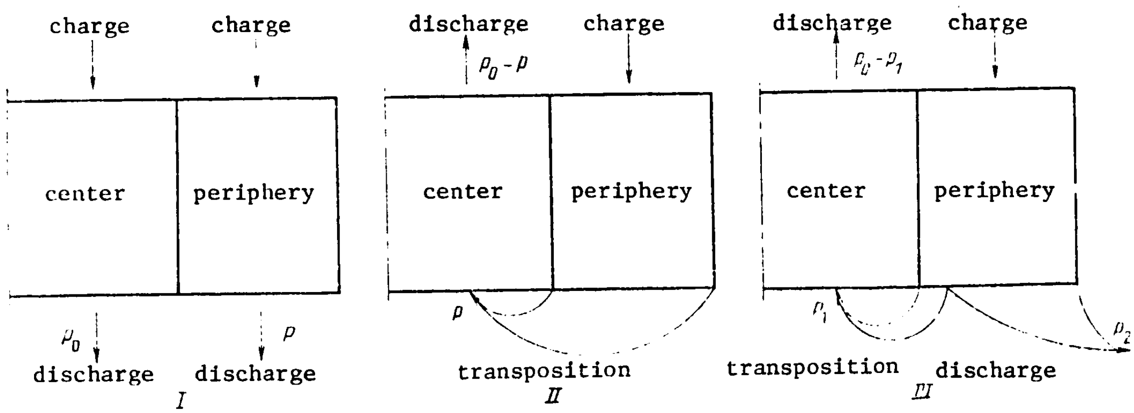

Fig. 1. Some modes of reactor recharging: I--independent recharging of center and periphery; II--all fresh fuel assemblies loaded into the periphery and all additionally burned in the center; III--all fresh fuel assemblies loaded into the periphery, and some additionally burned in the center

such a mode is possible, then uranium burnup in the CFA will vary from P to some level $P' > P$ at which the transposed fuel assemblies will be extracted. For continuous transpositions and linear dependence $k_\infty(P)$, the condition of criticality for the same profiling of multiplication properties will be the same average burnup of uranium in this region as in the first mode with independent recharging of center and periphery, i. e.

$$\frac{P' + P}{2} = \frac{P_0}{2},$$

whence

$$P' = P_0 - P. \qquad (1)$$

Since $P' > P$,

$$P < P_0/2. \qquad (2)$$

Conditions (1) and (2) are illustrated by Fig. 2.

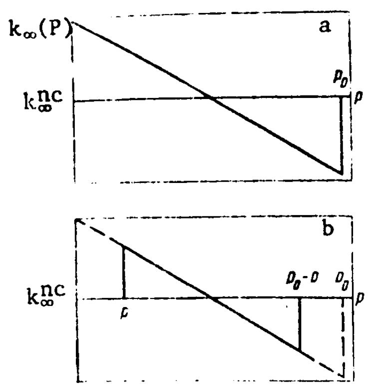

Fig. 2. Burnup of discharged uranium when the center is charged with fresh fuel assemblies (a) and with fuel assemblies with burnup P (b)

Continuing our comparison of modes I and II (see Fig. 1), let us assume for the sake of simplicity that the specific power of the uranium in the CFA's and PFA's (q, MW/kg) is the same and does not change with burnup (P, MW-days/kg). Let the number of CFA's be n, and the number of PFA's be An. Then for mode I the expenditure of CFA's and PFA's per day is

$$v_0 = nq/P_0; \quad v = Anq/P;$$

The average burnup of uranium discharged from the reactor is

$$\bar{P}_I = \frac{P_0 v_0 + P v}{v_0 + v} = \frac{1+A}{P + AP_0} P P_0 = \frac{1+A}{1 + A\left(\frac{P_0}{P}\right)} P_0. \quad (3)$$

In mode II (if it is possible), the additional burnup of uranium acquired by the fuel assemblies after transposition from the peripheral to the central region will be $\Delta P_c = P_0 - 2P$ (s Fig. 2b). Since the central region in this mode is continuously supplied only with fuel assemblies that have been depleted on the periphery, their expenditure in the central region must be equal to the expenditure on the periphery, i. e.

$$v_{II} = \frac{nq}{P_0 - 2P}; \quad v_{II} = \frac{Anq}{P},$$

whence

$$P = \frac{A}{1+2A} P_0. \quad (4)$$

Using expressions (1) and (4), we find that the average burnup of uranium discharged from the reactor in mode II is

$$\bar{P}_{II} = \frac{1+A}{1+2A} P_0. \quad (5)$$

Comparing expressions (3) and (5), we readily see that mode II is feasible and is more advantageous than mode I (i. e. $\bar{P}_{II} > \bar{P}_I$) when condition (2) is met.

Thus mode II, in which all fresh fuel assemblies are loaded into the periphery, used there until reactivity is exhausted, and then all fuel assemblies are additionally burned in the center, is advantageous only if the uranium burnup in the PFA's is less than half the uranium burnup in the extracted CFA's in mode I. In reactors of large dimensions, where neutron leakage is small, such a condition is not realizable in practice since it leads to a dip in neutron distribution in the center of the reactor core, and mode II is infeasible.

However, condition (2) can easily be met if PFA's are broken down into two groups, and rather than transposing all PFA's to the center, we transfer only

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the PFA's of the first group with relatively low burnup of uranium $P_1 < P_0/2$, while the remaining PFA's are used on the periphery up to some uranium burnup P_2 (see Fig. 1, III). Let us consider mode III also in comparison with mode I and let us assume that the specific power of the uranium q in the CFA's and PFA's is the same and does not change during burnup.

For mode III, using exactly the same fuel assemblies, the burnup of uranium discharged from the central region in accordance with expression (1) will be

$$P_C = P_0 - P_1, \qquad (6)$$

where P_1 is the burnup of uranium in PFA's of the first group after utilization on the periphery.

The additional burnup of uranium that these fuel assemblies acquire after being transposed and used in the center will be $(P_0 - 2P_1)$. Since in this case the central region is being continuously made up only with PFA's of the first group, the expenditure of fuel assemblies in the central region v_C must be exactly equal to the consumption of PFA's of the first group, i. e.

$$\left.\begin{aligned} v_C &= v_1; \\ v_C &= \frac{nq}{P_0 - 2P_1} \\ v_1 &= \frac{1}{P_1} Anq\alpha_1; \end{aligned}\right\} \qquad (7)$$

where α_1 is the fraction of PFA's of the first group among all PFA's.

For a given P_1, the value of α_1 is determined from condition (7), and the burnup of discharged uranium in PFA's of the first group is determined from the condition of criticality of the peripheral region that simultaneously ensures the required profiling of multiplication properties:

$$\frac{\alpha_1}{P_1}\int_0^{P_1} k_\infty(P)\,dP + \frac{\alpha_2}{P_2}\int_0^{P_2} k_\infty(P)\,dP = k_\infty^{np}, \qquad (8)$$

where α_2 is the fraction of PFA's of the second group, where $\alpha_1 + \alpha_2 = 1$. For linear dependence $k_\infty(P)$, criticality condition (8) has the quite simple form

$$\alpha_1 P_1 + \alpha_2 P_2 = P. \qquad (9)$$

Consumption of PFA's of the second group is

$$v_2 = \frac{1}{P_2} Anq\alpha_2.$$

The average burnup of uranium discharged from the reactor in mode III will be

$$\bar{P}_{III} = \frac{P_C v_C + P_2 v_2}{v_C + v_2}. \qquad (10)$$

Using conditions (7), (9) and (10), $\bar{P}^{III}$ can be represented as

$$\bar{P}_{III} = \text{const}\,\frac{AP(P_0 - 2P_1) - P_1^2}{P + A(P_0 - 2P_1) - 2P_1}.$$

A study of this expression shows that $\overline{P}_{III}$ has a maximum at $P_1 = \frac{P_0 - P}{1 + A} A$. It is important that in this case the burnup of uranium in discharged CFA's and PFA's of the second group be the same, i. e. $P_2 = P_C = P_0 - P_1$. In this case

$$\overline{P}_{III} = \overline{P}_{III}^{max} = \frac{P_0 + AP}{1 + A},$$

where $\overline{P}_{III}^{max} > \overline{P}_I$.

Thus the operating mode of a reactor in which all fresh fuel assemblies are charged only into the periphery, used there, and then some of the PFA's with optimum uranium burnup are transposed to the center where they are additionally burned, while the rest of the PFA's are used on the periphery until the reactivity of this region is exhausted, is more advantageous than independent reloading of the central and peripheral regions of the reactor.

TABLE 1

Relative increase in uranium burnup with transposition and operation of some PFA's in the center $\left(\frac{\overline{P}_{III}^{max}}{\overline{P}_I} - 1\right) \cdot 100$, %

P/P_0	A							
	1,0	0,9	0,8	0,7	0,6	0,5	0,4	0,3
0,9	0,28	0,28	0,27	0,27	0,26	0,25	0,23	0,20
0,8	1,25	1,25	1,24	1,21	1,17	1,11	1,02	0,89
0,7	3,21	3,21	3,18	3,11	3,01	2,86	2,62	2,28
0,6	6,67	6,65	6,58	6,46	6,25	5,93	5,44	4,73

As can be seen from Table 1, for the given assumptions and the values of A and P/P_0 encountered in practice, the proposed recharging method enables an increase in burnup of the discharged uranium by several percent with a corresponding reduction in the fuel component of cost of electric energy. To check out the approximate results, a stricter two-dimensional model of the reactor was used, enabling accounting for power and energy release of each channel. For this purpose, the heterogeneous QUM-3-HEP program was used [Ref. 4] as well as the VRM and VOR constant programs used in designing the RBMK [Ref. 5].

Let us note that the given calculations have qualitatively confirmed results of approximate calculations, although they showed less increase in uranium burnup. For example at $A = 0.36$ and $P/P_0 = 0.78$, burnup increase was ~0.7%, as against 1.3% according to the data of Table 1. Refinement is mainly by considering equalization of the neutron field with transpositions of fuel assemblies, leading to some increase in neutron leakage, and also by consideration of nonlinearity in the behavior of multiplication properties of the medium with uranium burnup.

