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THE SOVIET JOURNAL OF ATOMIC ENERGY

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CONTENTS

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CONTENTS

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ATOMIC SCIENCE AND TECHNOLOGY AND THE BUILDING OF COMMUNISM

V. S. Emel'yanov

Chairman of the Government Committee of the Council of Ministers, USSR, on the Use of Atomic Energy,
Translated from Atomnaya Energiya, Vol. 11, No. 4, pp. 301-312, October, 1961
Original article submitted August 31, 1961

In the project for the new Program of the Communist Party of the Soviet Union it is stated that " . . . the development of new technology will be used for the radical improvement and alleviation of the conditions of work of the Soviet man, for shortening the working day and providing a more convenient existence, for putting an end to heavy physical labor, and then to every kind of unskilled labor."

The progress of physical science, and, in particular, of nuclear physics opens up great new possibilities for achieving the goal set – building Communist society.

This new powerful source of highly concentrated energy – atomic energy – can considerably increase the amount of energy which the Soviet man has at his disposal, and can enable us to solve problems which it is practically impossible to solve with the usual sources of energy. Radioactive isotopes as a source of radiation offer noteworthy possibilities for the automation of industrial processes, then for replacing manual labor by the work of machines. Isotopes are being used more and more widely in medicine, scientific researches, and the most varied branches of the national economy.

Scientific research and investigation in the field of nuclear physics stands at various stages, and the scale of work on using the results is also different. Up to the present time the work that has been advanced further than any other is that in the field of using the fission energy of heavy nuclei – uranium and plutonium. These processes have found practical application – they are the basis for the design, operation, and building of atomic electric stations and power units.

The first atomic electric station of industrial type in the world, with an output of 5000 kw, was put in operation in the Soviet Union more than seven years ago, and from that time has operated successfully and without incident.

Instructions being completed on the first series of large atomic electric stations at Voronezh and in Beloyarsk.

The uranium-graphite reactor of the I. V. Kurchatov Beloyarsk atomic electric station, with an electrical output of 100,000 kw, is an original type of construction, developed by Soviet specialists. This reactor, using slightly enriched uranium, produces superheated steam at a pressure of 100 atm. Thus, in its operating characteristic the Beloyarsk reactor will be the best in the world from the point of view of present-day energy production.

The Novo-Voronezh atomic electric station uses water-water-reactors, each of which is designed for an electrical output of 210,000 kw.

Experimental atomic electric stations are being constructed in Czechoslovakia and in the German Democratic Republic with the aid of the Soviet Union. At the atomic electric station in Czechoslovakia, with a power of 150,000 kw, a reactor is being constructed in which the moderator is heavy water and the coolant is carbon dioxide gas. In the German Democratic Republic the output of the first unit of the atomic electric station, using a water-water reactor, is 70,000 kw.

The work of Soviet scientists and engineers in the field of atomic energy is accompanied by the construction of many research and experimental nuclear reactors and assemblies of different types and power levels. These include reactors using as moderator: graphite, heavy and ordinary water, organic liquids, and as coolant: ordinary and heavy water, organic liquids, fused metals, and other coolants. Reactors have been constructed working at various neutron energies and with various neutron flux densities in the steady and pulsed state.

As we know, the Soviet Union has enormous resources of organic fuel and water power, which are able to supply the country for quite a long period, although there are isolated regions in the Soviet Union which are considerably removed from the usual sources of energy. In the project of the new program of the Communist Party of the Soviet Union, which will be considered at the XXII Congress, it is stated: "As the production of atomic energy becomes cheaper, the construction of atomic electric stations will be expanded, especially in regions lacking in other energy sources . . . ".

From the design, construction, and operation of all these and other atomic electric stations with reactors of various types and powers, a large amount of experience will be collected, which will make possible analysis and engineering and economic evaluations leading to new paths of action and the building of even more perfected installations.

In particular, our scientists have constructed one of the most promising reactors at the present time, the experimental fast-neutron reactor, which reached criticality in June, 1958 and has already been operating successfully for more than three years. Reactors of this type make it possible to get an exchange for each kilogram of U^{235} or plutonium "burned up" up to 1.5 kg of plutonium or U^{233} from the improved neutron balance. This opens up the possibility of considerably more complete use of nuclear fuel resources.

While at the present time the usual thermal-neutron reactors use up only 0.4-0.5% of the uranium supplied, i.e., up to 5 kg of each 1000 kg, and thorium can be used as a nuclear fuel only at the cost of consuming a considerable quantity of U^{235}, in fast-neutron reactors it is possible to use up both the U^{238} and the thorium completely. With nuclear reactors of this sort it is possible to build atomic electric stations with large output and a comparatively small yearly uranium consumption.

Calculations show that it is possible to build atomic electric stations with a total electrical output, for example, of 100 million kw, which, using fast-neutron reactors, will consume less than 1000 tons of natural uranium per year. It is well known, that operating an ordinary coal electric station at a total output of 100 million kw requires a yearly consumption of 200-300 million tons of coal.

Up to the present time, considering reactors giving extensive breeding of the fissionable material and complete utilization of uranium and thorium, it may be concluded that from the scientific standpoint we are dealing with the problem which has been fundamentally solved and we are talking about using the fission chain reactions of heavy elements – uranium and plutonium – to produce large quantities of electrical energy. Atomic electric stations using reactors providing extensive breeding of nuclear fuel have not yet been tried out in fact, and the problem of producing large quantities of electrical energy from the nuclear fission reactions of uranium and plutonium has not yet been worked out in many of its engineering and economic features. Work in this direction is being carried out here, as well as in the USA, England, and France.

The initial expenditures of fissionable material for loading fast neutron reactors are still large. It is necessary to accelerate the conversion of nuclear fuel, as well as solve other technological problems.

Further automation and refinement of the processes for extracting and purifying plutonium or U^{233} from fission fragments, and automation of the production of fuel elements along with the development of economically feasible reactor designs, are some of the more important problems standing in the way of wide use of nuclear fuel for the development of a large atomic energy industry.

Reactors giving extensive breeding from nuclear fuel combined with other types of reactors should be carefully studied in relation to their application to the problems of electrification of the whole country and the wide industrial use of atomic energy.

Along with the developments in the construction of nuclear reactors for electric stations, as well as for research purposes, Soviet specialists have designed reactors for use in ship installations. The Soviet Union, which possesses first class atomic submarines guarding the water approaches to our country, has devoted considerable attention to the peaceful uses of atomic energy in the naval fleet. In 1960, the flagship of the Soviet icebreaking fleet, the atomic icebreaker "Lenin," made its first voyage on the northern sea route.

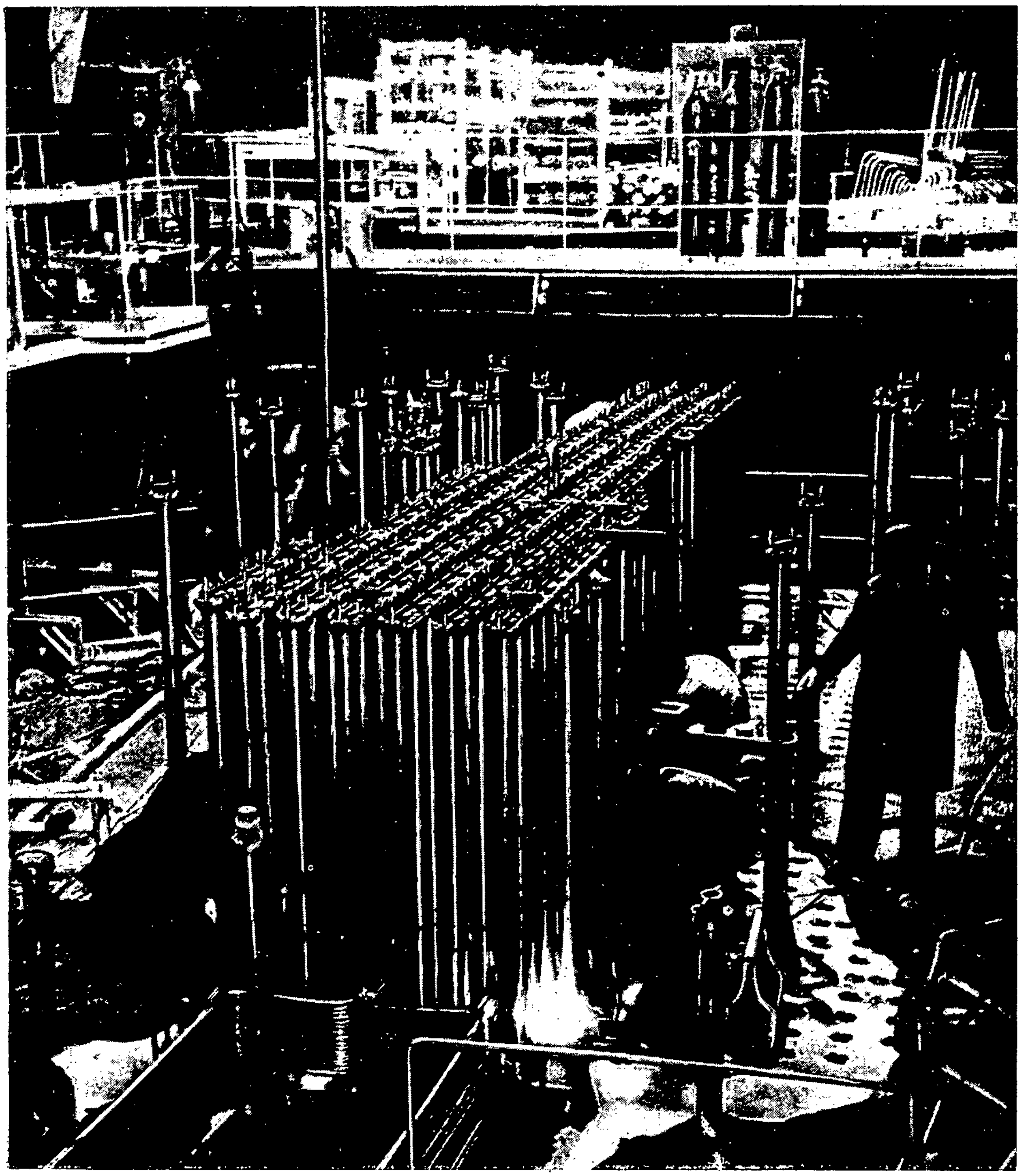

Fig. 1. Mounting of headers for the fuel channels on the top plate of the reactor of the I. V. Kurchatov Beloyarsk atomic electric station.

Some data is given below on the Soviet atomic ship as compared with the first American atomic commercial ship "Savannah."

	Icebreaker "Lenin"	"Savannah"
Date put into service	1959	1961 (Planned)
Displacement, thousands of tons	16	21.8
Propulsion power, thousands of hp	44	20

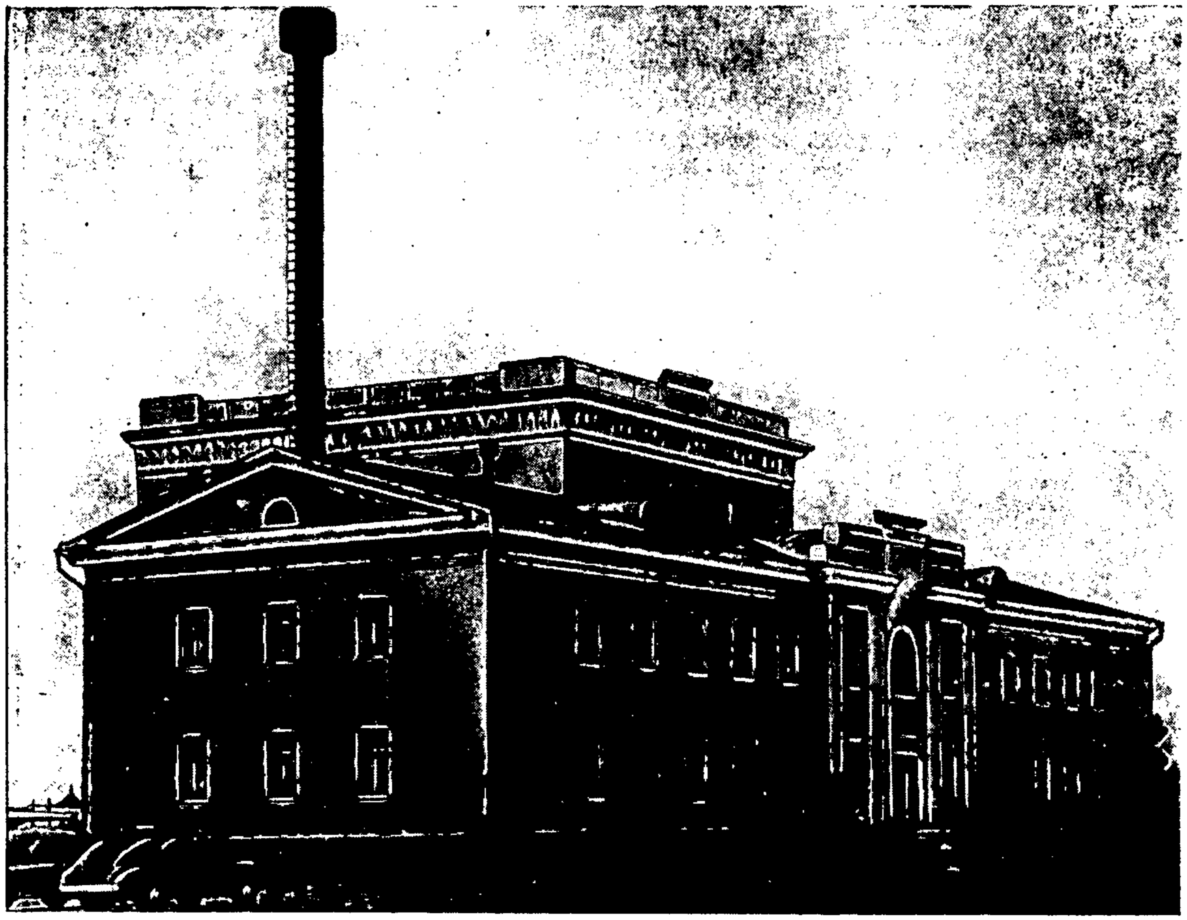

Fig. 2. Experimental fast-neutron reactor building, constructed in 1958.