Calculations showed one more advantage of the given method of reloading, which shows up in additional equalization of energy distribution due to transposition of partly burned fuel assemblies rather than fresh ones into the center, i. e. into the region with maximum neutron flux. If reloading is done on the working reactor, equalization may be intensified by ^{135}Xe in the transposed fuel assemblies. This advantage becomes especially important when an economically advantageous increase in uranium burnup by simply raising its initial enrichment is impossible due to an inadmissible increase in the coefficient of non-uniformity of energy distribution because of heat-transfer conditions. Such a situation is typical of reactors in which the minimum necessary reserve is provided up to the limiting power of the fuel channels, and in particular for the RBMK-1500 and the RBMKP.

The model indicated above was used for calculating steady-state conditions of recharging the block-section RBMKP-2400 reactor with nuclear superheating of steam [Ref. 6, 7], in which the plan provides for the given method of load changing. Consideration was taken not only of the configuration and makeup of the core (Fig. 3), but also of the fact that the power of the superheated channels must be approximately half that of the evaporative channels, and the region of elevated neutron flux density of the evaporative zones is made up of the central regions of these zones, whereas in the superheated zone the superheated channels in rows bordering on the zone of the evaporative channels make up the regions of high neutron flux density. The evaporative

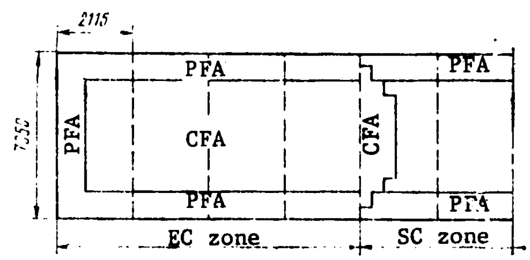

Fig. 3. Structure of the left half of the RBMKP-2400 reactor core. The broken line shows the boundaries of sections (the core consists of eight identical evaporative channel (EC) sections and four superheated channel (SC) sections. Each section contains 270 channels: 240 fuel channels and 30 for control rods)

fuel assemblies are reloaded and transposed during operation of the reactor, all fresh fuel assemblies being installed only in three peripheral evaporative channel zones, from which some are transposed to the center. The superheated fuel assemblies are reloaded and transposed with the reactor shut down, about 5% of the channels being renewed at one time. In the superheated zone, fuel assemblies are transposed from the three peripheral rows only to the three rows of superheated channels bordering on the evaporative channel zones (Fig. 3). No transposition of fuel assemblies is provided in the other regions of the superheated zone.

To simplify spatial calculations, a fixed periodic structure of the reactor core was assumed. Certain average values of uranium burnup were assigned to the fuel assemblies transposed and reloaded from each region. In each region the distribution of the remaining fuel elements with respect to uranium burnup from the fresh or transposed assembly to the unit about to be discharged or transposed was taken as discrete and uniform. Compensation of operative reserve reactivity was also fixed by control rods. All this enabled us to do variant calculations with minimum changes in load charting records without considering the history of each fuel assembly. Criticality and the required energy distribution in the reactor were ensured by varying the sought average values of uranium burnup in the fuel assemblies at discharge or transposition.

TABLE 2

Some characteristics of the RBMKP-2400 fuel cycle for different methods of reloading fuel assemblies

Characteristic	Without transposing fuel assemblies		With transposition of fuel assemblies	
	EC	SC	EC	SC
Enrichment of uranium to be loaded, %	2.0	3.0	2.4	3.6
Average burnup of discharged uranium, MW-days/kg	21.9	24.7	27.7	30.5
Specific consumption of enriched uranium, metric tons/GW-yr*	28.8	6.4	22.9	4.8
Specific consumption of natural uranium required for getting uranium of appropriate enrichment, metric tons/GW-yr*	108.6	37.9	106	35
Fuel component cost of electric energy, relative units	1.0		0.91	

*Power utilization factor was 0.8.

Calculations done at the same values of limiting power of the evaporative and superheated channels showed that the proposed transpositions of fuel assemblies into the region of elevated neutron flux density can appreciably increase the enrichment and burnup of uranium and improve the characteristics of the reactor fuel cycle (Table 2). In particular, there is a reduction in the requirements for enriched and natural uranium (by 20 and 4% respectively), and a 9% reduction in the fuel component of the cost of electric energy. It is also important that there is only a slight increase (by approximately 25%) in the total number of transport-technological operations with the fuel per unit of time thanks to the appreciable increase in uranium input despite the additional operations involved in transposing fuel assemblies.

In conclusion it should be stated that similar results to all appearances can be obtained by using more complicated recharging modes with double or multiple transpositions of fuel assemblies. As the simplest example we might mention transpositions of the periphery—center—periphery type, where fresh fuel assemblies are loaded only into the periphery, and after brief operation there are transposed to the center for appreciable energy production, then returned to the periphery to complete the fuel cycle. In this or other more complicated cases, the periphery must contain both high- and low-reactivity fuel assemblies in a combination ensuring the necessary profiling of multiplication properties. However, in practice the modes of operation with multiple transpositions of fuel assemblies have a considerable disadvantage since they lead to an appreciable increase in the number of transport-technological operations with irradiated fuel, and are also detrimental to conditions of gas-tightness of channels with repeated insertion of fuel assemblies.

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ENERGY-STORING SUBSTANCES AND THEIR UTILIZATION

Kiev ENERGOAKKUMULIRUYUSHCHIYE VESHCHESTVA I IKH ISPOL'ZOVANIYE in Russian 1980 (signed to press 28 Jul 80) pp 2, 238-239

[Annotation and table of contents from book "Energy-Storing Substances and their Utilization", by Il'ya L'vovich Varshavskiy, Izdatel'stvo "Naukova dumka", 1,000 copies, 240 pages]

[Text] Annotation

This monograph examines questions of the employment of certain substances as secondary energy carriers. A classification of energy-storing substances is given, along with an analysis of their energy storage capacity and methods for obtaining them. The possibility of using energy-storing substances to obtain hydrogen from water is evaluated.

The monograph is intended for scientific and engineering-technical workers specializing in the area of power engineering, machine building and transportation. 138 illustrations, 38 tables, 126 bibliographic references.

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6900
CSO: 1861/236

UDC: 621.313.222-81.019.3

RELIABILITY OF ELECTRICAL MACHINERY FOR POWER GENERATION

Kiev NADEZHNOST' ENERGETICHESKIKH ELEKTROMASHIN (SBORNIK NAUCHNYKH TRUDOV) in Russian 1981 (signed to press 3 Dec 81) pp 2, 174-180

[Annotation and abstracts from book "Reliability of Electrical Machinery for Power Generation", by G. G. Schastlivyy (editor-in-chief), Izdatel'stvo "Naukova dumka", 800 copies, 180 pages]

[Text] Annotation

This book presents theoretical and practical questions involved in increasing the reliability, load-carrying ability and service life of high-power turbine generators. Methods of constructing mathematical models, important in the design phase, of the generator elements and assemblies which carry the heaviest loads are examined which can be used to calculate loads under various operating conditions and during overloads; general principles of constructing systems for diagnosing and predicting the condition of generators operating in basis and manipulated modes, which are important in manufacture and operation, are also considered. New ways are analyzed for design facilitation of the problem of reliability and service life of generators. The book is intended for specialists in the area of modeling AC machinery.

Abstracts

UDC: 621.313.322-81.004:621.3.029.3

INVESTIGATION OF INFLUENCE OF MODES ON RELIABILITY OF STATOR IN HIGH-POWER TURBINE GENERATORS

[Abstract of article by G. G. Schastlivyy, A. M. Timoshik and A. I. Bondarenko]

[Text] This article investigates the influence of manipulative modes on the reliability of the end zones of the stator in high-power turbine generators based on statistical analysis of the susceptibility to damage of two groups of turbine generators making up a general set related to bases and manipulated operating conditions. The hypothesis of the influence of manipulated modes on the susceptibility to damage of the teeth of the end groups of stators of high-power turbine generators is confirmed. 3 tables, 6 bibliographic references.

UDC: 621.313.33.045.57

ANALYSIS OF STATISTICAL ANGULAR CHARACTERISTICS OF SYNCHRONOUS BIAXIAL DRIVEN TURBINE GENERATOR

[Abstract of article by I. M. Postnikov, N. G. Vas'kovskiy, Yu. N. Vas'kovskiy, S. M. Sergiyenko and Yu. N. Sitko]

[Text] This study analyzes the static angular characteristics of a 200 MW biaxially excited synchronous turbine generator with different rotor winding constructions. The required principles of connecting the rotor windings and adjusting the excitation currents in them are presented. 6 illustrations, 2 tables.

UDC: 621.313.3.001

PROBLEM OF TEMPERATURE DIAGNOSIS OF ROTOR IN ELECTRICAL MACHINE

[Abstract of article by G. G. Schastlivyy, A. I. Titko, V. V. Popov and E. I. Gurevich]

[Text] This article presents the approximate functional diagram of temperature diagnosis of the rotor of an AC electrical machine. The functional connections between individual units of the system are disclosed. The most important factors of temperature asymmetry are determined. Expressions are given for determining vibration caused by temperature asymmetry. 2 illustrations, 2 bibliographic references.

UDC: 621.3.019:62-50.72;681.322.05

STRUCTURAL-FUNCTIONAL ORGANIZATION OF SYSTEM FOR TECHNICAL DIAGNOSIS AND TESTING OF STATUS PARAMETERS OF HIGH POWER GENERATORS

[Abstract of article by G. L. Baranov, T. M. Slepysheva, and Ye. Yu. Komarenko]

[Text] A structural-functional diagram is proposed for a system for technical diagnosis and testing of state parameters of generators to control its operation reliability in a power system. The basic problems and principles of construction are examined. 1 illustration, 7 bibliographic references.

UDC: 621.313.322:537.312.62.001.24

CALCULATION OF TEMPERATURE FIELD IN CYLINDRICAL SHELL OF FINITE THICKNESS

[Abstract of article by V. N. Ostapenko and S. N. Shnyreva]

[Text] A method is proposed for calculating the temperature field in a cylindrical shell with finite thickness based on polynomial approximation of the temperature function in the radial direction. 3 bibliographic references.

UDC: 621.313.322:537.312.62.001.24

NONSTATIONARY TEMPERATURE FIELD IN CIRCULAR CYLINDRICAL SHELL OF FINITE THICKNESS

[Abstract of article by S. N. Shnyreva]

[Text] A method is proposed for calculating the nonstationary temperature field in a circular cylindrical shell of finite thickness which makes it possible to reduce the temperature determination to solving a Cauchy problem for ordinary differential equations with respect to the coefficients of Legendre polynomials. 3 bibliographic references.

UDC: 621.313.322;621.391

UTILIZATION OF CORRELATION ANALYSIS IN ACOUSTIC DIAGNOSIS OF BEARINGS IN ELECTRIC POWER MACHINERY

[Abstract of article by M. V. Myslovich]

[Text] This study describes correlation analysis of the recordings of acoustic noise occurring during operation of bearings in electrical power machinery. As a result of the analysis, singularities of the correlation functions are indicated which can be employed to diagnose bearings. The experimental data provide the basis for a mathematical model which describes the acoustic noise made by both defective and conditionally good bearings. 2 illustrations, 1 table, 3 bibliographic references.

UDC: (621.313.322:537.312.62)001.24

GENERALIZED MATHEMATICAL MODEL AND INVESTIGATION OF MAGNETIC FIELD, PARAMETERS AND ELECTRODYNAMIC FORCES IN FRONTAL SECTIONS OF ELECTRICAL MACHINES

[Abstract of article by N. A. Predolyak]

[Text] A generalized mathematical model is developed for calculating the magnetic field, parameters and electrodynamic forces in the frontal sections of electrical machines considering the shielding action of the pressure plate and rotor shroud. The influence of the thickness of the windings, straightening and shielding on these characteristics is investigated. 7 illustrations, 2 tables, 5 bibliographic references.

UDC: 621.313.322-81

EXPERIMENTAL INVESTIGATIONS OF HEATING AND LOSSES IN HIGH POWER TURBOGENERATORS WITH HELP OF DATA ACQUISITION, RECORDING AND PROCESSING SYSTEM

[Abstract of article by V. M. Bondarenko, A. A. But, N. V. Sirenko and G. M. Fedorenko]

[Text] An automated system for gathering, recording and processing experimental data is described which is designed for experimental research on thermal processes of powerful turbogenerators and which increases the accuracy and information yield of research. 2 illustrations.

UDC: 621.313.322:537.312/001.24

PHYSICAL NATURE OF EDGE EFFECT IN A CONDUCTING ELEMENT

[Abstract of article by A. I. Titko]

[Text] This article examines the electromagnetic edge effect phenomenon which is encountered in bounded conductive elements of high-current power devices. The essence of the manifestation of the edge effect in the basic situations in which it occurs is explained, and the concepts needed to analyze the phenomenon are given. The qualitative nature of the eddy current direction field in the regions of occurrence of the edge effect is demonstrated. 4 illustrations, 4 bibliographic references.

UDC: 621.321

EMPLOYMENT OF PIECEWISE-LINEAR ACOUSTIC SIGNAL CONVERTER TO DIAGNOSE ELECTRICAL MACHINE ASSEMBLIES

[Abstract of article by A. I. Krasil'nikov and M. V. Myslovich]

[Text] This article examines the utilization of a piecewise-linear converter to process acoustic noise arising in electrical machine assemblies in order to disclose diagnostic signs. The noise source is a bearing, which is an assembly which operates under the most difficult mechanical conditions and is the second most common source (after windings) of electrical machinery malfunctions. The operation of the converter is analyzed on the basis of a mechanical-acoustic model of a single-row bearing and its equivalent electrical circuit. 4 illustrations, 3 bibliographic references.

UDC: 621.313.013

MODELS AND ANALYTICAL EXPRESSIONS OF MAGNETIC FIELD EXCITATION SOURCES IN ELECTRICAL MACHINARY

[Abstract of article by N. A. Predolyak]

[Text] This article examines models of electrical machinery windings which are tangentially straightened and non-straightened; corresponding analytical expressions are obtained in the form of dual-layer functions of magnetic charges which are equivalent to the winding currents, as well as the components of the volumetric and surface current density. 3 illustrations, 3 tables, 8 bibliographic references.

UDC: 536.5.081.3:62-25

MULTICHANNEL OPTOELECTRONIC SYSTEM FOR MEASURING ROTOR TEMPERATURE OF ELECTRICAL MACHINERY

[Abstract of article by V. N. Bondar, G. M. Fedorenko and V. N. Nikolayev]

[Text] An optoelectronic system employing a pseudonoise data signal is examined in order to increase the accuracy of monitoring the operation of turbogenerators by providing constant monitoring of the temperature of the basic rotor parts. Formulas are derived for calculating the sensitivity, error and speed of the system. Results of experimental investigations are presented. 3 illustrations, 5 bibliographic references.

UDC: 681.3.06

IMPLEMENTATION OF REFERENCE FUNCTION IN DATA BASES

[Abstract of article by S. G. Kil'dishev]

[Text] This article provides a brief description of standard functions implemented by programs of the SPOD, BANK and OKA automated data bases during request processing, data base retrieval and response formation. 1 illustration, 3 bibliographic references.

UDC: 621.313.333.001.4

INVESTIGATION OF MECHANICAL CHARACTERISTICS OF INDUCTION MOTORS WITH HELP OF MAGNETOELASTIC TRANSDUCER

[Abstract of article by Yu. Ye. Sharshunov, I. M. Cheburakhin and L. N. Makarov]

[Text] This article substantiates the expedience of using a magnetoelastic torque transducer in dyanometer testing of induction motors. The construction and technical characteristics of a magnetoelastic transducer developed for laboratory conditions are given. 4 illustrations, 5 bibliographic references.

UDC: 621.313.0142.045.54

HIGHER HARMONIC EMF AND EXCITATION WINDING OF MULTIPHASE BRUSHLESS EXCITER

[Abstract of article by A. Ye. Mashnev]

[Text] This article gives an estimate of the higher harmonic emf induced in the excitation winding of a multiphase brushless exciter used to excite high-power turbogenerators and their influence on the operating reliability of the exciter. 2 tables, 5 bibliographic references.

UDC: 621.34.001.57-52:681.3.01.001.24

GAME-THEORETIC MODELING OF COMPLEX SYSTEMS

[Abstract of article by G. L. Baranov]

[Text] This article provides definitions of the structural states of complex systems and equilibrium conditions based on the extendibility of matched families of random transitions. An algorithm is proposed for an iterative process of regularizing an arbitrary abstract irregular complex corresponding to the complex system in question. 1 illustration, 7 bibliographic references.

UDC: 621.313.013

CALCULATION AND INVESTIGATION OF EDDY CURRENTS AND LOSSES IN ROTORS OF TURBINE AND CRYOTURBINE GENERATORS ALLOWING FOR VARIATION IN AXIAL DIRECTION

[Abstract of article by I. V. Khimyuk]

[Text] A three-dimensional mathematical model is developed for calculating eddy currents and losses in electrical machines allowing for axial variation. This model is used as the basis for investigating the influence of frequency and geometry on the spread of eddy currents and losses in the envelopes of the cryoturbogenerator rotor. The model can be used to investigate eddy currents in electrical machines with smooth rotors in linear approximation. 5 illustrations, 1 table, 2 bibliographic references.

UDC: 621.313.3.001

WINDING COEFFICIENT AND LONGITUDINAL AXIS OF CONSEQUENT-POLE ROTOR WITH IRREGULAR GROOVE ARRANGEMENT

[Abstract of article by Ye. V. Zozulin, G. G. Levchenko and V. A. Yakovenko]

[Text] A method is described for determining the position of the magnetic axes of an asymmetrical turbogenerator rotor. Expressions are derived for calculating the winding coefficients. 3 illustrations.

UDC: 621.313.333

UTILIZATION OF THEORY OF MAGNETIC CIRCUITS WITH COMPLEX PARAMETERS IN ANALYZING INDUCTION MOTORS

[Abstract of article by A. N. Cheldyshev]

[Text] Based on the general assumptions of the theory of magnetic circuits and methods of calculating induction machines with single- and two-group rotors, this article presents equivalent calculation circuits in which all of the elements in the magnetic circuit are represented by reluctances, including the stator and rotor windings. The values of the parameters of a calculation circuits are presented in accordance with the construction of the machine both for the basic and any spatial magnetomotive force of the stator. 3 illustrations, 1 table, 7 bibliographic references.

UDC: 621.313.322

SELECTION OF SUBSTITUTION CIRCUIT FOR POWERFUL SYNCHRONOUS GENERATORS

[Abstract of article by V. V. Tverdyakov and N. A. Kulichikhina]

[Text] This article examines substitution circuits for powerful synchronous generators. It is demonstrated that the experimental frequency characteristics can provide the basis for determining the parameters of a circuit which allows for differences in the relationship between the circuits of the rotor block, field winding and stator. 1 illustration, 1 table, 6 bibliographic references.

UDC: 62-83:621.313.333:621.3.012.6

INDUCTION ADJUSTABLE SUBWAY VENTILATOR ELECTRIC DRIVE

[Abstract of article by P. F. Verbovoy, G. A. Zemtsov, G. F. Lavrent'yev and V. V. Posun'ko]

[Text] An adjustable subway ventilator drive has been developed, built and studied under laboratory and operating conditions which includes a type TSUR thyristor voltage regulator and type AO2-92-8Rd induction motor with two-lamination rotor construction. The drive permits smooth start-up, braking, reversing and adjustment of speed, and allows the fan output to be adjusted within wide limits, increasing the efficiency of the unit and providing significant savings through reducing power consumption. The drive is recommended for subway fans and other ventilation installations with power of up to several tens of kilowatts. 1 illustration, 7 bibliographic references.