Fig. 3. The atomic icebreaker "Lenin" with a convoy of ships in the ice floes of the Arctic Ocean.

For the first time in the history of the Arctic a convoy of Soviet ships led by the atomic icebreaker "Lenin" moved out of the Kara Sea east to the Laptevs Sea. The icebreaker "Lenin" led 92 ships over the northern sea route through the Arctic ice floes, when the ice had reached a thickness of 2.5 meters.

Thus, we have had our first experience in using atomic energy in an icebreaker, which confirms the results of the diverse work done by Soviet specialists in nuclear reactors for ship installations.

* *

*

One of the important problems in the wide development and use of atomic energy is the problem of radioactive wastes. In the production of plutonium and the reworking of the fuel elements from atomic electric stations and power installations a large quantity of radioactive wastes is formed, which decompose only partially in a short period of time, while a considerable fraction remains dangerous to man for many decades. Some of the radioisotope fragments are beginning to find practical application in industry, medicine and other fields. However, such use has so far has not been on a considerable scale.

In our country, the radioactive wastes from the purification of fuel elements spent in the reactor are kept in special containers. In the USA and England, containers of radioactive wastes from plutonium production are discarded in seas and oceans, creating a potential danger from radioactive contamination of the plant and animal world of the seas and oceans, as well as a potential danger for human beings. Radioactive substances accumulate in plant and animal organisms, part of which is used for human consumption.

The studies in the field of biology and medicine and, in particular, the genetic side of this question indicate a detrimental effect of radioactive contaminants on human beings and require the development of special means to prevent the penetration of radioactivity into the human organism.

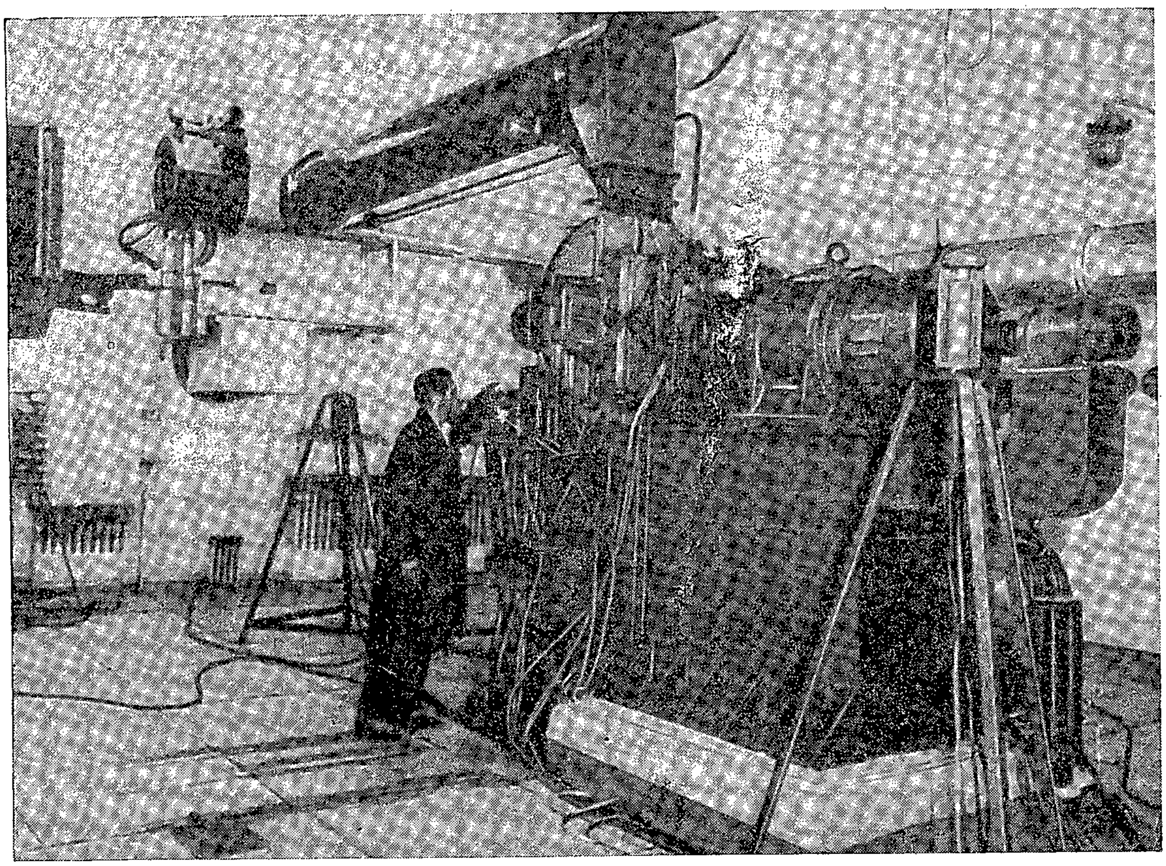

Fig. 4. Pulsed fast-neutron reactor of the United Institute of Nuclear Studies in Dubna.

Soviet scientists devote a large amount of attention to the study of radiological problems connected with all possible radioactive contaminations. Searches are being made for ways of burying radioactive wastes which will give a reliable guarantee that never, neither at the present time nor in the future, will this radioactivity get out of control, nor lead to infection of the surroundings, nor bring harm to man.

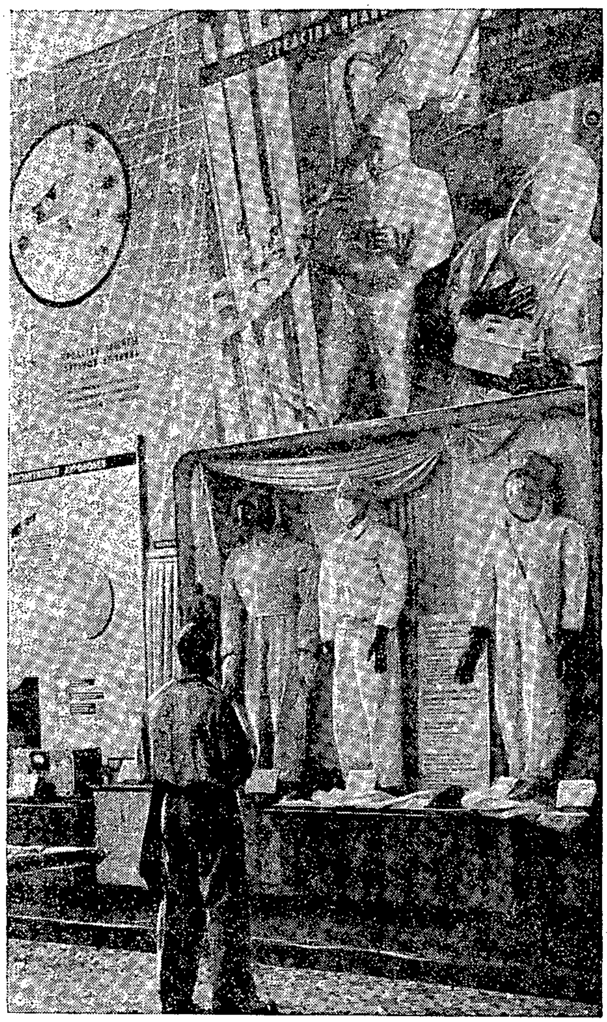

Fig. 5. Exhibit of protective clothing used in monitoring radioactive contamination (Pavillion "Atomic energy for peaceful purposes" VDNKh, 1961).

In order for the atomic energy industry to play a material role in the over-all energy industry of the country, in addition to the solutions of the problems indicated, there must be a considerable reduction in the inherent cost of the electrical energy developed in atomic electric stations.

One of the greatest scientific problems in the field of atomic energy is the direct transformation of the energy of nuclear processes into electricity.

In the Soviet Union, work on the direct transformation of heat into electricity has been going on for a long time. Academician A. F. Ioffe has not only worked out the theory of thermoelectric converters, but under his direction the first thermal batteries were constructed. New semiconductors, developed by Soviet scientists, have even higher working coefficients, and retain their properties for a long time.

In a nuclear reactor the energy may be produced at a very high temperature, which gives the promise of high efficiencies in the transformation of fission energy into electricity. Direct transformation of nuclear energy into electricity considerably simplifies the engineering scheme of producing electrical energy and will have tremendous importance in many branches of technology. Therefore, in the project of the new program of the party, there is a direct statement of the need to extend the work on methods " . . . of direct transformation of heat, nuclear, solar, and chemical energy into electricity . . . ." It is obvious, that with the great promise awaiting the atomic energy industry, special attention should be given to the physics of nuclear reactors. Soviet scientists are carrying on various types of work in this field, and will extend them systematically to provide a basis for industrial development. As an example, we can indicate one of the directions of this work.

In 1960, the United Institute of Nuclear Studies in Dubna began to operate a new Soviet nuclear reactor intended for studies in the field of neutron physics, which is distinguished by a good deal of originality. This is the only reactor in the world using plutonium rods and a disc of U^{235} rotating at 5000 rpm. At the pulse maximum the reactor power reaches 3000 kw. The reactor makes it possible to obtain periodically, 8.3 times per second, an over-all neutron flux equal to 10^{17} neutrons/sec at the pulse maximum.

* * *

In the past few years, in addition to the use of atomic energy for power installations, the use of radioactive isotopes in nuclear radiations has been greatly developed.

At the present time, radioactive and stable isotopes and nuclear radiations are being used in our country by more than 2500 research, medical, and industrial organizations. Now, radioactive isotopes are being used in practically all branches of the national economy, although to different degrees. The industries of the Soviet Union now produce more than 300 radioactive and stable isotopes, and from them prepare sources of radiation and labelled chemical compounds.

Isotope production is widely distributed inside the country and exports are made to the People's Democratic Countries, as well as to Japan, the United Arab Republic, Iraq, Mexico, and other countries.

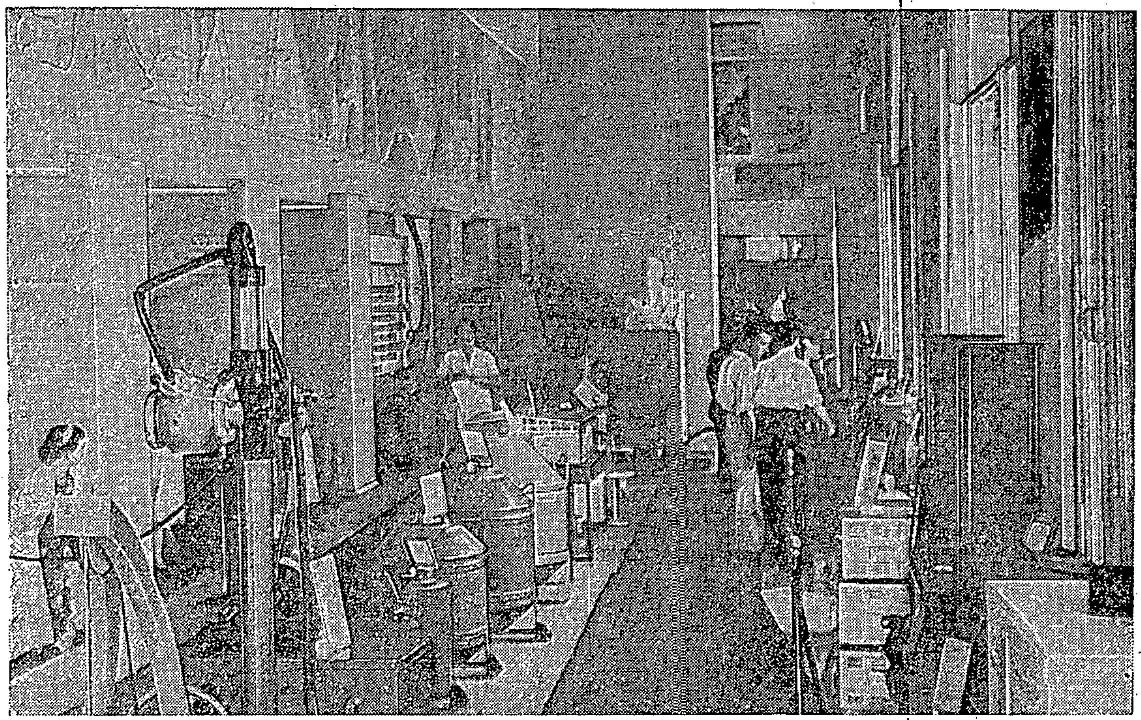

Fig. 6. Demonstration Hall of the Moscow "Isotopes" Store.

However, the practical use of isotope methods is really only beginning. It will be continuously enlarged: The new radical force of nature must be employed to full. It should be noted in this connection that at the present time only one-tenth of the radioactive and stable isotopes known to science are being used for practical purposes.

The use of radioactive isotopes as tracer atoms for scientific investigations and many other purposes is firmly entrenched in practice. Methods have also been widely developed based on the penetrating power of ionizing radiations and their destructive action, and on energy release on the activation of other materials, etc.

The various devices based on the use of radioactive isotopes to a high degree meet present-day requirements of industry, which is characterized by a rapid increase in the rate of flow of various processes, a transition to high temperatures and pressures, and by the use of continuous automatically-regulated processes. Thus, for example, in heavy and light metallurgy, radioactive isotopes and ionizing radiations make it possible to have continuous monitoring of the mixing of metal during crystallization, and to create a technology of continuous monitoring of the thickness of rolled sheets and plates, and the loading of layers of materials in blast furnaces. In the construction of machinery, isotope methods are used in examining the product for defects, and observing the wear of machine and instrument parts. In construction work, isotope methods are used to monitor the quality of concrete structures while the concrete is being laid and checks can be made on reinforced concrete structures.

Radioactive methods are firmly entrenched in geologic prospecting practice as a means of searching for and prospecting useful ores. From data of the Institute of Economics of the Academy of Sciences, USSR, in the oil fields of Azerbaijan and western Ukrainia alone, more than 2.2 million tons of high quality petroleum have been found by tracing out neglected deposits with these methods. From the same data, the economic effect of the use of radioactive methods in prospecting and exploiting useful ores amounted to more than 45 million rubles in 1960.

Great possibilities are opened up by the use of ionizing radiations to produce various radiation chemical reactions.

As an example of reactions which are economically important, we can already mention the radiation oxidation of organic compounds, benzene in particular, and the radiation polymerization of a number of organic compounds, which makes it possible to prepare materials with substantially improved and new properties. The radiation synthesis of polyethylene makes it possible to carry on the reaction at a pressure of 250-300 atm and a temperature of 30-80° C without the use of catalysts. The use of insulation made out of thermally stable polyethylene in electrical engineering makes it possible to reduce the copper required two or three times because of the larger current densities that can be used without shortening the life of the conductor.

These and many other fields where radioactive isotopes are used show that radioisotope technology is an important method in the development of technology in the national economy.

At the present time in the Soviet Union radioactive and stable isotopes are being used to prepare more than 700 different chemical compounds.

Great possibilities for reelective isotopes in nuclear radiations are opened up in medicine, and they find wide application in the diagnosis and treatment of a number of diseases. For example, radioactive isotopes may be used to study the functions of various organs and systems of the body without disturbing their integrity. Thus, the isotope I^{131} is used for a diagnosis of diseases of the thyroid gland. The isotope P^{32} makes it possible to determine the quantity of blood circulating in the organism. Then in the diagnosis of tumors of the central nervous system in the brain, use is made of the radioactive isotopes of radon, xenon, and iodine. A technique has been worked out for external irradiation in the tele-gamma-apparatus using Co^{60} and Cs^{137} for the treatment of cancerous diseases of the skin, the esophagus, and the lungs, as well as other diseases.

Radio surgical methods have been worked out for radiation therapy inside the cavities and tissues of the body, which are used in combination with external irradiation. For this purpose, use is made of the isotopes Co^{60}, Cs^{137}, and Au^{198} in the form of a colloidal solution, granules of Y^{90},etc.

The examples given of the use of radioactive isotopes and radiations in medicine only partially illustrate the enormous possibilities of the peaceful uses of atomic energy for the welfare of man.

A great contribution can be made by the use of isotopes in agriculture. New possibilities and prospects are to be expected in the future, in particular, the use of radioactive radiations for preserving agricultural products.

Present-day technology has a large range of radioactive isotopes at its disposal, with different energies, different half-lives, and other special properties. This makes it possible for the technologist to solve problems which could not even have been dreamed about previously. For example, the use of radioactive isotopes in automation of production may become a powerful means of solving one of the problems presented in the plan of the new program of the Communist Party of the Soviet Union: ". . . putting an end to heavy physical labor, and then to every kind of unskilled labor." Thus, for example, in the mining and smelting branches of industry in the grinding, transportation, cleaning and smelting of ores and coal, where simple monotonous operations require a man to be in ore and coal dust, in the midst of the clamor of operating machinery, the use of equipment with radioactive isotopes makes it possible to automate the production processes completely and replace the labor of human beings with the work of machines. The first production experiments on the use of radioactive apparatus in the Krivorozh'e South Mining and Smelting Combine and at the Slantsy Mine in the Estonian SSR show that the method is completely possible, and open up one more method of using radioisotopes.

The use of isotopes in the coal industry for automatic stabilization of the motion of the coal combine at the "coal-sorting" junction makes possible constant automatic control of the position of the cutting instrument and thus makes complete use of the speed capabilities of the combine. This is a trend which may lead subsequently to the complete automation of subterranean work with the control of the machinery transferred to the surface.

It is clear from what has been said that atomic energy is now finding practical application not only for warlike purposes but in various branches of the national economy as well. It has come out from behind the walls of the laboratories into wide ranges of industrial application. After the atomic electric stations and reactors which

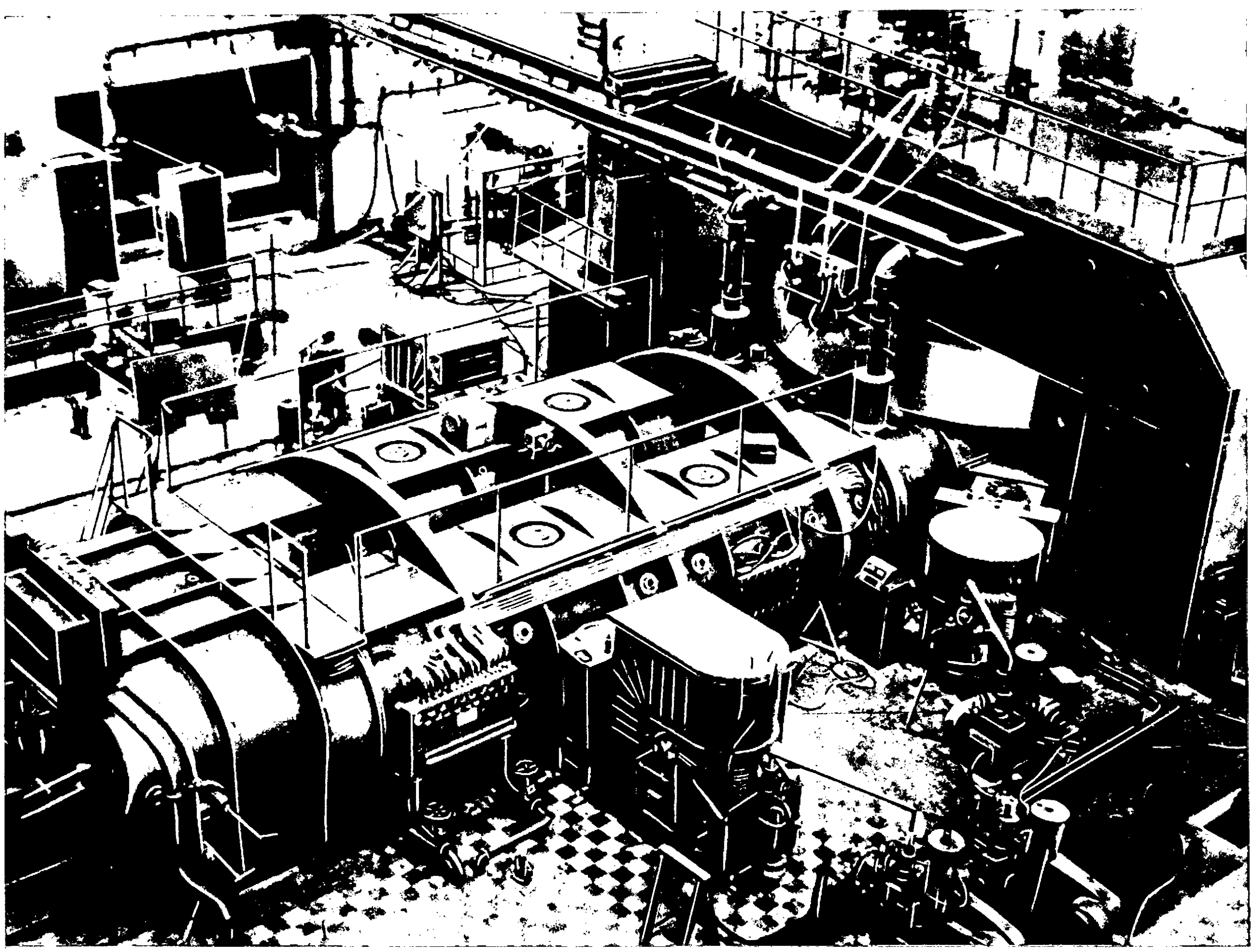

Fig. 7. General view of the cyclotron for accelerating multiply-charged ions.

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have been built and are being built have been tested in operation, after the work of construction and evaluation of various types has been completed, and it has been found out which are the best, the most economical and the most reliable types of equipment, wide prospects will be opened up for the construction of electric stations and power installations, and radioactive isotopes and radiations will find even broader application in the national economy.

The foundation of our work on the use of atomic energy is its powerful scientific basis, the development and enlargement of which has received a large amount of attention from our Communist Party. This basic scientific structure ensures, in particular, that new scientific and practical prospects will be opened up.

The scientific treatment of the various problems of nuclear physics is already at the present time showing us now even more attractive possibilities with use of the energy from nuclear reactions.

The use of atomic energy from the fission of heavy nuclei is not the only possible way of using the energy hidden in the atomic nucleus. Here, above all, attention should be called to the problem of controlled thermonuclear reactions, the solution of which is one of the more important tasks assigned by the Communist Party of the Soviet Union.

Academician I. V. Kurchatov, as early as 1956, appearing at the Twentieth Congress of the Communist Party of the Soviet Union, pointed out how large a role would be played in science and economics by the solution of the problem of the controlled thermonuclear reaction. He spoke of the fact that in the hydrogen bomb we already know how to create the conditions necessary for the fusion of hydrogen nuclei, i.e., effect thermonuclear synthesis, but we must now control this reaction in such a way as to avoid an explosion.

In the USSR work on controlled thermonuclear synthesis is being carried out on a wide front. To carry out the research in physics a number of large installations of various types have been created, including the very large "Ogra" experimental installation with a vacuum chamber 1.4 meters in diameter and 12 meters long. Several installations are in the process of construction. We are convinced that the problem of practical utilization of controlled thermonuclear reactions will be solved.

In the work on thermonuclear synthesis, reactions are being studied which occur at temperatures of millions of degrees, where matter becomes plasma, a new, little-studied state. A new field has been added to physics — plasma physics. The development of this field is of fundamental importance, since, if the work on thermonuclear synthesis is successfully completed, it will completely cover every energy requirement of the whole population of the terrestial globe for an unforeseeable length of time. This work is also important because of the fact that the developments are sure to uncover a number of new scientific results and data important in practice. Thus, in plasma work we must have a technique of producing very high vacua (10^{-10} - 10^{-11} mm Hg) in large volume. Experience in this field is of value to a number of branches of the national economy. Plasma work entails the production of powerful magnetic fields (50,000 - 200,000 oersteds).

Recently, as a result of the researches of Soviet scientists, intermetallides have been discovered which show superconductivity and make it possible to produce powerful magnetic fields at practically realizable helium temperatures, which, naturally, is of considerable importance for other branches of science and technology.

But nuclear physics is still far from exhausting all its possibilities. Thus, studies on the atomic nucleus have led scientists to discover new atomic particles, the antiparticles. In recent years, for example, more than ten antiparticles have been discovered. The majority of them have a lifetime less than a hundred thousandth of a second, while some of them are stable or have a long lifetime.

Data on some of the antiparticles is given below:

	Mass	Mean Lifetime	Year of discovery
Antiproton	938	Stable	1955
Antineutron	940	Stable	1956
Positron	0.511	$1.013 \cdot 10^{3}$ sec	1932

Union of the proton with its antiparticle, the antiproton, produces annihilation, accompanied by an extremely high yield of energy, approximately 1000 times greater than in fission of nuclei or in thermonuclear synthesis. The problem of particle annihilation has serious scientific importance, and treatment of the problem will give a more profound understanding of the structure of matter.

A powerful means of studying the structure of the nucleus of the atoms of matter is to study the effect on nucleus of other nuclei and particles raised to high energies by means of powerful accelerators. This is the technique in most universal use at the present time, and in the coming years it will continue to develop. Thus, in the near future new powerful accelerators will be put into service. Recently, construction was started on the most powerful accelerator in the world with sharp focusing at a nominal proton energy of 50-70 Bev. The more important parameters of this accelerator are as follows:

Nominal proton energy, Bev	50-70
Mean radius of orbit, meters	236
Maximum field, oersteds	10,000-12,000
Injection energy, Mev	100
Number of magnets	120
Total magnet weight, tons	> 20,000

The new accelerator installations still further strengthened the material basis of Soviet research on the atomic nucleus.

Considerable scientific interest is presented by the cyclotron for accelerating multiply-charged ions, recently constructed at the United Institute for Nuclear Studies in Dubna. At the beginning of September, 1960, the cyclotron produced the first beam of accelerated particles, and at the present time the accelerated ions have reached an energy and intensity sufficient to begin experimental work on the study of reactions in complex and heavy nuclei. However, even wider prospects are opened up by new methods of accelerating particles, which provide practically unlimited possibilities for interaction with matter, thus broadening our understanding of the structure of matter.

Our whole country comes to the Twenty-Second Congress of the Communist Party of the Soviet Union with great achievements. There are substantial advances in the field of utilization of atomic energy as well. Our achievements form the basis for multiplying our efforts in the progressive movement ahead.

Having methods of utilizing atomic energy on an economical basis means creating a new energy industry, which is the economic basis of a new society which will realize the great principle "from each according to his abilities, to each according to his needs."

A greater supply of energy means higher productivity of labor which is the decisive factor in the victory of the new social structure – Communism. The grandiose scale of this task inspires all workers in the field of the utilization of atomic energy to unrelenting labor in the name of a glorious future.