UDC: 621.313.33.13.001

CALCULATION OF MAGNETIC FIELD OF INDUCTION MACHINE WITH SOLID ROTOR USING FINITE ELEMENT METHOD

[Abstract of article by Ye. V. Strunevich, Yu. A. Shumilov and V. I. Postnikov]

[Text] On the basis of the finite-element method, this article presents a numerical solution to the problem of joint consideration of eddy currents in a smooth solid rotor and its saturation. The method is applied to calculating the magnetic field in the active section of a model machine. The results of the numerical calculation are compared with the results of the analytical theory. 3 illustrations, 5 bibliographic references.

UDC: 621.3.019.3:62-50.72:681.322.05

ESTIMATION OF CALCULATED PARAMETERS FOR PREDICTING AVAILABLE ACTIVE AND REACTIVE POWER OF GENERATOR CONSIDERING RELIABILITY

[Abstract of article by Ye. Yu. Komarenko]

[Text] A method and model are proposed for estimating parameters to predict available active and reactive generator power considering reliability. 2 illustrations, 5 bibliographic references.

6900
CSO: 1861/222

NAVIGATION AND GUIDANCE SYSTEMS

NAVIGATION AND CONTROLLING MOVEMENT OF MECHANICAL SYSTEMS

Kiev NAVIGATSIYA I UPRAVLENIYE DVIZHENIYEM MEKHANICHESKIKH SISTEM (SBORNIK NAUCHNYKH TRUDOV) in Russian 1980 (signed to press 31 Dec 80) pp 2, 142-149

[Annotation and abstracts from book "Navigation and Controlling Movement of Mechanical Systems (Collected Scientific Works)", editor-in-chief V. N. Koshlyakov, corresponding member, UkSSR Academy of Sciences, 400 copies, 141 pages]

[Text] Annotation

The collection contains a series of papers on the theory of gyroscopic navigation systems and moving vehicle control systems. An examination is made of problems of optimization, precision and motion stability.

Intended for specialists working in the field of theory and design of navigation systems and control systems, and for upperclassmen and graduate students.

Abstracts

UDC: 531.01

STABILITY OF TWIN-ROTOR GYROSCOPIC PENDULUM-TYPE COMPASSES

[Abstract of article by V. N. Koshlykov]

[Text] The Lyapunov function is constructed for equations of small oscillations of a spatial gyroscopic compass; the compass is shown to be unstable in the presence of arbitrarily small dissipative forces when the vertical component of its angular velocity exceeds in absolute value the Schuler frequency. 4 bibliographic references.

UDC: 629.13.014.69.506.4

UNIVERSAL EQUATIONS FOR INERTIAL NAVIGATION SYSTEMS

[Abstract of article by O. F. Boychuk, V. N. Kalinovich and S. M. Onishchenko]

[Text] Universal equations of ideal operation, and hence error equations, are derived for inertial navigation systems which describe the behavior of platfor and non-platform inertial navigation systems and which can be used to allow

for the specific orientation of the reference trihedral (platform) in each individual case, which provides a significance convenience in analytical investigations and in integrating different inertial navigation systems.
3 bibliographic references.

UDC: 531.01

MATHEMATICAL MODEL OF MOVEMENT OF SINGLE-ROTOR CORRECTABLE GYROCOMPASS

[Abstract of article by V. P. Vasilenko]

[Text] A mathematical model is constructed for the movement of a single-rotor correctable gyrocompass in linear statement and with a more detailed description than exists elsewhere in the literature. The equations allow for variability of the kinetic moment of the gyroscope, cross-connections between the torsion angles of the torsion bars and the angles of horizontal and vertical mismatching of the rotor shaft and the tracking ball, as well as the moments applied to the tracking ball through the torsion bar from the rotor. 6 bibliographic references.

UDC: 531.36

SUFFICIENT CRITERION FOR INSTABILITY OF SYSTEMS WITH INVARIANT PHASE SPACE

[Abstract of article by S. P. Sosnitskiy]

[Text] This article investigates the stability of systems with invariant phase space. A theorem is proved which indicates sufficient conditions for instability of systems with invarient phase space. The theorem obtained is applied to the stability of equilibrium of scleronomic systems. 5 bibliographic references.

UDC: 531.01

UTILIZATION OF GYROCOMPASS PLATFORMS TO BUILD INERTIAL NAVIGATIONAL SYSTEMS

[Abstract of article by V. N. Kalinovich]

[Text] This study examines the possibility of using gyrocompass platforms to build inertial systems with the object moving at a variable distance with respect to the center of the earth. Determination is made of the type of correcting moments which ensure imperturbability of the gyrocompass platforms and their required azimuth orientation. Platform oscillations are considered which are caused by imprecise initial setting, the presence of outside moments and errors and the newtonometer readings. 10 bibliographic references.

UDC: 513.01

OSCILLATIONS OF GYROPLATFORM ORIENTED IN GEOGRAPHIC MERIDIAN

[Abstract of article by V. P. Vasilenko and A. N. Polishchuk]

[Text] This article investigates oscillations of a gyroplatform which is oriented in a geographic meridian. Expressions are derived for the characteristic indicators which determine the stability of movement and frequency of intrinsic oscillations of the platform. 4 bibliographic references

UDC: 629.13.014.69-506.4

CORRECTABLE INERTIAL SYSTEMS. OBSERVABILITY AND MODAL EQUATION

[Abstract of article by S. F. Boychuk]

[Text] This article states the problem of the damping of the oscillations of inertial navigation systems when outside data is available as a problem of observability, estimation and optimal (modal) equation. A general scheme for optimal utilization of additional information available aboard the device is constructed on the basis of Kalman's formalism. Nonstationary statement of the problem is used to prove the assertion of the uniform observability of the error vector, which consists of errors in computing the latitude and bearing and horizontal stabilization errors of the platform, with outside information available about velocity and latitude of the moving object. 8 bibliographic references.

UDC: 629.13.014.69-506.4

USE OF QUATERNIONS IN INERTIAL NAVIGATION

[Abstract of article by S. M. Onishchenko]

[Text] This article investigates singularities of the use of various kinematic parameters (Euclidean vectors, Euler's parameters, finite revolution vector, direction cosines of Euler-Krylov angles, Rodrigues-Hamilton parameters, quarternions, Cayley-Klein parameters) in the equations of self-contained inertial navigation systems during numerical computer processing. It is concluded that coding and processing of numerical information in inertial navigation system operating algorithms using a non-positional system of residue classes is promising. 11 bibliographic references.

UDC: 531.383:62-50

INVESTIGATION OF VARIOUS POSSIBILITIES OF CONTROLLING GYROSCOPIC COMPASS

[Abstract of article by V. V. Novitskiy]

[Text] This article investigates versions of schemes for controlling a twin-rotor gyroscopic compass which can be implemented in practice. It is demonstrated that the smallest number of equations for this gyroscopic compass is 1. Two of four controlling moments are selected which are best for controlling the gyrocompass. 6 bibliographic references.

UDC: 62-50

WEAK DISCRETE EQUATION OF WEAKLY DAMPED SYSTEMS

[Abstract of article by V. B. Larin and K. I. Naumenko]

[Text] This article presents an algorithm for synthesizing a system for controlling a weakly damped object in which the control is done over equal time intervals. The method of synthesis is based on a generalized Boss relation and on the method of perturbations of the eigenvalues of an orthogonal matrix. 7 bibliographic references.

UDC: 62.502

OPTIMAL SYNTHESIS PROBLEM FOR DISCRETE SYSTEMS IN ABSENCE OF INFORMATION REGARDING CERTAIN COORDINATES OF MOVING OBJECT

[Abstract of article by V. N. Suntsev]

[Text] This article presents a solution to the synthesis problem for discrete systems when there is no information regarding certain of the coordinates of the object when the control principle is formed in the feedback circuit. 7 bibliographic references.

UDC: 62-502

STABILIZATION OF PERIODIC SYSTEMS WITH INCOMPLETE FEEDBACK

[Abstract of article by F. A. Aliyev and V. B. Larin]

[Text] This article examines a procedure for constructing an observer (system for obtaining estimates of phase coordinates of controlled object) for a linear periodic controlled system (analog and discrete). The proposed algorithm is compared with known identifiers. 13 bibliographic references.

UDC: 62-502+629.762.2(075)

ANALYTIC CONSTRUCTION OF STABILIZATION SYSTEMS FOR FLIGHT VEHICLES AND ESTIMATION OF EFFECTIVENESS OF RESULTS USING EXAMPLE OF HELICOPTER STABILIZATION CHANNEL

[Abstract of article by L. N. Blokhin and S. I. Osadchiy]

[Text] This study uses the example of selecting the optimal structure for the autopilot of a helicopter control channel in the hovering state to demonstrate the effectiveness of analytical construction algorithms based on ideas of optimal filtering in problems of synthesizing flight vehicle stabilization systems. Relatively simple synthesis algorithms are presented which are convenient for solving problems in many practically encountered cases. 5 illustrations, 1 table, 5 bibliographic references.

6900
CSO: 1861/218

CONTROL SYSTEM FOR ELASTIC MOVING OBJECTS

Leningrad SISTEMY UPRAVLENIYA UPRUGIMI PODVIZHNYMI OB"YEKTAMY in Russian 1981 (signed to press 10 Apr 81) pp 3-5, 193-200

[Foreword, bibliography and table of contents from book "Control System for Elastic Moving Objects", by Aleksandr Nazar'yevich Sinyakov, Izdatel'svo Leningradskogo universiteta, 1928 copies, 200 pages]

[Text] Foreword

The design of systems for controlling elastic moving objects involves significant difficulties resulting from the elastic properties of the controlled object. Cases are known [57] in which failure to account for this phenomenon during the design process has led to substantial degradation in the control process during flight, and even to malfunction of the flight vehicle. Methods of designing systems for controlling elastic moving objects, primarily flight vehicles, are the subject of the work of V. A. Bodner [6], S. M. Belotserkovskiy, Yu. A. Kochetkov, A. A. Krasovskiy and V. V. Novitskiy [61], A. G. Butkovskiy [7], S. V. Yemel'yanov [52], G. M. Kashin and G. I. Fedorenko [14], K. S. Kolesnikov and V. N. Sukhov [19], A. A. Krasovskiy [20,21], N. T. Kuzovkov [22, 23], S. V. Luchko [2], B. N. Petrov [50, Ye. P. Popov [36, 37], T. K. Sirazetdinov [49], Yu. I. Topcheyev [31, 61], S. M. Fedorov [2, 29] and A. S. Shatalov [4, 57]. While a significant portion of the questions in linear statement can be considered resolved already, fairly complex problems arise when allowances are made for nonlinearities, both incidental and those specially introduced (nonlinear correcting devices). The influence of the signals from high frequency elastic oscillations on the angular stabilization contour with limitation of the speed of the actuating device was first examined by Ye. P. Popov [36].