We recognize that we are only at the threshold of a new era, we recognize the whole importance of our efforts for the movement of our country ahead toward communism, and we shall apply all our energies ". . . to fortify the leading positions won by Soviet science in the more important branches of knowledge, and to occupy a leading position in world science in all fundamental directions."

INTERACTION OF CHARGED-PARTICLE BEAMS WITH PLASMA

Ya. B. Fainberg

Translated from Atomnaya Énergiya, Vol. 11, No. 4, pp. 313-335, October, 1961.
Original article submitted July 28, 1961

The interaction of charged-particle beams with plasma is of great importance in various kinds of gas-discharge devices used in research intended to achieve CTR.* Beam-plasma interactions are also of great importance in new methods of accelerating charged particles and in plasma devices for amplification and generation of microwaves.

In spite of apparent differences and the rich variety of interaction mechanisms between beams and plasmas, there are only three basic processes involved in these interactions: the Cerenkov effect, the Doppler effect (anomalous and normal), and plasma polarization produced by the passage of a charged particle through the plasma. There is another mechanism, which operates when charged particles or oscillators move through a bounded or spatially-periodic plasma . This is the so-called parametric Cerenkov effect.

In most cases the plasma density n_0 is relatively small ($n_0 \simeq 10^{12}$ - 10^{14}) so that the energy lost via these mechanisms for an individual charged particle traveling a unit distance $d\mathcal{E}/dx$ is insignificant, being of the order of 10^{-3} - 10^{-5} ev/cm. In most cases, however, a beam of charged particles interacts with the plasma. In this case the effective strength of the interaction increases markedly [1] because the self-modulation of the beam produced by the interaction means that in the final analysis we are dealing with a coherent interaction between a beam of charged particles and a plasma [2].

The energy loss of the beam particles due to oscillations is quite significant and can be as high as 10^3-10^4 ev/cm per particle when the number of particles in a bunch is $N \simeq 10^7$ - 10^8. Because of the appreciable intensity of the interaction between beams or charged-particle bunches and a plasma it is reasonable to assume that these interactions are responsible for a number of the effects observed in gas discharges. It would appear, for instance, that these interactions lead to many plasma instabilities, produce a Maxwellian distribution in the absence of collisions, and affect various transport phenomena (conductivity, diffusion) in a plasma.

The high interaction energy of charged-particle beams or bunches in a plasma (compared with the interaction energy for an individual particle) can be exploited in plasma injection in magnetic-mirror systems, plasma heating, in measurement of plasma parameters, in the determination of distribution functions, and for various other purposes.

As far as CTR systems are concerned, the most important aspect of this problem is the investigation of conditions associated with the production and suppression of instabilities due to the interaction of charged-particle beams with a plasma.

The motion of a beam in a plasma is said to be unstable if any initial perturbation (fluctuation) of the beam or plasma tends to grow. A necessary condition for the appearance of an instability is that the conditions corresponding to at least one of the basic mechanisms considered above (Cerenkov effect, anomalous or normal Doppler effect) be satisfied. Inasmuch as radiation processes can be accompanied by absorption processes, the number of particles in the beam that give energy to the electromagnetic field must be greater than the number of particles that absorb energy from the field.** There is one other condition that must be satisfied before an instability can arise: Particle bunching must occur in a phase region in which particles lose energy to the electromagnetic field. In a number of cases this requirement on particle bunching is satisfied automatically if the radiation condition is satisfied for an individual particle. The electromagnetic fields due to radiation by particles in the beam cause bunching, i.e., "self-modulation" of the beam; in turn the increasing modulation of the beam causes an increased

* CTR – controlled thermonuclear reactions.

** This requirement imposes certain conditions on the unperturbed velocity distribution functions for the particles in the beam and in the plasma (see below).

radiation intensity, because particle bunching enhances coherent radiation. Hence, in its initial stages the growth of an instability is exponential.

From the point of view of quantum theory [3], an instability implies that because of greater populations in "upper" energy levels (beam particles) there are more transitions in which induced emission occurs than in which absorption occurs. For example, in a beam of free particles the "upper" levels are associated with particles of higher velocities. Hence, an instability arises if the derivative of the distribution function for particles in the beam is positive at velocities for which the particles can interact strongly with the plasma. This result also follows from classical considerations.

1. Theoretical investigations of the excitation of longitudinal oscillations by a beam of charged particles have been carried out by A. I Akhiezer and the author, and by Bohm and Gross [1]; these investigations pointed up the importance of beam-plasma instabilities and showed that the instability becomes particularly strong if the ordered beam velocity V_0 becomes greater than the thermal velocity of the plasma electrons V_{Te}, i.e., $V_0 > V_{Te}$. The elementary mechanism in this interaction is the Cerenkov effect [4] for the longitudinal plasma waves. When $n_1 \ll n_0$ the spectrum of excited high-frequency oscillations is determined by the Cerenkov condition and lies in the frequency region $\omega \simeq \omega_0$.* The growth rate of the instability $\delta = \mathrm{Im}\,\omega$ is rather large, $\delta \simeq \omega_0 \left(\frac{n_1}{n_0}\right)^{1/3}$ in this case.

Similar effects are found in the interaction of two or more beams [5]. For example, when two electron beams (Maxwellian distribution of ordered velocities) interact [6], instabilities can arise if the condition $|V_{01} - V_{02}| > V_{Te1} + V_{Te2}$ is satisfied, where V_0 and V_{Te} are respectively the ordered velocity of a beam and the thermal velocity of the electrons. The growth rate is also quite high for these instabilities. For certain beam parameters the conditions for the longitudinal Doppler effect can be satisfied and the excited frequencies are given by $\omega \simeq \frac{\omega_{02}}{1 - \frac{V_{02}}{V_{01} - \sqrt{3}\,V_{Te}}}$.

Further investigations of excitation processes in plasma, carried out by G. V. Gordeev [7] have shown low-frequency oscillations and ion waves (in the absence of a magnetic field) can be excited if $V_{Te}\mu^{1/2} < V_0 < V_{Te}$, that is to say, these modes can be excited at low ordered velocities and consequently, low currents.

A large number of papers concerned with the interaction of charged-particle beams and "oscillator" beams with plasma have been published in the last several years. This work has revealed the existence of a large number (about 20) of different kinds of instabilities.

Most of these instabilities can be classified into three main groups corresponding to the three basic excitation mechanisms:

1. Instabilities due to the Cerenkov interaction of electron and ion beams with a plasma in a magnetic field.

These instabilities arise when the ordered beam velocity V_0 is equal to the phase velocity of the wave V_{ph} and lead to the excitation of low-frequency and high-frequency oscillations. The low-frequency oscillations include ion-acoustic waves, Al'fven waves, and magnetoacoustic waves; the high-frequency oscillations are the longitudinal electron oscillations in the magnetic field.

Low-frequency oscillations can also be excited by drift currents in an inhomogeneous plasma [8, 9]. In this case the drift motion plays the role of the ordered motion and the instability condition is given by $V_{dr} = V_{ph}$ (here, V_{dr} is the drift velocity).

2. Instabilities due to the anomalous Doppler effect.

This effect requires that the velocity of the radiating particle be greater than the phase velocity of the plasma wave ($V > V_{ph}$). In this case the radiated frequencies are determined by the relations $\omega - k_3 V_0 = -\omega_{res}$ or $\omega = \frac{\omega_{res}}{\frac{V_0}{V_{ph}} - 1}$ (here, ω_{res} is the natural frequency of the radiating particle in its own rest system and $k_3 = \frac{\omega}{V_{ph}}$

* A table of the notation used in the present work is given at the end of the paper.

is the projection of the wave vector in the direction of motion of the beam). The excited frequency computed in the reference system in which the beam is at rest coincides with the resonant frequencies of the beam, in particular, the Langmuir frequency ω_0 (in which case we have a longitudinal Doppler effect), or the Larmor frequencies ω_H ($\omega = \omega_0$; $\omega = n\omega_H$; $n = 1,2 \ldots$).

An important feature of the anomalous Doppler effect, first pointed out by V. L. Ginzburg and I. M. Frank [3] is the fact that the radiation process is accompanied by transitions to higher energy levels. Hence, it can occur only in unperturbed oscillators, in particular a beam of charged particles with no initial transverse energy in a plasma in a magnetic field. The conversion of freely moving particles into radiation oscillators takes place at the expense of the energy associated with the longitudinal motion.

Instabilities due to the anomalous Doppler effect include those associated with the excitation of ion-cyclotron waves in a plasma by electron or ion beams. The anomalous Doppler effect also causes high-frequency electron oscillations (frequencies $\sim \omega_H$; $\sqrt{\omega_0^2 + \omega_H^2}$); however the growth rate is smaller than for oscillations caused by the Cerenkov effect. In all the cases cited above the oscillation frequency in the beam reference system is close to the beam Larmor frequency. When plasma oscillations are excited by a high-density beam it is also possible for the longitudinal Doppler effect to operate, in which case the oscillation frequency in the beam system is close to the Langmuir frequency of the beam ω_0. In this case the oscillation frequency is $\omega_0 \simeq \omega_0 \mu^{1/3}$.

3. Instabilities due to the normal Doppler effect.

If electrons in a beam in a magnetic field have initial transverse energies, in moving through a plasma such a beam can cause an instability due to the normal Doppler effect. An important feature of this instability is the fact that it can arise when the beam velocity $V_0 < V_{ph}$*, in particular, when $V_0 = 0$. Thus, radiation due to the normal Doppler effect is always possible. The only condition necessary for the appearance of this instability is that the particle bunching in the phase region in which the particles lose energy to the electromagnetic field be stronger than in the phase region in which the particles absorb energy from the field.** A mechanism for this bunching effect has been suggested by A. V. Gaponov [10]. This mechanism is based on the energy dependence of the oscillation frequency of a particle.

When an oscillator moves in a spatially inhomogeneous field and the oscillator frequency $\omega \simeq \omega_{res}$, the mean displacement of the oscillator in a time large compared with the period of the oscillations is different from zero and depends on the initial phase of the oscillator. This effect leads to spatial bunching of oscillators in a wave field.

In Tables 1-3 we show the basic features of instabilities due to the Cerenkov effect, the anomalous Doppler effect, and the normal Doppler effect. ***

2. These tables show that instabilities can arise at relatively low electron velocities ($V_0 \gtrsim V_{Te} \mu^{1/2}$ and $V_0 \geq V_A$).

A reduction of the electron velocity for which an instability arises means essentially a reduction in the minimum current necessary for exciting an instability; this current value can be smaller than the minimum current for hydrodynamic instabilities. We may note, however, that the minimum current is not only determined by the critical velocity of the ordered motion, but also by the electron density that is involved. For this reason, a number of instabilities associated with high values of the ordered velocity can actually occur at low current values because the instabilities are excited at relatively low-ordered electron densities.

* The frequencies radiated in the normal Doppler effect are given by $\omega - k_3 V_0 = \omega_{res}$.

** Resonance ("currentless" or "beamless") methods of heating based on the ordered motion of ions across a magnetic field also lead to the development of low-frequency ($\omega = \Omega_H$) and high-frequency electrostatic instabilities.

*** Tables 1-5 are for purposes of illustration only. They contain the simplest and most striking cases. The appropriate relations for instabilities in more general cases are given in the papers to which reference is made in the tables. These tables are based on all pertinent work on this problem known to the authors. Both the general cases and the cases given in the tables are considered in work to which references are made.

TABLE 1. Instability Due to the Cerenkov Effect.

Excited oscillation	Excitation condition	Frequency spectrum	Growth rate $Im\omega/Re\omega$	Example $(Im\omega)n_0=10^{12}$; $n_1=10^9$; $v_0=3\cdot10^9$	Literature reference
Longitudinal waves (low density electron beam)	$V_0 > V_{Te}$; $\frac{V_{Te}}{V_0} \ll \left(\frac{n_1}{n_0}\right)^{1/3}$; $\frac{V_{T1}}{V_0} \gg \left(\frac{n_1}{n_0}\right)^{1/3}$	ω_0 $\sim \omega_0$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_1}{n_0}\right)^{1/3}$; $\sim \frac{n_1}{n_0}\frac{V_0^2}{V_{T_1}^2}$	$4\cdot10^9$ sec^{-1}; $5\cdot10^8$ sec^{-1}	[1]
Ion acoustic waves	$\left(\frac{T_e}{M}\right)^{1/2} < V_0 < \left(\frac{T_e}{m}\right)^{1/2}$	$k\left(\frac{T_e}{M}\right)^{1/2} \times (1+k^2\lambda_D^2)^{-1/2}$	$Im\,\omega = \omega_{0i} \times \frac{V_0 - \left(\frac{2Te}{3M}\right)^{1/2}}{2V_{Te}}$	$2\cdot10^8$ sec^{-1}; $V_0 = \frac{V_{Te}}{3} = 10^8$	[7] [11]
Ion acoustic waves in a magnetic field	»	$k\left(\frac{T_e}{M}\right)^{1/2} \times \left[1+k_{\parallel}^2\lambda_D^2 + k_{\perp}^2\frac{T_e}{T_i}\right]^{-1/2}$	»	»	[12]
Al'fven waves	a) ordinary wave $V_0^2 > V_A^2\left(1+\frac{n_0}{n_1}\right)$; b) extraordinary wave $V_0^2\cos^2\theta > V_A^2\left(1+\frac{n_0}{n_1}\right)$	$\sim kV_A\cos\theta$; $\sim kV_A$	$\left[\frac{V_0^2}{V_A^2} - 1 - \frac{n_0}{n_1}\right]^{1/2}$; $\left[\frac{V_0^2}{V_A^2}\cos^2\theta - 1 - \frac{n_0}{n_1}\right]^{1/2}$		[13] [14] [15] [16]
Longitudinal waves in magnetic field (electron beam $\omega_H\Omega_H < \omega_0^2 << \omega_H^2$; $\Theta \neq \pi/2$)	$k_3V_0 \simeq \omega_0 \mid\cos\theta\mid$; $\omega_H < k_3V_0 < \sqrt{\omega_H^2+\omega_0^2\cos^2\theta}$	$\sqrt{\omega_H^2+\omega_0^2\sin^2\theta}$; $\omega_0\mid\cos\theta\mid$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{\omega_1^2\omega_0^2}{\omega_H^4}\cot^2\theta\right)^{1/3}$; $\frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_1}{n_0}\right)^{1/3}$		[15] [16]

* T is the temperature in degrees.

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TABLE 1 (Continued)

Excited oscillation	Excitation condition	Frequency spectrum	Growth rate $\mathrm{Im}\omega/\mathrm{Re}\omega$	Example $(\mathrm{Im}\omega)$ $n_0=10^{12}$; $n=10^9$; $v_0=3\cdot10^9$	Literature reference
Longitudinal waves across magnetic field (ion beam $\omega_0^2 >> \omega_H^2$; $\Theta \simeq \pi/2$)	$k_3 V_0 \simeq (\omega_H \Omega_H)^{1/2}$	$(\omega_H \Omega_H)^{1/2}$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_1}{n_0}\right)^{1/3}$	$3\cdot10^7$ sec^{-1}	[17]
Magneto-acoustic waves ($n_1 << \mu n_0$)	$V_{Ti} < V_0 < S$; $V_A < V_0 < V_{Te}$	kV_A	$\left(\frac{n_1 \cos^2\theta}{\mu n_0}\right)^{1/3}$	$n_1 = 10^8$; $6\cdot10^5$ sec^{-1}	[18] [19]
Instability in inhomogeneous plasma	$\frac{\partial \ln T_0}{\partial \ln H_0} > 1$	kV_{dr}	—	—	[9]
Instability of ion beam in a plasma	$\left(\frac{n_1}{n_0}\right)^{1/3} \frac{V_0}{V_{Te}} \gtrsim 1$	kV_0	~ 1	—	[20]
Longitudinal waves in electron-ion beams	$\lvert V_{eo}\rvert > \lvert V_{io}\rvert + V_{Te} + V_{Ti}$; $\lvert V_{io}\rvert > \lvert V_{eo}\rvert + V_{Te} + V_{Ti}$; $\lvert V_{eo}\rvert > V_{ph} + V_{Te}$; $\lvert V_{io}\rvert > V_{ph} + V_{Ti}$	—	—	—	[21]

The growth rates are very large for the instabilities given in the tables. The growth time for a high-frequency instability is of the order of 10^{-9} sec; the growth time is longer for low-frequency oscillations (since the growth factor is smaller than or of the same order as the perturbed frequency). However, the growth time is still very small for these instabilities (approximately 10^{-4} - 10^{-6} sec). If we assume that the initial energy of the oscillations is of the order of the thermal fluctuations, the time in which the energy of the ordered motion is converted into oscillation energy is generally of the order of 10^{-4} - 10^{-8} sec.

In a number of cases the plasma containment time is greater than the instability growth times given above. It follows that not all of the instabilities listed above are important. Using the values of the growth rates, we can compare the energy loss for individual particles and for particles moving in beams. The loss per particle is appreciably greater in the second case because of the coherent interaction of the beam with the plasma; the importance of coherence was first pointed out by V. I. Veksler [2].

TABLE 2. Instability Due to the Anomalous Doppler Effect.

Form of oscillation	Excitation condition	Frequency spectrum	Growth rate $\mathrm{Im}\,\omega/\mathrm{Re}\,\omega$	Numerical example $(\mathrm{Im}\,\omega)$ $n_0 = 10^{12}$; $n_1 = 10^9$; $H_0=10^3$; $V_0=3.10^9$	Literature reference
Instability of transverse waves in an electron beam	$\omega + \omega_H \simeq k_3 V_0$; $\omega_0^2 \gg \omega_H^2$	$\omega < \omega_H$	$\frac{\omega_1}{\omega_0}\left\lvert \frac{\omega_H}{\omega} - 1 \right\rvert$	$3 \cdot 10^8$ sec^{-1}	[22]
Longitudinal oscillations (two stream)	$k_3 V_{01} \simeq \frac{\omega_{02}}{1 - V_{02}/V_{01}}$	$\omega \simeq \frac{\omega_{02}}{1 - \frac{V_{02}}{V_{01}}}$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_1}{n_2}\right)^{1/3}\left(1 - \frac{V_{02}}{V_{01}}\right)^{-2/3}$	$\sim 4 \cdot 10^9$ sec^{-1}	[5; 6]
Longitudinal electron-ion oscillations (electron plasma forms the beam)	$\omega_0 \simeq k_3 V_0$	$\sim \omega_0 \mu^{1/3}$	$\sqrt{3}$	$5 \cdot 10^9$ sec^{-1}	[23, 79]
Longitudinal oscillations (electron plasma forms the beam)	$V_{ph} \gg V_T$	$\omega \ll k_3 V_0$	$Im\,\omega \simeq \mu^{1/2}\omega_0$	$1.5 \cdot 10^9$ sec^{-1}	[24]
Ion-cyclotron waves produced by an electron beam	$\omega_H \simeq k_3 V_0$	$\sim \Omega_H$	$\frac{\omega_1}{2\omega_0}\frac{V_0^2}{V_A^2}\mu(1 + \cos^2\theta)$	$3 \cdot 10^4$ sec^{-1}	[17, 15]
Ion-cyclotron waves produced by an ion beam	$2\Omega_H = k_3 V_0$; $V_0 < V_A$	$\sim \Omega_H$	$\frac{\omega_1}{8\omega_0}\frac{V_0^2 \sin^2\theta}{V_A^2}$	$V_0 \simeq 10^8$ cm/sec; $8 \cdot 10^4$ sec^{-1}	[16]
Plasma waves across magnetic field excited by an electron beam	$\omega_H \simeq k_3 V_0$; $\theta = \frac{\pi}{2}$; $\omega_0^2 \gg \omega_H^2$	$\sim \sqrt{\omega_H \Omega_H}$	$\frac{\omega_1}{2\omega_0}\left(\frac{m}{M}\right)^{1/4}$	$4 \cdot 10^7$ sec^{-1}	[17]
Longitudinal electron waves produced by an electron beam	$\omega_H \simeq k_3 V_0$; $\theta \neq \frac{\pi}{2}$; $\omega_0^2 \ll \omega_H^2$	$\omega_+ \simeq \sqrt{\omega_H^2 + \omega_0^2 \sin^2\theta}$; $\omega_- \simeq \omega_0 \cos\theta$	$\frac{\omega_1 \omega_0}{2\omega_H^2}\sin^2\theta$; $\frac{\omega_1}{2(\omega_0\omega_H)^{1/2}}\frac{\sin\theta}{\sqrt{\lvert\cos\theta\rvert}}$		[15]

TABLE 3. Instability Due to the Normal Doppler Effect

Form of instability	Excitation condition	Frequency	Growth rate $\mathrm{Im}\,\omega/\mathrm{Re}\,\omega$	Example $\mathrm{Im}\,\omega$	Lit. ref.
Instability of an electron beam of oscillators $[f_e=\delta(v_\parallel)\delta(v_\perp-v_\perp^0)]$	$k_\perp v_\perp^0 \simeq \omega_H;\ \theta=\frac{\pi}{2}$; $k_\perp v_\perp^0 \leqslant \omega_H;\ \theta\neq\frac{\pi}{2}$;	$\omega\sim n\omega_H$; $n=\pm1;\ \pm2$	~ 1	—	[26]* [27]
Instability of transverse waves interacting with a relativistic flux of oscillators $[f_e=\delta(p_\parallel-p_\parallel^0)\delta(p_\perp-p_\perp^0)]$	$\omega(1-\beta_\perp^2)\leqslant k_\parallel V_0$; $\left(\beta_\perp=\frac{v_\perp}{c}\right)$; $\theta=0$	$\omega=\frac{ck}{n_j}\simeq kV_0-\omega_H$	$\sim\left\{\frac{\omega_1^2}{\omega}\,\frac{\frac{kV_0}{\omega}+\beta_\perp^2-1}{\frac{d}{d\omega}\left(\omega^2 n_j\left[(\omega)\right]\right)}\right\}^{1/2}$	—	[22]
Instability of ion beam of oscillators $[f_i=\delta(v_\parallel)\delta(v_\perp-v_\perp^0)]$	$a_i=\frac{k_\perp v_\perp^0}{\Omega_H}\leqslant 1;\ \theta\neq\frac{\pi}{2}$; $V_\perp^0\gg V_{Te}$	$\omega\simeq n\Omega_H$; $n=1$	$\sim\left[\frac{v_\perp^{0^2}}{V_A^2}\left(\frac{I_n^2(a)}{a^2}+\frac{\cos^2\theta-I_n'^2(a)}{n^2}\right)+\mu I_n^2(a)\right]^{1/2}$	$v_\perp^0=10^8;\ n_1=10^9$; $H_0=10^4$; $2\cdot10^5\,\mathrm{sec}^{-1}$	[28]
Excitation of longitudinal oscillations in a plasma by an electron beam of oscillators	$a_e=\frac{kv_\perp^0}{\omega_H}\leqslant 1$; $V_\parallel^0\gg V_{Te}$	$\omega_+\simeq\sqrt{\omega_H^2+\omega_0^2\sin^2\theta}$ $(\omega_0^2\ll\omega_H^2)$; $\sim k_\parallel v_0+n\omega_H$; $\omega\sim\omega_0\lvert\cos\theta\rvert$	$\frac{\delta_1}{\omega_+}\simeq 0.4\left(\frac{n_1}{n_0}a_e^2\frac{\omega_0^4}{\omega_H^4}\sin^2\theta\cos^2\theta\right)^{1/3}$ $(n=1)$; $\frac{\delta_2}{\omega_+}=0.4a_e^{2/3}\frac{\delta_1}{\omega_+}\ (n=2)$; $\frac{\delta_1}{\omega_-}\simeq 0.4\left(\frac{n_1}{n_0}a_e^2\right)^{1/3}\ (n=1)$; $\frac{\delta_2}{\omega_-}\simeq 0.4a_e^{2/3}\frac{\delta_1}{\omega_-}\ (n=2)$	$n_0=10^{12};\ n_1=10^9$; $H_0=10^4;\ a_e=0.1$; $\delta_1\simeq 2\cdot10^8\ \mathrm{sec}^{-1}$; $\delta_2\simeq 1.6\cdot10^7\ \mathrm{sec}^{-1}$	[29] [30]

* The instability of the distribution function in the absence of beams due to temperature anisotropy has been established and studied by Sagdeev, Rudakov, Vendenov [25] and by Rosenbluth [78].

A number of instabilities are characterized by discrete frequency spectra; however there are also instabilities with continuous spectra. The presence of an instability with a continuous spectrum implies appreciable absorption of energy of the ordered motion; it is difficult to develop techniques for suppressing an instability of this kind.

These tables indicate that the effect of a velocity spread in a beam is to reduce the growth rate, i.e., to attenuate or even suppress an instability. In a number of cases, however, a large velocity spread leads to the appearance of new instabilities; as a rule, however, the growth rates are small for these instabilities. The instabilities considered here all pertain to a homogeneous plasma $\nabla n = \nabla T = 0$. Inhomogeneities can cause appreciable attenuation or even suppression of instabilities but, as has been pointed out by Rudakov and Sagdeev, inhomogeneities can also lead to new instabilities [9].

We now consider briefly certain instabilities that can appear in the stellerator.

In the stellarator $V_0 < V_{Te}$, so that the instabilities of greatest importance are the low-frequency instabilities, arising when $V_0 > V_{Te}\,\mu^{1/2}$, that is, ion acoustic waves in a magnetic field. These instabilities are characterized by a frequency spectrum $\omega \lesssim \omega_{0i}$ and a growth rate of order $\delta_{max} \simeq \omega_{0i} \dfrac{V_0 - V_{Te}\,\mu^{1/2}}{V_{Te}}$ [12]. Since the instability appears if $V_0 > V_{Te}\,\mu^{1/2}$, the critical current density $I_{cr} = eV_{Te}\,\mu^{1/2}\,n_0$ for ion acoustic instabilities is rather low. For example, in the Model C Stellarator the critical current is 30-100 amp/cm². It appears that the low-frequency instabilities are of the greatest importance as far as diffusion processes in the plasma is concerned.*

From the point of view of loss of ordered electron energy it is found that the high-frequency oscillations are most important, in particular, longitudinal oscillations caused by runaway electrons. As is well-known, an instability appears when $\dfrac{\partial f}{\partial v_z} > 0$ [here, f is the distribution function and $v_z = \dfrac{eF}{m}(t - t_0)$] i.e., the number of particles with velocities $v_z > V_{ph}$ must be greater than the number of particles with velocities $v_z < V_{ph}$. A. V. Gurevich [32] has shown that regions characterized by $\dfrac{\partial f}{\partial v_z} > 0$ can arise in the distribution function in a stellarator at the current plateau; at this point the critical field, which determines the rate at which runaway electrons are generated, increases with time, reducing the flux of electrons through the runaway limit. The flux of runaway electrons S is related to the distribution function f (when $v_z > \sqrt{E_s/Ev_{Te}}$) by the relation

$$\frac{\partial S}{\partial t_0} = -\frac{e^2F^2}{m^2}\frac{\partial f}{\partial v_z}; \quad \left[v_z = \frac{eE}{m}(t - t_0)\right]$$

(Here, E is the electric field and E_c is the critical electric field). A reduction in the flux of runaway electrons with time leads to the appearance of a region where $\dfrac{\partial f}{\partial v_z} > 0$. The instability will occur if the growth rate $\delta \simeq \simeq \pi \dfrac{\partial f}{\partial v_z} v_z^2 \dfrac{\omega_0}{N_e}$ is greater than the binary collision frequency. This condition can be used to determine the development time of the instability. It is 10^{-4} - 10^{-5} sec and agrees with the experimental data. In the present case the frequency of the high-frequency oscillations is 10^{10} - 10^{11}. This figure also agrees with the experimental data.