The work of Ye. P. Popov [37], Ye. I. Khlypalo [55], S. N. Sharov [59], S. M. Fedorov [29], A. V. Bakakin, V. I. Utkin, K. K. Zhil'tsov and B. V. Yefimov [50], among others, is devoted to a development and investigation of nonlinear correcting devices in oscillating systems.

The primary mathematical apparatus employed in this work is Ye. P. Popov's harmonic linearization.

R. A. Nelepin's studies [30] are devoted to methods of synthesizing nonlinear control systems based on precise analytical methods. The cross-section space method which he developed is extremely promising for analyzing and synthesizing systems for controlling elastic moving objects. Extremely important findings regarding the employment of self-adjusting systems for controlling moving objects have been obtained by a group of authors under the supervision of B. N. Petrov and S. V. Yemel'yanov [50].

The present monograph is devoted to the development of methods which can be used to increase the efficiency of systems for controlling elastic objects.

The first chapter exampines mathematical models of elastic moving objects. This question is of major methodological importance in selecting the mathematical apparatus and the methods of designing control systems.

The second chapter contains a very short exposition of problems of optimal synthesis, as well as the operating singularities of systems for controlling elastic objects with concomitant nonlinearities.

The basic findings are presented in the following chapters.

The third chapter contains research on increasing the efficiency of systems for controlling elastic moving objects by introducing autonomous feedback.

The fourth chapter examines methods of neutralizing noise from elastic oscillations of the objects in the control systems. Special attention is devoted to adaptive processing methods based on the employment of nonlinear sections.

The fifth chapter is devoted to synthesizing null-finite control of elastic moving objects.

The sixth chapter presents the results of research on employing nonlinear correcting devices in systems for damping elastic oscillations.

The seventh chapter also contains original material, but is auxiliary in nature. It is devoted to using the logarithmic transitional process method to investigate and optimize dynamic systems, including systems for controlling elastic moving objects.

Because of its limited size, the book does not include matters associated with analyzing familiar schemes for constructing systems for controlling elastic objects or with the singularities of employing digital computers for control purposes. These matters are explained thoroughly in the literature [1-4, 14, 20-22, 34, 41, 44, 56, 61, etc.].

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6900
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HIGH-ENERGY DEVICES, OPTICS AND PHOTOGRAPHY

UDC 535.8: 531.717.8

OPTICAL DEVICES FOR MEASURING SURFACE ROUGHNESS

Leningrad OPTICHESKIYE PRIBORY DLYA IZMERENIYA SHEROKHOVATOSTI POVERKHNOSTI in Russian 1981 pp 2-3

[Annotation and foreword from book "Optical Devices for Measuring Surface Roughness", by A. A. Kuchin and K. A. Obradovich, Izdatel'stvo "Mashinostroyeniye", 197 pages]

[Text] Annotation

The book considers the special features of measuring surface roughness parameters by means of contactless optical devices, as well as the effect of the arrangement of their parameters, residual aberrations and design on the measurement accuracy. A system is described for providing unity of surface measurement by various methods,and the applicability boundaries are shown for each of these methods.

This book is intended for engineering-technical workers involved in the development and operation of optical devices for monitoring surface roughness. It may be used by technologists and workers in central measurement and monitoring laboratories concerned with various methods of surface machining.

Foreword

Optical devices for measuring roughness parameters, such as microinterferometers and light chopping devices, have been manufactured since 1933. Since the production of the first devices their design has constantly improved and new optical devices have appeared, including grating microscopes, microprofile meters for which other measurement methods were employed. These devices found wide usage in measurement and research laboratories since unlike contact devices (profile meters) they can be used for contactless measurements of surface roughness.

In recent publications such as "Surface roughness and methods for its measurement" by A. I. Kartashev, "Interferometers" by Yu. V. Kolomiytseva and "Measurements and analysis of roughness, waviness and out-of-round of surfaces" by I. V. Dunin-Barkovskiy and A. N. Kartasheva, principles are described of optical devices action for measuring roughness parameters and their design.

However, these books consider primarily the theory of the two-beam interference, while there are no theories of other methods and principles of existing optical devices. Moreover, until now, methods for normalizing metrological characteristics of optical devices to measure surface roughness parameters, methods for calculating the measurement accuracy of roughness parameters under actual conditions, as well as metrological provisions for these devices were not considered. These questions acquired special importance after GOST 2789-73 "Surface roughness. Parameters, characteristics and designations" was issued.

In this book which is offered to the reader, the theory of light chopping and grating methods is described in greater detail. The results are given of metrological investigations of all types of optical devices carried out under the guidance and with the participation of the authors. The results of these investigations were used as a basis for the new GOST 9847-79 "Optical devices for measuring roughness parameters. Types and basic parameters," which contained norms for error characteristics for all optical devices of simultaneous profile conversion.

The book contains five chapters of which one and four and sections 2.5, 3.4 and 3.5 were written by K. A. Obradovich and the remaining chapters were written by A. A. Kuchin.

The authos express their graditude to F. M. Solodukho for useful advice in writing chapters two and four.

2291
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FLUID MECHANICS

UDC: 532.516

HYDRODYNAMIC THEORY OF LUBRICATION AND ANALYSIS OF PLAIN BEARINGS OPERATING UNDER STATIONARY CONDITIONS

Moscow GIDRODINAMICHESKAYA TEORIYA SMAZKI I RASCHET PODSHIPNIKOV SKOL'ZHENIYA, RABOTAYUSHCHIKH V STATSIONARNOM REZHIME in Russian 1981 (signed to press 5 Nov 81) pp 2, 314-316

[Annotation and table of contents from book "Hydrodynamic Theory of Lubrication and Analysis of Plain Bearings Operating under Stationary Conditions", by Aleksey Konstantinovich Nikitin, Kamil Samedovich Akhverdiyev and Boris Ivanovich Ostroukhov (editor-in-chief Candidate of Technical Sciences M. V. Korovchinskiy), Izdatel'stvo "Nauka", 1600 copies, 316 pages]

[Text] Annotation

Based on Navier-Stokes nonlinear equations and Hencky-Il'yushin equations, the present monograph presents new methods for analyzing plain bearings using viscous and viscoplastic lubricants, radial bearings with infinite and finite length in the presence of lubrication sources, porous bearings, bearings with partially filled clearance and bearings in which the shaft moves in helical fashion. The results can be used extensively in calculating and designing various types of bearings, drilling rigs and advanced metal cutting and grinding machines.

The book is intended for scientific and engineering-technical workers. 40 illustrations, 2 tables, 101 bibliographic references.

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6900
CSO: 1861/217

INCREASING HEAT EXCHANGE EFFICIENCY IN POWER EQUIPMENT

Leningrad POVYSHENIYE EFFEKTIVNOSTI TEPLOOBMENA V ENERGETICHESKOM OBORUDOVANII in Russian 1981 (signed to press 30 Nov 81) pp 2, 190-195

[Annotation and abstracts from book "Increasing Heat Exchange Efficiency in Power Equipment", by Candidate of Technical Sciences Ye. D. Fedorovich, editor-in-chief, Izdatel'stvo "Nauka", 1350 copies, 189 pages]

[Text] Annotation

This collection presents lectures read at the 6th All-Union Conference on Heat Exchange and Hydraulic Resistance in Power Machinery and Equipment Elements which was held by the Scientific Council on the Integrated Problem of "Thermal Physics" of the USSR Academy of Sciences and the Department of Physical-Technical Problems of Power Engineering of the USSR Academy of Sciences in Leningrad 16-19 January 1979.

These materials provide a complete characterization of the current level of research in leading heat engineering organizations in this country on such problems as heat exchange during condensation of steam and under high pressure, the hydrodynamics of two-phase flow at high velocities, heat exchange in the near-critical (thermodynamic) region of parameters, hydraulic analysis of equipment in presence of generation and condensation of steam, etc.

The book serves as a useful aid for scientific workers involved in thermal physics and technical hydrodynamics, graduate students and powerplant and factory engineers.

Abstracts

UDC: 532.526.536.24

MODERN PROBLEMS OF INTENSIFICATION OF HEAT EXCHANGE DURING MOVEMENT OF TWO-PHASE FLOWS IN CHANNELS

[Abstract of article by E. K. Kalinin and G. A. Dreytser]

[Text] This article examines findings concerning the method of intensifying heat release with single-phase and two-phase flow in heat exchangers. Primary attention is devoted to threaded pipes and their optimization. Other methods of intensifying heat exchange during boiling are also analyzed -- twisting of the flow, depositing coatings of heat-insulating or porous materials on the heat exchange surface and employing non-isothermic fins. Findings from the research on intensification of heat release during condensation on threaded pipes are presented. 9 bibliographic references, 8 illustrations.

UDC: 621.181.5-143-001.57

INVESTIGATION OF NONSTATIONARY HYDRAULIC MODES AND STEAM-GENERATING SECTIONS OF FLOW-THROUGH BOILER INSTALLATIONS USING MATHEMATICAL MODELING

[Abstract of article by M. A. Kvetnyy, O. M. Baldina and I. I. Velyakov]

[Text] A method is presented for computer analysis of nonstationary hydraulic modes in steam-generating sections of flow-through boilers with both sub-critical and supercritical pressure; analytical experience using the proposed method is also provided. The mathematical model developed can be used to determine variation in the parameters over time and along the steam-generating circuit, and also for branched pipes of individual elements in various nonstationary modes associated with disturbances resulting from changes in the consumption of the working medium, heat load, pressure, etc. Modes are examined which simulate start-up period (heating up from cold and hot states). The use of the proposed method is explained using examples of investigating the reliability of water walls in large flow through steam boilers. Some constructive recommendations are obtained. 9 bibliographic references, 4 illustrations.