3. In the analysis of instabilities it is usually assumed that the particle distribution function for the ordered motion is Maxwellian; this assumption is then used in computing the spectra of the excited oscillations and their growth rates.

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* The important effects of low-frequency ion oscillations in a plasma in a magnetic field on diffusion processes in the stellarator have been indicated by Spitzer [12, 31]. In our opinion, however, the diffusion coefficient given in [31] is not convincing because the correlation function is not valid if one considers diffusion due to nonstationary oscillations; on the other hand, the derivation is not conclusive for diffusion under stationary conditions because a linear theory does not allow the amplitude of the stationary oscillations to be determined. The effect of beam instabilities on the diffusion can be analyzed only for the case of a small nonlinearity.

The distribution function can be an arbitrary function of velocity if binary collisions do not occur in a plasma. It is important in this connection to find the necessary and sufficient conditions for an instability for the case of an arbitrary distribution function.

The instability conditions for longitudinal oscillations in the absence of external fields have been established by Penrose [33], Neidlinger [34], and Akhiezer, Lyubarskii and Polovin [35]. In [35] these instability criteria have been extended to the case of a plasma in an external electric or magnetic field. If there are no external fields the instability conditions are

$$f_0'(u_e) = 0; \int \frac{f_0'(u)}{u - u_e} du > 0; \; f_0''(u_e) > 0,$$

where $f_0(u) = \int f(\mathbf{v})\, d\mathbf{v}$ (here, $f(\mathbf{v})$ is the distribution function; $\mathbf{v}_\perp$ is the velocity component perpendicular to the wave vector $\mathbf{k}$ and $\underline{u}$ is the velocity component parallel to $\mathbf{k}$, i.e., $\mathbf{v}_\parallel$).

The conditions $f'_0(u_e) = 0$ and $f''_0(u_e) > 0$ mean that there is a velocity region $v > u_e$ in which $f'_0(v) > 0$. If $f'_0(v = V_{ph}) > 0$, the number of particles moving faster than the wave, and thus able to feed energy to the wave, is greater than the number of particles moving slower than the wave and capable of absorbing energy from it; this situation leads to a growth of the oscillations in time, i.e., an instability. The condition $\int \frac{f_0'(u)\, du}{u - u_e} > 0$ implies the possibility of propagation in the plasma of waves with phase velocities $v_{ph} > u_e$.

The nature of an instability is important for both theoretical and practical reasons.* An instability is absolute if an initial perturbation increases in time at any fixed point in space. However, if the initial perturbation grows but also moves in the direction of motion of the beam, so that it diminishes in time at any given point in space, it is a convective instability. In the case of a convective instability, a perturbation that has not had time to grow to high values can be carried out of the system. The method of distinguishing between absolute and convective instabilities given by Landau and Lifshits [36] reduces to an investigation of the asumptotic behavior ($t \to \infty$) of the integral $\int \exp[-i\omega(k) \times t]\, dk$ that describes the wave packet.

The instability is absolute if this integral grows without limit as $t \to \infty$. If the integral remains finite as $t \to \infty$ the instability is convective.

It has been shown by Sturrock [37] that the interaction of two opposing beams leads to an absolute instability; on the other hand the interaction of two beams moving in the same direction leads to a convective instability. In general, an absolute instability arises in cases where some feedback mechanism operates.

Investigations of the interaction of a beam with a hot plasma, carried out by the author together with V. I. Kurilko and V. D. Shapiro [38], and by Sturrock [39], have shown that the instability in this case is convective. The instability associated with a self-modulated electron-ion beam is also convective.

In a number of cases, it is difficult to establish whether a wave is attenuated or amplified because the dispersion equation allows a growing solution even in a system in which there are no energy sources to provide a growing wave. For example, this is the case in the penetration of a high-frequency field into a plasma at frequencies $\omega < \omega_0$ or in the propagation of a wave in waveguides beyond cutoff. In such cases, making use of the radiation condition we retain only the solution corresponding to attenuation. However, when a beam moves through an infinite system the usual radiation conditions do not hold and in order to distinguish the amplified waves we must investigate the behavior of a perturbation in the form of a wave packet. Amplification occurs only when a perturbation described by a wave packet vanishes as $x \to \infty$ for any given time $\underline{t}$. If this requirement is not met a growing wave can not exist in the system for $x \to \infty$.

* A system is unstable with respect to small perturbations [proportional to exp. $(-i\omega t + ikx)$], if the dispersion equation for the system $D(\omega, k) = 0$ allows complex solutions for ω or k. If the frequency ω is complex for some region in which k is real the instability can be absolute or convective.

It has been shown by V. I. Kurilko [40] for example, that when a plasma moves through a plasma waveguide, the complex values of $\underline{k}$ correspond to evanescence rather than amplification. If a plasma moves in a medium with a dielectric constant ϵ in crossed electric and magnetic fields ($V_0 > \frac{c}{\sqrt{\epsilon}}$ or $V_0 < \frac{c}{\sqrt{\epsilon}}$ it is found that real values of ω correspond to complex values of $\underline{k}$. However, amplification occurs only when $V_0 > \frac{c}{\sqrt{\epsilon}}$ while $V_0 <$ $< \frac{c}{\sqrt{\epsilon}}$ corresponds to evanescence [41].

Criteria for distinguishing between gain and evanescence and a simple method for distinguishing between absolute and convective instabilities have been given by Sturrock [37]. A comprehensive discussion of these criteria and their limits of applicability has been given by R. V. Polovin [41].

4. Above, we have considered the interaction of infinite beams and plasmas. For this reason, strictly speaking the relations we have obtained apply only when the geometrical dimensions of the system $L_{\parallel}$ and $L_{\perp}$ are much greater than a wavelength, that is to say $\kappa_{\parallel} L_{\parallel} \gg 1$, $\kappa_{\perp} L_{\perp} \gg 1$.

These conditions are not satisfied in many systems and for this reason there is a considerable discrepancy between the theoretical and experimental results. The most striking difference between finite and infinite plasmas is found in the absence of a magnetic field. Slow transverse waves cannot propagate in an infinite plasma in the absence of a magnetic field because $\epsilon = 1 - \frac{\omega_0^2}{\omega^2} < 1$ at all frequencies. Obviously, under these conditions there cannot be an effective interaction between free particles and waves in the plasma; in particular, the Cerenkov condition cannot be satisfied. *

If the plasma is bounded in the radial direction, slow waves can propagate in spite of the fact that ϵ can be smaller than unity and even negative in the region occupied by the plasma. A similar situation obtains in a plasma bounded in the direction of propagation of the wave, in particular, a spatially periodic plasma. In this case the system is again capable of propagating slow waves even when the dielectric constant is smaller than unity or negative; in addition, a system of this kind exhibits the properties of an anisotropic medium.

The dispersion properties of a bounded plasma in a magnetic field determined by the anisotropy and gyromagnetic effects of the medium must be considered in conjunction with the waveguide properties associated with the geometry of the system. This again leads to a marked contrast in the dispersion properties of finite and infinite plasmas. Inasmuch as the elementary processes responsible for the interaction of the beam with the plasma are sensitive to the dispersion of the system, i.e., the dependence of phase velocity on frequency, one expects that the instability criteria will be modified in going from an infinite plasma to a finite plasma (in particular, the critical velocity and the beam current); one expects that the frequency spectra and growth rates would also be modified.

Investigations of instabilities in finite beam-plasma systems have shown that if the wavelength in the plasma (V_0/ω_0) is comparable with the beam radius $\underline{a}$ then the wavelength corresponding to the onset of instabilities becomes greater and the growth rate becomes smaller. For example, in the electron-ion beams which have been considered by G. I. Budker [42], the ratio of growth rates for a finite plasma and an infinite plasma is

$$\frac{Im\omega\,(a \ll \lambda)}{Im\omega\,(a \gg \lambda)} \simeq \frac{V_0}{\omega_0 a}\, e^{-\frac{2V_0^2}{\omega_0^2 a^2}}\;;\quad \frac{\omega_0 a}{V_0} \ll 1.$$

In the excitation of longitudinal plasma waves by a beam, a situation which has been considered by M. F. Gorbatenko [17] and by Sturrock [39] and in [43], the reduction in growth rate can be quite large — a factor of 5 or 10. The amplitude of the waves is thus reduced markedly. The parameters can be chosen in such a way that the minimum wavelength is greater than the length of the system. Under these conditions the instabilities in

* According to Neufeld and Doyle [77], when a beam interacts with a plasma it is possible to excite electromagnetic waves under these conditions: In contrast with the case of an individual particle moving through a plasma, the presence of a beam in the plasma changes the dielectric constant and can reduce the phase velocity to values equal to the velocities of particles in the beam.

question will not be excited. This feature of the interaction of finite beams with a plasma is important in connection with the search for methods for suppressing plasma instabilities.

5. In spite of the successes which have been achieved in the theory of particle-plasma interactions, the discovery of various new instabilities, and the experimental verification of the basic theory, our level of understanding in this field is still not sufficient to allow evaluation of these instabilities in processes occurring in various kinds of discharges. This situation is a result of the fact that most of the analyses that have been carried out can only determine the spectrum of excited oscillations and the growth rates. These analyses do not allow us to determine one of the most important characteristics — the oscillation amplitudes. To determine these amplitudes we must know the energy spectrum of the initial fluctuations and must take account of the feedback effect of the oscillations on the plasma distribution function and the motion of the beam particles; the transition from linear to nonlinear regimes must also be considered and the amplitude of the stationary oscillations must be known.

It should be noted that nonlinear effects become important at relatively low electric fields. For nonresonant plasma waves the criterion for linearity is $\dfrac{eE_0\lambda}{mc^2\beta_{ph}\left(1-\dfrac{V_0}{V_{ph}}\right)^2} \ll 1$. Hence, nonlinear effects are very important at long wavelengths and small phase velocities. In most cases the excitation conditions reduce to the requirement $V_0 \gtrsim V_{ph}$, so that the role of nonlinear effects in the presence of beams becomes still more important. It can be shown that in the case of ion oscillations nonlinear effects appear at very high field intensities. Actually, however, nonlinear effects should appear even at small intensities since the ion interaction is strongest with slow waves and, at the low frequencies corresponding to ion oscillations, slow waves imply long wavelengths λ. For example, with $\beta_{ph} \simeq 10^{-3}$, we have $\lambda \simeq 10^3$ and $E_{cr} < 10$ v/cm. Nonlinear effects are almost certain to appear at resonances. For example, in the presence of a magnetic field the criterion for nonlinearity contains the factor $\left(1-\dfrac{\omega_H}{\omega}\right)^{-1}$.*

As the amplitude of the excited wave increases, a number of nonlinear effects appear that tend to weaken the instability [45-48]. Since the phase velocity of the wave depends on its amplitude, as the amplitude increases the synchronism between the beam and the wave is disturbed and the effectiveness of the interaction is reduced. Synchronism can also be distributed because of a reduction in beam velocity resulting from the loss of energy in the excitation of oscillations. The feedback effect of the excited oscillations on the distribution function for the electrons in the beam means that the number of particles giving energy to the wave is reduced while the number of particles absorbing energy from the wave is increased. Thus, the distribution function is equalized in the region $V \simeq V_{ph}$ and the instability is suppressed [48, 45, 46]. Nonlinear effects in a beam — plasma interaction also tend to increase the temperature of the beam and the plasma even when there are no binary collisions.

The first and third mechanisms are important when $\dfrac{V_{T_1}}{V_0} \ll \dfrac{\delta}{\omega}$; the second mechanism is important when $\dfrac{V_{T_1}}{V_0} \gg \dfrac{\delta}{\omega}$.

These mechanisms are listed in Table 4 for purposes of illustration.

Examination of this table indicates that, in general, nonlinear effects tend to do the following: 1) reduce growth rates, 2) limit the ordered velocity of the beam and the reduction in conductivity σ ($\sigma = I/E$) of the plasma due to the conversion of energy of ordered motion into oscillation energy, and 3) increase beam temperature.

These conclusions apply for small nonlinearities only; it is still necessary to develop a theory for arbitrary nonlinearities. The existence condition for arbitrary nonlinear periodic solutions for the interaction in question has been given in [50]. At the present time the problem of beam interaction with a plasma for an arbitrary nonlinearity has been treated only for the excitation of stationary electron and ion longitudinal oscillations. This analysis has made it possible to determine the maximum amplitude of the field, taking account of the thermal motion and the maximum field gradients which are proportional to the variation of plasma density (see Table 5).

* These nonlinear effects has been observed experimentally by O. G. Zagorodnov, Ya. B. Fainberg, B. I. Ivanov and L. I. Bolotin [44].

TABLE 4. Nonlinear Effects in Beam-Plasma Interactions

Type of interaction	Retardation of the beam (ΔV)	Temp. increase ($\theta_{\parallel}$; $\theta_{\perp}$)	Relaxation time (τ_{rel})	Increment	$v_{ph}(E)$	Lit. reference
Electron beam in ion plasma ($E_0 > E_{cr}$; $\mu M = m$; $E_q = en_0^{2/3}$; $\lambda_D^2 E_D = e$; $\tau = \omega_0 t$)	$V_0 \frac{\theta_0}{\theta_\perp}\left(\frac{E_q}{E_0}\right)^3 \times \frac{e^{\alpha\tau}}{\alpha\tau^{5/2}}$; $\alpha = 0.05$	$\theta_{\parallel} = \theta_0\left(\frac{E_q}{E_0}\right)^3 \frac{e^{\alpha\tau}}{\tau^{7/2}}$; $\theta_\perp = \theta_0\left(\frac{E_D e^{\alpha\tau}}{E_0 \tau^{3/2}}\right)^{1/2}$	$\frac{1}{\alpha\omega_0} \ln\left(\frac{\theta_\perp}{\theta_0} \times \frac{E_0^3}{E_q^3}\alpha^{-5/2}\right)$	—	$V_0 \mu^{1/3} 2^{-4/3} \times \left(1 + \frac{27}{16} \times \frac{2^{1/3} e^2 E_k^2 F^*}{m^2 V_0^2 \omega_0^2 \mu^{1/3}}\right)$	[23]; [45]
Monoenergetic beam in a plasma $\left(\frac{V_{T1}}{V_0} \ll \mathcal{E} = \left(\frac{n_1}{n_0}\right)^{1/3}; \omega_0 t = \tau\right)$	—	$\theta_{\parallel} = \frac{\mathcal{E}^{1/2}\theta_0 \omega_0^5 d^2}{15 n_0 V_0^5} \times \left(1 + \frac{\mathcal{E} m V_0^2}{\theta_0}\right) \frac{e^{\mathcal{E}\tau}}{\tau^{5/2}}$	$\frac{1}{\omega_0 \mathcal{E}} \ln \times \left(\frac{m V_0^2}{\theta_0 + \mathcal{E} m V_0^2} \times \frac{n_0 V_0^5 \tau^5}{\omega_0^5 d^2} \mathcal{E}^{3/2}\right)$	$\mathcal{E}\omega_0\left(1 - \frac{e^2 E_k^2 F}{8 \mathcal{E}^3 m^2 V_0^2 \omega_0^2}\right)$	$V_0\left(1 - \mathcal{E} 2^{-4/3} - \frac{5}{8} \frac{e^2 E_k^2 F}{\mathcal{E}^3 m^2 V_0^2 \omega_0^2}\right)$	[46]; [47]
Ionacoustic oscillations (monochromatic wave)	—	$\theta_i \sim \frac{e^2 E_k^2}{M\omega^2} e^{2\int \delta_k d\tau}$	—	$\frac{\delta_k(t)}{\delta_k(0)} \simeq \exp \times \left\{-\frac{e^2 E_k^2 k^2}{m^2} \times \int_0^t \frac{d\tau}{\delta_k^3} \exp \times \left[2\int_0^\tau \delta_k d\tau'\right]\right\}$	—	[48]; [45]
High-frequency oscillations of an electron beam with a plasma ($\omega \simeq -\omega_H + k_{\parallel} V_0$)	$\frac{\Delta\theta_\perp}{m V_0}$	$\frac{\Delta\theta_\perp}{\theta_0} = \frac{3\sqrt{2}}{\pi} \frac{\omega_H^3}{n_1 V_0^3} \times \frac{1}{\tau} \exp\left[\frac{5}{8} \times \left(\frac{\omega_0}{\omega_H} \frac{n_1}{n_0}\right)^{1/2} \tau\right]$	—	—	—	[49]

* $F = \exp\left\{2\int_0^t \delta_k \, d\tau\right\}$

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TABLE 5. Beam Plasma Interaction for Arbitrary Nonlinearity

Type of interaction	E^2_{max}	$\left(\frac{dE}{dx}\right)_{max}$	Example ($V_0=10^9$; $n_0=10^9$; $n_\pm=10^{11}$)	Literature reference
Electron oscillations in a plasma	$4\pi n_+ m V_{ph}^2\left[1-\left(\frac{8V_T}{\pi V_{ph}}\right)^{1/2}\frac{n_-}{n_+}\Gamma\left(\frac{3}{4}\right)\right]$	$4\pi n_+ e\left(\frac{V_0}{2\pi V_{ph}}\right)^{1/2}\frac{n_-}{n_+}\Gamma\left(\frac{1}{4}\right)$	$V_{ph}=1.1\cdot10^9$; $V_T=10$; $E\simeq10^4\frac{V}{cm}$	[51]
Electron oscillations in a plasma with a beam	$4\pi m(V_0-V_{ph})^2\times\left[n_1-n_-\frac{V_T}{2\sqrt{\pi}V_{ph}}\left(1-\frac{V_0}{V_{ph}}\right)^2\right]$	∞	$E\simeq100\frac{V}{cm}$	[51]
Ion oscillations	$4\pi M V_{ph}^2 n_+$	∞	$E\simeq10^4\frac{V}{cm}(V_{ph}=3\cdot10^7)$	[52, 53]

Examination of Table 5 indicates that the amplitudes of the stationary oscillations can be very high. For example, at a plasma density $n\simeq10^{14}$ and $V_{ph}\simeq\simeq10^8$, we find $E_{max}\simeq30$ kv/cm. There is a maximum field for longitudinal waves above which the solutions are no longer unique. Since shock waves cannot appear in the one-dimensional case (if ion motion is not taken into account), the nonunique solutions would appear to correspond to opposing particle streams. It also follows from Table 5 that as the number of streams increases, the field intensity at which beam breakup occurs is reduced. These effects are of great importance in the development of new methods of plasma thermalization and the realization of CTR with opposing particle streams.

An important question is the stability of high-amplitude longitudinal waves that are excited by beams. Recent studies of high-amplitude longitudinal waves excited by a monoenergetic beam [54, 55] show that these waves are unstable, at least, against perturbations with wavelengths appreciably smaller than the wavelength of the stationary oscillations. The nonlinear solutions in the form of bounded pulses excited in the interaction of a beam with a plasma are also unstable. Since the analysis of nonlinear problems is a problem of great mathematical difficulty, the study of transitions from linear regimes to nonlinear regimes, the effects of spectral decay,* and the formation of opposing beams and breakup of the particle streams are most conveniently carried out by means of high-speed computing machines. An investigation of the formation of opposing beams and the thermalization of plasma at high oscillation amplitudes [23, 56] shows that the strong interaction between individual plasma layers produces a relative motion which, in turn, converts the initial wave energy into energy of relative motion of the individual layers. The relaxation time for this process is very short. For example, [56], if the initial amplitude of the oscillations is 7% greater than the critical amplitude, 70-80% of the wave energy is transformed into energy of relative motion within 10 Langmuir periods. If a relatively small disordered motion is superposed on the initial oscillation (additional energy amounting to about 5% of the initial wave energy) the relaxation time is reduced to a single period of the high-frequency oscillations. Thus, the mechanism under discussion is very effective for transforming the energy of ordered oscillatory motion into energy of relative motion of plasma particles.

* Spectral-decay is the name given to the nonlinear interaction of waves with nonparallel wave vectors, which leads to the generation of new waves (this process is accompanied by the dissipation of the energy of the initial waves in a time of the order of 10^{-8} sec [76]).

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The results cited above refer to electron oscillations. It would appear that there are conditions for which similar processes would obtain for ion oscillations. In this case, the important thing would be the long-lived relative motion of the ions, a feature of interest in the development of methods for realizing CTR.

6. Before analyzing the available experimental data we shall dwell briefly on possible methods of suppressing instabilities; this is the most important arpect of the problem. Work on this problem has only started, so that the considerations given below are necessarily qualitative. In the final analysis, instabilities arise as a result of one or more basic interaction mechanisms together with phase focusing or particle bunching, the latter causing the interaction to be enhanced because of coherence. Thus, to avoid instabilities we try to produce conditions for which these basic mechanisms cannot operate and for which phase focusing or bunching of the particles cannot occur.

If the Cerenkov effect and the anomalous Doppler effect are to operate,the velocity of the particle or oscillator must be greater than or equal to the phase velocity of the wave. Hence, an instability can be avoided if this condition is disturbed by changing the velocity of the wave or the velocity of the particle. Changes in the dispersion properties, in particular the phase velocity of a wave, can be achieved by varying the system geometry (for finite beams and plasma), by placing the plasma in a magnetic shell, by utilizing the dependence of phase velocity on amplitude (this effect can automatically limit the instability because an increase in amplitude causes a change in phase velocity and thereby disturbs the synchronism between the field and the wave), and by changing the relative concentration of various components in a multi-component (for example, DT or DH) plasma.

By changing the phase velocity of the wave we can completely suppress the instability or, at least, modify its frequency spectrum and reduce the growth rate. By changing the velocity of the beam particles we can disturb the condition $V \simeq V_{ph}$ and completely avoid the instability or modify the oscillation spectrum markedly. Ion oscillations are excited if the particle velocity lies in the range $V_{Te}\mu^{1/2} < V_0 < V_{Te}$. If the particle velocity $V_0 > V_{Te}$, then electron oscillations are excited, but ion oscillations are not. The beam velocity may change automatically as it is retarded. Furthermore, there may be a rapid increase in beam velocity during the relaxation time τ_{rel}, during which corresponding instabilities cannot develop. From this point of view the stellarator is at an important disadvantage because the electron velocities in this machine vary slowly from $v = 0$ to v_{max} and under these conditions a succession of instabilities may be encountered. Injection of a plasma in the stellarator at some finite velocity would reduce the spectrum of instabilities and would facilitate the suppression of instabilities.

The conditions for the basic mechanisms such as the Cerenkov effect and the Doppler effect can also be disturbed as a result of nonlinear processes associated with the motion of the particles and oscillators,and nonlinear effects associated with the propagation of waves in the plasma. As is well-known [57], the basic mechanisms responsible for instabilities can be interpreted in terms of a resonance between the characteristic oscillations of the system (plasma in the present case) and a driving force, which is associated with the motion of the charged particles and oscillators. In this interpretation the Cerenkov condition and the Doppler effect become resonance relations. The nonlinear effects indicated above disturb the resonance relationships and thus serve to inhibit instabilities. On the other hand, it is possible that other nonlinear resonances can arise; these require further investigation.

Another way to avoid instabilities is to prevent the phase focusing (particle bunching) process which is responsible for the coherent interactions.

The following techniques may be capable of weakening instabilities or even suppressing them entirely:

1) Introducing an artificial spread in beam velocity. For purposes of illustration we compare the growth rate $\delta(V_{Te} = 0)$ when a plasma is excited by a monoenergetic beam and when it is excited by a beam with a weak ($V_{Te} < V_0$) thermal spread δ:

$$\frac{V_{Te}}{V_0} \gg \left(\frac{n_1}{n_0}\right)^{1/3}; \quad \delta \sim \left[\left(\frac{n_1}{n_0}\right)^{1/3} \frac{V_0}{V_{Te}}\right]^2 \delta\,(V_{Te}=0).$$

It is evident that a velocity spread tends to reduce the growth rate considerably or can even remove it completely;*

2) Premodulation of the beam. It is well-known that the exponential growth of an instability is due to the fact that the field caused by the onset of the instability increases the particle bunching and that the enhanced

* It should be noted, however, that in a number of cases a large thermal spread in the beam velocity can lead to the production of new instabilities; in general however, these are characterized by small growth rates.

bunching leads to further amplification of the field. Premodulation of a beam at some desired frequency serves to inhibit the bunching at other frequencies and can thus serve to suppress a whole spectrum of instabilities. In this case we must make sure that the coherence conditions $\underline{a} < \lambda_{pl}$ are not satisfied for characteristic plasma oscillations. Premodulation of the beam may make it possible to suppress an instability at some given frequency. This result can be accomplished if the wavelength of the modulation λ_m is made $\lambda_m = a^* / 2$. It should be noted that in avoiding ordinary instabilities we may produce instabilities associated with parametric resonances. However, the bandwidths of parametric resonances are small so that under actual conditions the effects of inhomogeneities or collisions can suppress these instabilities;

3) Variable system geometry. As we have indicated above, the frequency spectra and growth rates are completely different for finite and infinite plasmas. By changing the geometry of a system we can produce conditions for which the minimum wavelength of an instability becomes greater than the dimensions of the system, so that the instability cannot be supported;

4) Feedback effect of the excited oscillations on the distribution function causing the number of particles giving energy to the wave to become equal to the number of particles absorbing energy from the wave;

5) Exploiting the nonlinear nature of the motion of particles and oscillators;

6) Varying the phase velocity along the system in such a way that $\frac{\partial V_{ph}}{\partial z} < 0$. In actual systems this condition can be easily realized by changing the plasma parameters, for example the density. In a number of systems it can be satisfied automatically.

Comparison of the Theoretical and Experimental Results

7. Because of the complexity of the processes involved in the interaction of charged particles with a plasma and the importance of nonlinear effects, the experimental investigations in this field are of extreme importance.

The basic problems of the experimenter are to discover instabilities, to determine the conditions under which they arise, to determine their frequency spectra, growth rates, and relaxation lengths, to measure the loss of energy of ordered electron motion in the excitation of oscillations, and to determine the effect of these instabilities on plasma conductivity and diffusion. This information is then used in the important problem of devising techniques for suppressing instabilities.

As is well known, experimental research on plasma oscillations started with the work of Langmuir and Penning in 1921-1929 [58]. An investigation of oscillation processes in plasma carried out in 1939 by Merrill and Webb [59] was of great value. The instabilities due to excitation of longitudinal plasma waves by a mean of electrons in a uniform plasma with no magnetic field were demonstrated experimentally in 1957-1958. The basic characteristics of the instabilities were determined in this work.

We now describe some of the general results obtained in this work.