UDC: 536.7:530.17

METHOD FOR MODELING DYNAMIC PROCESSES IN CIRCULATION LOOPS OF THERMOELECTRIC INSTALLATIONS IN DESIGN STAGE

[Abstract of article by V. B. Khabenskiy and Yu. A. Migrov]

[Text] A description is given of the general scheme of an analytical experimental method for modeling dynamic modes in circulation loops of thermoelectric installations in the design stage. The method is based on a combination of investigations of transient processes in complex systems with the help of a mathematical model and a group of physical models intended for verifying and clarifying the mathematical model. In accordance with the methodological approach proposed, an integral physical model of the installation is used to find effects which are either not accounted for in mathematical model or are not described accurately enough. Experimental investigations of the local processes disclosed are made on the basis of physical models of individual elements. The results of the investigations are then used to clarify the mathematical model of the installation under design. 5 bibliographic references, 1 illustration.

UDC: 532.517

CALCULATIONS OF VARIABLE HYDRODYNAMIC FORCES IN STABILIZED-PHASE FLOW

[Abstract of article by B. S. Fokin and A. F. Aksel'rod]

[Text] An analytical method is developed, on the basis of a nonstationary hydrodynamic model, for investigating the intensity of pressure pulsations, longitudinal and transverse pressure differentials, gas content and tangential friction stress on the walls of the channel during movement of an adiabatic stabilized two-phase flow. Cases of harmonic and chaotic oscillations of the stream parameters are examined. The analytical results are compared with experimental findings. The experimental data on the mean-square intensity of pulsations in the parameters of a two-phase flow are located mostly between the calculated lines corresponding to harmonic and chaotic oscillations of phase consumption. 16 bibliographic references, 6 illustrations.

UDC: 621.039.534.25

OPTIMIZATION OF NATURAL CIRCULATION LOOPS FOR MAXIMUM CIRCULATION CHARACTERISTICS

[Abstract of article by V. G. Popov and L. F. Fedorov]

[Text] This article formulates theoretically and solves the problem of optimization of construction elements in natural circulation loops for the case in which the volume of the circulation loop is given on the basis of design considerations. The optimization results are compared with computer calculations of circulation characteristics and experimental data. Results of optimization of construction elements of an evaporation channel of the Field-tube type are presented. 5 bibliographic references, 2 illustrations.

UDC: 532.551

DETERMINATION OF INITIAL CROSS-SECTION OF STEAM GENERATION IN STREAM OF UNDERHEATED FLUID

[Abstract of article by V. M. Borishanskiy, G. S. Bykov and A. S. Simkin]

[Text] This article proposes the method for calculating the separation diameter of a bubble and the cross-section of intensive steam generation. The separation diameter is calculated considering the forces acting upon the bubble in a stream of fluid circulating under pressure. The proposed analytical method generalizes experimental material well for pressures of 2-14 MPa, mass velocities of 130-$1.5 \cdot 10^3$ kg/($m^2 \cdot$sec), channel diameters of (10-21)10^{-3} m, water and freon-11 and -21. 9 bibliographic references, 1 illustration.

UDC: 532.526.536.24

CALCULATION OF ACTUAL STEAM CONTENT BY VOLUME AND CRITICAL LOADS IN EVAPORATION CHANNELS

[Abstract of article by V. M. Borishanskiy, G. S. Bykov, A. S. Simkin, V. I. Kamshirin, and L. S. Svetlova]

[Text] This article examines heat-exchange crisis during surface boiling of underheated fluid and shows the relationship between critical heat loads and the structure of the flow. The influence of the separation diameter of the bubble on the critical load value is demonstrated. Recommendations are given for calculating the separation diameter of the bubble, the initial steam generation cross section and the actual steam content by volume; conditions for the transition from bubble to disperse-annular flow structure are examined. 6 bibliographic references, 2 illustrations, 1 table.

UDC: (621.311.25:621.039):621.181.61

EXPERIMENTAL INVESTIGATION OF HEAT RELEASE ON MODEL OF ECONOMIZER SECTION OF STEAM GENERATOR

[Abstract of article by B. L. Paskar', I. S. Kudryavtsev, B. M. Kozlov, V. I. Kucherov, L. N. Artemov and V. A. Malkis]

[Text] This article presents the results of investigating heat exchange using a model of the economizer section of a vertical steam generator for water-cooled reactors. The experiments were made using full-scale heat carriers with parameters corresponding to the parameters of the economizer section of a 250-MW vertical steam generator. The influence of natural convection on heat release in the region of Ra/Re^2 complex values $>2 \cdot 10^{-4}$ is disclosed. It is shown that heat release in this region can be calculated using the method developed for the case of flow within a channel. Experimental data on heat release in the forced convection region agree with the calculated data beginning with values of $Ra/Re^2 < 2 \cdot 10^{-4}$. 2 bibliographic references, 4 illustrations.

UDC: 532.526.536.24

INGESTIGATION OF HEAT EXCHANGE CRISIS AND HYDRAULIC RESISTANCE IN BUNDLE OF HEAT-EXTRACTION RODS WITH INTENSIFYING DEVICES

[Abstract of article by Yu. D. Barulin, A. S. Kon'kov, A. I. Leont'yev, N. V. Tarasova, T. I. Blagovestova, A. I. Ryabov and V. N. Filippov]

[Text] This article examines the effectiveness of intensification of heat exchange by various intensifying devices as applied to bundles of rods in boiler-type reactors. Three designs of distancing devices used as intensifiers are investigated. The findings of this investigation of heat-exchange crisis and hydraulic resistance are generalized and compared with the findings of other authors. An empirical relationship is recommended for determining the maximum steam content and calculating hydraulic pressure during flow of a water-steam mixture in a bundle of heat extraction rods with various intensifying devices in the range of mode parameters investigated. 7 bibliographic references, 4 illustrations, 1 table.

UDC: 621.181.61:535.24

TEMPERATURE PULSATIONS OF HEAT-TRANSFER SURFACE DURING TRANSITION TO DEGRADED HEAT EXCHANGE IN FLOW-THROUGH STEAM GENERATING CHANNEL HEATED BY SODIUM

[Abstract of article by Yu. V. Krasnoukhov, I. S. Kudryavtsev, B. L. Paskar', A. V. Sudakov, Ye. D. Fedorovich and A. V. Shchedrin]

[Text] This study examines the statistical characteristics of temperature pulsations of heat-transfer walls of a pipe (intensity, probability density function, autocorrelation function, spectral density, effective period) measured with microthermocouples installed directly on the steam generating surface during the transition to degraded heat exchange in straight-pipe and coiled channels heated by sodium. A connection is obtained between the statistical characteristics and the determining mode parameters (pressure, specific thermal flow, mass velocity). The influence of heat-insulating deposits on the heating surface on the pulsation characteristics of the layer is demonstrated. 9 bibliographic references, 10 illustrations.

UDC: 533:6:621:165

INVESTIGATION OF TRANSSONIC FLOWS IN NOZZLES AND BLADE CASCADES

[Abstract of article by L. M. Zysina'molozhen, L. A. Fel'dberg, I. G. Shapiro, and A. L. Dobkes]

[Text] Nonstationary phenomena are observed during transsonic flow in nozzles and blade cascades which are associated with the occurrence of pulsating compression shocks and condensation and breaking away of the boundary layer. Their nature is determined by the parameters of the flow and the geometry of the channel. Investigations of the local values of the heat release coefficients along the contour of the blade indicated that significant changes in the temperature stresses are possible in pulsating modes. An optical device which was developed for photoelectric recording of the signal in combination with shadow grams and interferograms made it possible to estimate the intensity of stream pulsations in the blade cascades. When there is a pulsating compression shock on a curvilinear suction face of a blade there is a significant increase in the intensity of the pulsation and variation in the forces in that blade zone which must be allowed for. 2 bibliographic references, 9 illustrations.

UDC: 532.55

HYDRAULIC RESISTANCE OF HELICAL COILS DURING MOVEMENT OF SINGLE-PHASE AND TWO-PHASE FLOWS

[Abstract of article by Yu. V. Krasnoukhov and Ye. D. Fedorovich]

[Text] This study presents data on the hydraulic resistance of helical coils (D_{co}=0.11 m, d_{he}=0.16 m, coil pitch t=0.03 m) during movement of single-phase and two-phase flows. Relationships are found which describe well the experimental values of the resistance. An equation is recommended for determining the transition from laminar movement with macro-eddies to turbulent movement. A formula is given which extends the experimental data on hydraulic resistance when air is circulated, around the outside of helical coils. 34 bibliographic references, 4 illustrations, 1 table.

UDC: 621.1.013;541.12.012

INFLUENCE OF LOCAL RESISTANCES ON HYDRODYNAMICS OF FLOW OF BOILING LIQUID IN PIPES

[Abstract of article by V. V. Fisenko, V. I. Sychikov and G. I. Mulyava]

[Text] It is demonstrated that when an adiabatically boiling stream flows out of a pipeline, the influence that flow-restricting devices have on the flow rate results both from dissipative losses and due to the compressibility of the two-phase mixture which is formed. Experimentally measured static pressure profiles in a pipe with local resistance are given, and relative total pressure losses are shown as a function of pressure at the input to the runoff channel and the diameter of the diaphragm. 3 bibliographic references, 6 illustrations.

UDC: 536.24:621.039.526

TEMPERATURE MODE OF COILED HEATING SURFACE OF BN STEAM GENERATORS

[Abstract of article by I. S. Kudryavtsev, M. Ye. Lebedev, N. V. Mizonov, B. L. Paskar', L. V. Savina, E. V. Firsova and Yu. V. Krasnoukhov]

[Text] This study examines processes occurring both in the tubes and the inter-tube space of a steam generating element designed as a coil with a small pitch radius which is heated by liquid sodium. Temperature pulsations of the inside wall of the pipe are measured experimentally, and the intensity of the pulsations and their effective period are determined. Formulas are obtained for calculating heat release when liquid metal flows about the outside of the coiled surface. 8 bibliographic references, 6 illustrations.

UDC: 621.311.25:621.039.621.028

INVESTIGATION OF PARALLEL OPERATION OF VERTICAL STRAIGHT-PIPE HEAT EXCHANGE DEVICES WITH CONDENSATION

[Abstract of article by P. N. Artemov, V. F. Desyatun, I. L. Kreydin, B. L. Kreydin, V. A. Lokshin, V. F. Moskvichev and B. I. Sheynin]

[Text] This study provides an analysis of the conditions of disruption of the normal hyraulic mode in vertical straight-pipe heat exchange devices using saturated or slightly overheated steam as the heating medium, and also presents results of bench tests of steam condensing heating surfaces connected in parallel along with results of industrial tests of steam reheater-separators. 2 bibliographic references, 5 illustrations.

UDC: 621.382.026.017.72

COMPACT TWO-PHASE THERMOSIPHONS FOR AIR-EVAPORATION COOLING OF POWERFUL SOLID STATE DEVICES

[Abstract of article by A. I. Isakeyev, I. G. Kiselev, V. V. Filatov, N. I. Istomin and B. B. Batov]

[Text] This study examines results of investigating heat exchange during boiling and condensation, as well as the influence of the degree of filling of two-phase thermosiphons with heat carrier on the thermal stream released. A machine method is given for thermal analysis of two-phase thermosiphons used to cool high-power solid state devices. 3 bibliographic references, 5 illustrations.

UDC: 621.165.51:621.177

EXPERIENCE IN CREATION AND INVESTIGATION OF SUPERHEATER-SEPARATORS FOR UNITS WITH VVER REACTORS

[Abstract of article by A. B. Anapol'skiy, L. N. Artemov, A. F. Bakanov, N. V. Zozulya, V. G. Morozov, V. F. Moskvichev, B. L. Paskar', Yu. L. Sorokin and Ye. D. Fedorovich]

[Text] This article describes the creation of the SPP-220 superheater-separators for units using VVER-440 reactors. A brief description is given of the construction of the series-produced equipment in research work aimed at improving and debugging the equipment. This work includes investigating the thermohydraulic characteristics of the pipe bundle and separation elements, adjustment of technological processes involved in welding the longitudinal fins and testing the devices at nuclear powerplants. Recommendations were given for improving the construction of the equipment, its manufacturing technology and operation. 3 bibliographic references, 2 illustrations.

UDC: 621.187.30;621.18.016.4

WATER-CHEMICAL MODES AND THERMOPHYSICAL PROPERTIES OF INTRA-PIPE FORMATIONS

[Abstract of article by I. I. Chudnovskaya, G. P. Sutotskiy, Z. Yu. Shtern and T. O. Sokolova]

[Text] This study presents the results of investigating the influence of various parameters of SKD [not explained] boilers on the structural state and thermic resistance of the layer of intra-pipe formations when exposed to hydrazine-ammonia complexon and neutral-oxidizing water conditions. Materials on the period between flushing are given for different types of SKD boilers. 10 bibliographic references, 4 illustrations, 1 table.

UDC: 621.175

DETERMINATION OF LOCAL VALUES OF COEFFICIENTS OF HEAT- AND MASS-RELEASE FROM CONDENSED STEAM DURING ZONE ANALYSIS OF CONDENSERS

[Abstract of article by A. A. Promyslov]

[Text] This article substantiates formulas derived by generalizing experimental data for determining the local values of the heat exchange coefficient from practically pure moving steam and the coefficient of mass release during condensation of steam from a moving steam-air mixture. In zone computer calculation of condensers, the proposed formulas make it possible to reproduce the reduction in the local coefficient of heat exchange from a moving steam-air mixture under the influence of various factors which is observed during condenser testing more completely than using previous formulas. 16 bibliographic references, 2 illustrations.

UDC: 621.311.25:621.039.621

RESULTS OF INVESTIGATION AND EXPERIMENTAL INDUSTRIAL CHECKING OF EFFECTIVENESS OF EMPLOYMENT OF SHAPED PIPES IN STEAM TURBINE CONDENSERS

[Abstract of article by Yu. N. Bogolyubov, V. P. Porovkov, G. V. Grigor'yev, N. V. Zozulya and V. A. Permyakov]

[Text] Experimental industrial tests of condensers made of pipes with annular and spiral knurling produce good results. The increase in heat transfer achieved is not accompanied by an increase in pollution or a noticeable degradation in the technical properties of the pipe. 9 bibliographic references, 2 illustrations.

UDC: 620.191.8:620.192.47

EXPERIMENTAL AND THERORETICAL INVESTIGATIONS OF HEAT CONDUCTIVITY OF INTERNAL IRON OXIDE DEPOSITS IN STEAM GENERATOR PIPES

[Abstract of article by V. P.Glebor, I. R. Mikk, R. A. Kruus, Kh. A. Kyaar, N. B. Eskin, V. M. Zusman, A. L. Lubny'gertsyk and V. A. Vares]

[Text] A description is given of a structural model of deposits based on octahedral crystals. Analytical relationships are derived on the basis of the model for the effective heat conductivity of the deposit layer. Special investigations are made of the heat conductivity of magnetite, the material of which the deposits consist. The analytical formulas were checked for the model by solving the problem numerically. Comparison with the experimentally determined coefficients of effective heat conductivity of iron oxide deposits indicated no mathematical divergence. 11 bibliographic references, 5 illustrations.

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UDC: 532:550:662

APPLIED PROBLEMS IN HYDROMECHANICS

Kiev PRIKLADNYYE ZADACHI GIDROMEKHANIKI (SBORNIK NAUCHNYKH TRUDOV) in Russian 1981 (signed to press 7 Dec 81) pp 182-188

[Abstracts from book "Applied Problems in Hydromechanics", by A. Ya. Oleynik (editor-in-chief), Izdatel'stvo "Naukova dumka", 700 copies, 188 pages]

[Text] Abstracts

UDC: 629.12:582.59.041

EFFECT THAT BOUNDARY CONDITION IMPROVEMENT IN VELOCITY POTENTIAL BOUNDARY VALUE PROBLEM HAS ON CALCULATED SHIP WAVE DRAG

[Abstract of article by V. G. Sizov]

[Text] The wave resistance of a vessel is calculated by computer based on the singularity density expressed by 1 (Mitchell), 2 and 3 terms of the series expansion of the kinematic condition on the surface of the vessel with the smallest possible Froude number. The calculation is limited to 2 terms of the series for an arbitrary Froude number. 3 illustrations, 3 bibliographic references.

UDC: 629.12:53.2.59.041

HYDRODYNAMIC FORCES ACTING UPON VESSEL DURING DRIFTING AND YAWING IN WAVES

[Abstract of article by Yu. L. Vorob'yev]

[Text] This article describes an asymptotic theory of lateral rocking of a ship steaming without headway in deep water and shallow water. Solutions to the problem are defined separately at a distance from the vessel (external zone) and near the vessel (internal zone) and are then compared asymptotically. The problem is solved in the internal zone employing an original method which is of independent importance. Formulas for the hydrodynamic forces are described. 8 bibliographic references.

UDC: 629.12:532.59.041

APPARENT MASS OF FRAME CONTOUR DURING HIGH FREQUENCY VERTICAL OSCILLATIONS IN SHALLOW WATER

[Abstract of article by Yu. L. Vorob'yev]

[Text] This study solves the problem of the apparent mass of frame contour during high frequency vertical oscillations in shallow water. Results of calculating the apparent mass are given for a series of frame contours with systematically varying parameters for differing shallow water depth. 5 illustrations, 8 bibliographic references.

UDC: 629.12.532.5:629.125.8

ONE TRANSFORMATION OF THE INTEGRAL PLANING EQUATION DURING SHIP MOVEMENT IN CHANNEL WITH RECTANGULAR CROSS SECTION

[Abstract of article by V. K. Labaznikov]

[Text] This article presents the transformation of the integral planing equation during movement of bearing surfaces in the center plane of a channel with unbounded depth. In existing forms of these integral equations, the half-width of the channel is part of the arguement of the oscillating functions, which are members of infinite series, leading to difficulties in solving them. An original representation is obtained for the integral equation which allows it to be solved efficienty. 2 bibliographic references.

UDC: 532.593

WAVE RESISTANCE DURING NON-STEADY STATE MOVEMENT OF SYSTEM OF SURFACE PRESSURES

[Abstract of article by G. I. Zil'man and Ye. M. Shifrina]

[Text] The problem of the wave resistance of a system of surface pressures during non-steady state motion is solved. The theory of low-amplitude gravity waves is employed. A method is proposed for calculating the wave resistance of the plane-elliptical systems with large pressure gradient at their boundary. Results of calculating the wave resistance for uniformly accelerated movement are presented. 2 illustrations, 4 bibliographic references.

UDC: 622.242:550.822

TRANSPORTABLE ISLAND BASE FOR PETROLEUM PROSPECTING AT SHALLOW DEPTHS

[Abstract of article by Ya. S. Barik, Yu. A. Plenkin and N. V. Shaybo]

[Text] This article describes a submersible base with an original anti-listing stabilization system. Results are given for model tests to determine the operability of the system for providing stability of the structure during submersion and flotation, and an estimate of the towing resistance of the structure in calm and rough water is given. 5 illustrations.

UDC: 633.6.013.42

PROBLEMS OF APPLIED HYDRODYNAMICS OF FLEXIBLE FILAMENTS IN FLOWS

[Abstract of article by A. Ya. Oleynik, N. V. Saltanov and V. A. Gorban']

[Text] This article reviews a number of studies and also analyzes individual questions of the current status of research on the dynamics of flexible filaments in flows. Some problems of hydrodynamics are examined which are associated with the development of models and calculations of the movement of flexible constructions in liquid. Promising research directions are noted. 50 bibliographic references.

UDC: 626.02

EXPERIMENTAL DETERMINATION OF BENDING MOMENTS ACTING UPON OCEAN PIPELINE DURING INSTALLATION

[Abstract of article by V. I. Korolev, K. Ya. Kapustin and M. A. Kamyshev]

[Text] This article presents a method for modeling and experimental determination of the stressed state of the model of a pipeline laid on the ocean bottom. The relationship between the static and dynamic moments in different pipeline sections and basic factors is examined. 4 illustrations, 7 bibliographic references.

UDC: 534.141

OSCILLATIONS OF FLEXIBLE FILAMENT IN TRANSVERSE FLOW WITH VARIABLE VELOCITY PROFILE

[Abstract of article by V. I. Korolev]

[Text] This article presents the results of experimental investigation of vibration of filaments in a transverse flow with variable flow velocity along the filament. Experimental spectra are obtained for the oscillations which indicate a major influence of the fundamental frequency of the filament in standing water on the frequency of induced vibration. The basic regularities determining the shape of the frequency spectra of the oscillations are established. 4 illustrations, 7 bibliographic references.

UDC: 534.11

INTERACTION BETWEEN OSCILLATING FILAMENTS AND FLOW

[Abstract of article by V. I. Poddubnyy and N. V. Saltanov]

[Text] Based on a discrete model, a computer is used to investigate oscillations of a tensile thread-body system in a flow considering nonlinear hydrodynamic forces in the geometrically nonlinear case. The filament is assumed tensile according to Hooke. It is shown that steady-state induced oscillations of the filament occur about a quasistationary position displaced along the flow from the equilibrium position. In a certain sense, this effect is equivalent to increasing the "effective" coefficient of hydrodynamic resistance of the filament. 4 illustrations, 7 bibliographic references.

UDC: 534.11

INVESTIGATION OF OSCILLATION OF FLEXIBLE FILAMENTS IN FLOWS BASED ON DISCRETE MODEL

[Abstract of article by V. I. Poddubnyy]

[Text] This study proposes, for cases in which the filament has the shape of an arbitrary spatial curve, seeking the characteristics of the tensile filament body system on the basis of a discrete model. The use of a developed computational scheme is illustrated by examples which provide evidence of its effectiveness. It is demonstrated that within the practically interesting range of variation of system parameters even a relatively small number of discrete elements provides sufficient computational accuracy. 2 illustrations, 4 bibliographic references.

UDC: 518:517.9:532

METHOD WITH ENHANCED ACCURACY FOR NUMERICAL INVESTIGATION OF NONSTATIONARY FLOW ABOUT ARBITRARY BODY OF REVOLUTION PUT INTO MOTION SIMULTANEOUSLY

[Abstract of article by V. I. Kravchenko]

[Text] This article proposes a numerical method for solving complete Navier-Stokes equations written in terms of the current in eddy function in a natural coordinate system connected with the surface of the body located in the flow. A finite-difference scheme with fourth-order accuracy with respect to spatial variables is constructed for the problem of investigating nonstationary flow about a body of revolution put into movement simultaneously. The question of selecting a method for computing eddy formation on the solid boundary is examined. An essentially implicit modification is proposed for the procedure of calculating the eddy on the surface of the body in the flow. 5 illustrations, 14 bibliographic references.

UDC: 532.58

ONE PROPERTY OF THE RESISTANCE CURVE OF A BODY DURING NON-STEADY STATE MOVEMENT IN LIQUID

[Abstract of article by V. G. Belinskiy]

[Text] This article establishes the property of the curve of the coefficient of resistance of a body during non-steady state movement in a liquid which makes it possible to divide the coefficient of resistance into inertial and viscosity components of the coefficients of resistance of a disk and cylinder located in a non-steady state flow. 4 illustrations, 11 bibliographic references.

UDC: 532.529:532.582

APPARENT MASS OF SYSTEMS OF ELLIPSOIDS

[Abstract of article by V. A. Gorban' and S. M. Srebnyuk]

[Text] This article examines the problem of the motion of systems of oblate ellipsoids in an ideal liquid. The Blokh-Ginevskiy method is used to determine the coefficients of the apparent masses for chains and lattices of ellipsoids. The calculation results are compared with experimental data. 4 illustrations, 9 bibliographic references.

UDC: 533.69.011

INVESTIGATION OF DEVELOPMENT OF LIFTING FORCE DURING MOVEMENT OF THIN PROFILE NEAR EDGE WITH BREAK

[Abstract of article by I. P. Akimenko, V. G. Belinskiy and I. I. Yefremov]

[Text] A method is proposed for solving the nonstationary problem of the movement of a plate near a boundary with various corner angles. Examples of calculation are given. 5 illustrations, 3 bibliographic references.

UDC: 532.5

PROBLEM OF LOADING OF BODIES IN LIQUID

[Abstract of article by V. V. Popov]

[Text] A numerical method is proposed for solving the hydrodynamic problem of loading of a body by inertia in an ideal incompressible weightless fluid. In contrast to existing solutions, the present one allows for deformation of the free boundary of the fluid and change in the potential on it. 2 illustrations, 4 bibliographic references.

UDC: 629.12

THEORETICAL INVESTIGATION OF INFLUENCE OF INITIAL TURBULENCE AND SHAPE OF CONTOUR OF MODEL ON TRANSITION FROM LAMINAR TO TURBULENT BOUNDARY LAYER

[Abstract of article by L. F. Kozlov]

[Text] This article presents the results of theoretical investigations of the influence of various geometrical parameters which characterize the shape of the contour in initial turbulence on the length of laminar sectors in the boundary layer of models of oceangoing transport ships. Variation in these parameters is shown to have a significance on the hydrodynamic resistance of the models. 7 illustrations, 8 bibliographic references.

UDC: 532.517.4

BEHAVIOR OF COMPONENTS OF TURBULENCE ENERGY DURING SELF-SIMILAR DEVELOPMENT OF TURBULENT LAYER

[Abstract of article by V. S. Maderich]

[Text] This study examines the evolution of normal Reynolds stresses during self-similar development of a layer of turbulized liquid of finite thickness after application of an instantaneous source to its surface. It is demonstrated on the basis of solving the problem for eigenvalues and numerical calculation that the anisotropic components of the normal Reynolds stresses in the region of self-similar development consist of the sum of the non-interacting self-similar solution, each of which has its own exponential principle. 1 illustration, 7 bibliographic references.

UDC: 532.593

SOME EMPIRICAL RELATIONSHIPS OF TURBULENT FLOW OF A DILUTE POLYMER SOLUTION

[Abstract of article by S. A. Matviyevskiy]

[Text] This article presents the results of experimental investigation of the flow of dilute solutions of polyoxyethylene in a pipe. The threshold friction stress on the wall is found to be a function of polymer concentration in the solution. The limits of applicability of previous empirical relationships between the characteristics of the flow and polymer solutions are analyzed, and a refined empirical relationship is given. 4 illustrations, 14 bibliographic references.

UDC: 532.593

TURBULENT BOUNDARY LAYER ON PLATE IN STREAM OF UNIFORM POLYMER SOLUTION

[Abstract of article by S. A. Matviyevskiy]

[Text] The flow of a turbulent boundary layer on a plate in a stream of a uniform solution of polymer of optimal concentration is investigated. The boundary layer equations are solved employing the implicit finite dimensional method. The influence of the rate of flow on the changes induced by the polymer solution in the flow is examined. 4 illustrations, 11 bibliographic references.

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MECHANICS OF SOLIDS

UDC: 621.178.311

OSCILLATIONS OF KINEMATICALLY-DRIVEN MECHANICAL SYSTEMS CONSIDERING ENERGY DISSIPATION

Kiev KOLEBANIYA KINEMATICHESKI VOZBUZHDAYEMYKH MEKHANICHESKIKH SISTEM S UCHETOM DISSIPATSII ENERGII in Russian 1981 (signed to press 10 Sep 81) pp 2, 217-218

[Annotation and table of contents from book "Oscillation of Kinematically-Driven Mechanical Systems Considering Energy Dissipation", by Georgiy Stepanovich Pisarenko and Oleg Yevgen'yevich Boginich, Izdatel'stvo "Naukova dumka", 1300 copies, 219 pages]

[Text]

Annotation

This monograph is devoted to an analytical investigation of oscillations of nonconservative elastic systems of plates and rods with concentrated and lumped parameters considering incomplete elasticity of cyclically deformed material. The oscillations in these systems are excited kinematically by means of various plane-parallel and angular harmonic movements of their fastening which vary according to a defined principle.

The book is intended for scientific and engineering-technical workers involved in matters of mechanical system oscillations. 23 illustrations, 62 bibliographic references.

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UDC: 634

TWO-DIMENSIONAL VIBRATION IMPACT SYSTEMS: DYNAMICS AND STABILITY

Moscow DVUMERNYYE VIBROUDARNYYE SISTEMY: DINAMIKA I USTOYCHIVOST' in Russian 1981 (signed to press 13 Oct 81) pp 2-4

[Annotation and table of contents from book "Two-Dimensional Vibration Impact Systems: Dynamics and Stability", by Anatoliy Aronovich Kobrinskiy and Aron Yefimovich Kobrinskiy, Izdatel'stvo "Nauka", 2650 copies, 336 pages]

[Text] Annotation

This book is devoted to dynamic analysis of the unidimensional and two-dimensional vibration impact systems which must be studied when calculating and building numerous machines, instruments and devices used in various branches of technology.

The book presents methods for finding periodic modes of movement of such systems, discloses their nonlinear properties and features, especially those associated with two-dimensional structure, and studies their dynamic, dissipative and accuracy properties dictated both by the system parameters and excitation as well as the geometric characteristics of the elements participating in the impacts.

The theoretical results are illustrated using examples of specific engineering systems and devices.

The book is intended for designers working in various branches of impact technology, and for specialists in questions of the theory of oscillations of mechanical systems.

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