In an experiment carried out by Kharchenko, Nikolaev, Lutsenko and Padenko and the author [60] it was shown that an initially unmodulated electron beam passing through a plasma (with no magnetic field) excites longitudinal high-frequency oscillations at frequencies close to the Langmuir frequency. The excitation of these oscillations is accompanied by self-modulation of the beam. The energy loss per beam particle was approximately 100 ev/cm; this is to be compared with the energy loss of a single charged particle for this case — approximately 10^{-6} ev/cm. The high losses are due to the coherent nature of the interaction between the beam and the plasma that results from the self-modulation caused by plasma oscillations. In these experiments, the effect of plasma inhomogeneities, in particular the effect of sheaths in the region of the cathode fall, was avoided by using a high-frequency discharge and injecting an electron beam from outside at an energy of 50-70 kev, an energy appreciably greater than the energy acquired by an electron in the boundary Debye layer. The initial perturbations were due to fluctuations in the plasma and in the beam.

* The quantity $\underline{a}$ is the length of a particle bunch.

Papers by Demirkhanov, Gevorkov, Popov, et al. [62] describe the observation of longitudinal oscillations, the determination of the relaxation length, and the production of harmonics of the excited waves.

The spatial structure of the excitation region and the energy lost by a beam in moving through the plasma have been studied by Gabovich and Pasechnik [63].

The amplification of electromagnetic waves due to interaction of a beam with longitudinal waves in a plasma has been observed in experiments by Boyd, Field, and Gould and by Kislov, Bogdanov, and Chernov [65,66]. In these experiments the initial perturbation was imposed by an external source and growing high-frequency longitudinal waves were excited in the system.*

These experiments were found to be in contradiction to the experiments carried out by Looney and Brown [67] in which beam instabilities were not observed. The reason for this discrepancy is the fact that Looney and Brown used beams with small transverse dimensions. We have indicated earlier that the growth rate is diminished when the beam radius is reduced. The theoretical growth rate for the Looney and Brown experiments is approximately 2.5 cm^{-1}. Hence the field should increase by one order of magnitude for a beam-plasma interaction length of 1.5 cm. In these experiments the initial perturbation was due only to fluctuations in the beam and plasma so that the oscillation amplitudes were small and difficult to detect. In contrast with the Looney-Brown experiments, in all the experiments listed above the beam radius and interaction length were quite larger. The theoretical gain in these experiments is approximately 10^3-10^5.

The theoretical and experimental growth rates are found to be in satisfactory agreement (Table 6). There are some discrepancies in the experimental data obtained by different authors and between the experimental data and the theoretical values for the relaxation length for the beam-plasma interaction, i.e., the distance in which the energy of the ordered motion is converted into oscillation energy. Before a more meaningful comparison of the experimental and theoretical data can be made it will be necessary to refine the measurements of beam velocity spread and plasma temperatures because these parameters have an important effect on relaxation length.

Experiments on the interaction of charged-particle beams and a plasma in a magnetic field were carried out in 1959-1960 (I. F. Kharchenko et al.) [68]. In these experiments both low-frequency and high-frequency oscillations were excited and both modulated and unmodulated beams were used. The high-frequency spectrum is described well by the theoretical relation $\omega \simeq \sqrt{\omega_0^2 + \omega_H^2}$; $\omega \simeq \omega_H$. These oscillations are especially strong if $\omega_0 \simeq \omega_H$ for the case $\omega \simeq \sqrt{\omega_0^2 + \omega_H^2}$. The low-frequency oscillations are distributed in bands at tens, hundreds and thousands of kilocycles. These occur near regions corresponding to ion-cyclotron and magnetohydrodynamic waves. In order to obtain more accurate information on the kinds of waves that are excited it will be necessary to measure the wavelength (β_{ph}) and to determine the angular dependence of the electromagnetic fields.

Because the oscillation frequencies are low, in investigations of beam-plasma interactions under pulsed conditions one can observe the development of an instability and determine the growth time. Oscillations at frequencies of 100 kc are characterized by an instability development time of approximately 50 μsec, i.e., approximately ten oscillation periods [49].

In addition to the observations of low-frequency and high-frequency oscillations cited above, there are observations of parametric oscillations in a modulated beam.

Examination of Table 6 reveals the following:

1) At the present time most of the instabilities analyzed above have been observed experimentally;

2) The basic features of the instabilities (excitation conditions, growth rates, frequency spectra, relaxation lengths) have been shown experimentally to be in agreement with the theoretical results in most cases;

3) The development of an instability is accompanied by oscillations and a marked reduction in the energy of ordered motion of the beam. Even in a rarified plasma ($n_0 \simeq 10^{11}$) the losses are approximately 100 ev/cm per particle;

* The growth rate in space was determined from the ratio of powers at the output and input of the system.

TABLE 6. Comparison of Theoretical and Experimental Values of Growth Rates and Relaxation Lengths.

Form of oscillation	Frequency	Growth rate		Relaxation length		Lit. ref.
		experiment	theory	experiment	theory	
Amplification of longitudinal waves in a beam by a plasma	$\sim \omega_0$ $(2 \cdot 10^{10})$	—	—	—	—	[64]
Excitation of longitudinal waves in a plasma by a beam	$\sim \omega_0$ $(2 \cdot 10^{10})$	$Im\,\omega \simeq 0.16\omega_0$	$Im\,\omega \simeq 0.15\omega_0$	$\frac{d\mathcal{E}}{dx} \simeq 50\,\frac{eV}{cm}$	$\frac{d\mathcal{E}}{dx} \simeq 100\,\frac{eV}{cm}$	[60]
Amplification of longitudinal waves in a beam by plasma	$\sim \omega_0$ $(2 \cdot 10^{10})$	$Imk \simeq 0.2\ cm^{-1}$	$Imk \simeq 0.15\ cm^{-1}$	—	—	[65]
Excitation of longitudinal waves in a plasma by a beam	$\sim \omega_0$ $(1.5 \cdot 10^{10})$	$Imk \simeq 0.12\ cm^{-1}$	$Imk \simeq 0.15\ cm^{-1}$	7 cm	8.4 cm	[61]
Scattering of a beam on plasma oscillations	$\sim \omega_0$ $3 \cdot 10^9$ to $3 \cdot 10^{10}$	—	—	1 cm	4—10 cm	[63]
High-frequency oscillations in a magnetic field	$\omega \simeq \omega_H\ (10^{10})$; $\omega \simeq (\omega_0^2 + \omega_H^2)^{1/2}$ $(2\ \text{to}\ 4 \cdot 10^{10})$	1 to $2 \cdot 10^8$; 1 to $2 \cdot 10^9$	$0.5 \cdot 10^9$	—	—	[68]
Low-frequency oscillations in a magnetic field	$\sim (6\ \text{to}\ 120) \cdot 10^3$; $\sim \Omega_H\ (6\ \text{to}\ 30) \cdot 10^5$	1 to $20 \cdot 10^3$ $(n0^{\Delta\omega/\omega})$	—	$\delta_{rel} \simeq 5 \cdot 10^{-6}$	—	[68]
High-frequency oscillations in a magnetic field	$\sim \omega_H\ (4.2 \cdot 10^9)$; $\sim (\omega_0^2 + \omega_H^2)^{1/2}$	$\sim 10^8$	—	—	—	[69]
Low-frequency oscillations in a magnetic field	$\omega_H < \omega < (\omega_0^2 + \omega_H^2)^{1/2}$	$Imk \simeq 0{,}7$ $(\omega \simeq \omega_0)$	$Imk \simeq 0.7$ $(\omega \simeq \omega_0)$	—	—	[70]
Low-frequency ion oscillations	$\omega \simeq 6 \cdot 10^5$ $(\sim \omega_{0i})$	—	—	—	—	[71]
High-frequency oscillations in a magnetic field	$\omega \simeq 1$ to $2 \cdot 10^9$	—	—	—	—	[72]*

* The author is indebted to S. D. Vinter for acquainting him with this work.

4) The development of an instability also leads to a marked increase in the energy of the plasma electrons. For example, in experiments on beam-plasma interactions in a magnetic field this energy is 10-20 kev [68];

5) The development of an instability is accompanied by an appreciable increase in the ion and electron flow across the magnetic field.

Thus, all the predicted "dangerous" consequences of instabilities have been established experimentally.

In addition, however, experiments that have been carried out indicate the possibility of suppressing instabilities. For example, beam modulation can serve to inhibit a whole spectrum of instabilities because the modulated beam can excite oscillations at wavelengths far from the resonance wavelength. On the other hand, modulation of beams and plasma can cause parametric instabilities, but since the width of the excitation region is very small, the presence of a density inhomogeneity in the plasma serves to suppress these parametric instabilities. A number of instabilities are also suppressed by a relatively small spread in beam velocity. In general, the growth rate is a sensitive function of system geometry, i.e., the radius of the beam and the plasma; hence, an instability can also be suppressed by choosing appropriate values for these parameters. Finally, a number of experiments indicate that the increasing amplitude of the excited waves leads to nonlinear effects which then limit the development of instability.

Further research into instabilities and techniques for suppressing instabilities will require experiments in which the plasma density can be increased to $n_0 \simeq 10^{13} - 10^{14}$ and in which the degree of ionization can be made 50-100%. It will also be necessary to increase the electron current to $I \simeq 10^2 - 10^3$ amp. These experiments will probably be carried out most conveniently in plasmas produced by powerful high-frequency discharges, in a cesium plasma, or in a plasma formed in a linear betatron. It will also be necessary to carry out experiments in which direct observations can be made of the effect of oscillations on conductivity and diffusion in a high-density plasma.

We have been speaking of experiments in which beam-plasma interactions were investigated in systems designed especially for this purpose, in which the interaction was observed in "pure" form, uncomplicated by other processes.

There are experiments in which beam-plasma interactions have been studied directly in systems designed for investigating CTR; among these we may mention the work of Bernstein et al. [73] and Ellis et al. [74]. The most important result of this work is the experimental proof that instabilities arise in the stellerator at currents appreciably below the critical current associated with magnetohydrodynamic instabilities. The observed instabilities are accompanied by an increase in the high-frequency noise level, which is appreciably above the thermal noise level. Radiation is observed in the frequency region 10,000-70,000 Mc corresponding to Langmuir oscillations. Measurements of the x-ray radiation show that the instability is accompanied by the appearance of electrons with high energies — up to 3 Mev. The work by Ellis et al. [74] showed that the instability develops when conditions are satisfied for the generation of an appreciable number of runaway electrons. In this case, the energy acquired by an electron in one mean free path must be comparable with the energy of the thermal motion $\left(\gamma = \frac{E}{E_{cr}} \simeq 1\right)$. In these experiments the quantity γ is 0.1-0.2. When these values are reached the current in a stellarator falls off sharply in spite of the increasing electric field. This reduced current can be explained by assuming that the electrons lose energy in the excitation of oscillations. The time in which γ reaches the critical value and in which the sharp current reduction is observed is approximately 200-800 μsec. The experiments considered here indicate the important role of high-frequency instabilities in the stellarator. It is as yet difficult, however, to evaluate the effect of high-frequency oscillations on plasma diffusion in the stellarator.* A shortcoming of the experiments is the fact that the spectrum of excited oscillations was not investigated and that no correlation was looked for between these oscillations and the conditions for onset of an instability. Among other things, the maximum of the excited frequencies is related simply to the number of runaway electrons. These frequencies are $(\omega_{0e}'^2 + \omega_{0i}^2)^{1/3} \times \omega_{0e}^{1/3}$, where ω_{0i} is the ion Langmuir frequency, ω_{0e}' is the plasma Langmuir frequency for the plasma at rest and ω_{0e} is the Langmuir frequency of the moving plasma.

8. At the present time the main effort in beam-plasma research has been concentrated on instabilities, since these represent one of the chief stumbling blocks in attempts to achieve CTR. It should be noted, however, that the

* The low-frequency instabilities should have the greatest effect on diffusion in the stellarator.

beam-plasma interaction also provides a strong "collisionless" exchange of energy between the charged particles and the plasma and this can play a useful role. It is of both theoretical and experimental interest to investigate the use of this mode of energy exchange for plasma thermalization. As we have indicated above, when electron beams interact with a plasma the energy of the ordered electron motion can be converted into longitudinal-wave energy in a very short time (approximately 10^{-6} - 10^{-8} sec). As the amplitude of these waves increases, they can cause relative motion of electrons and ions with appreciable velocities. Relative motion also appears in instabilities due to transverse motion, for example cyclotron resonances.

An effective transfer of energy from the electron beam to the plasma ions is possible in this interaction. The dimensions of the electron bunches or the modulation wavelength a must be such that the conditions for coherent interactions are satisfied for the ion oscillations but not for the electron oscillations. It is necessary that $\lambda_e < a < \lambda_i$. In contrast with the binary collisions, under these conditions the electrons transfer most of their energy to the ions.

It is possible to develop methods of injecting charged particles into a plasma such that the coherent energy losses in motion through the plasma can become very high (100-1000 ev/cm).

Thus, the interaction of beams with a plasma can be used for injection and for heating. Here, the basic difficulty is that appreciable diffusion can be produced. It should be noted, however, that there are a number of kinds of instabilities, for example longitudinal plasma oscillations, in which there is a strong exchange of energy between the beam and the plasma which does not directly increase diffusion.

The considerations given above may not be completely justified at the present time, but in our opinion they are worthy of further investigation.

The interaction of charged-particle beams with a plasma is also of interest from the point of view of plasma diagnostics. It is possible to determine the plasma density, the collision frequency, and the velocity distributions of the electrons and ions. The oscillations grow exponentially in a beam-plasma interaction and appear when the growth rate is greater than the collision rate; hence measurement of the collision frequency at the excitation threshold should be a very sensitive diagnostic technique.

By inverting the dispersion equation it is possible to obtain a relation between $f_0(v)$ and the phase and group velocities of waves in a plasma and the growth rates [75]. Hence, by measuring the frequency dependence of the phase velocity and the growth rate it may be possible to determine the plasma particle distribution function.

Although the other aspects of beam-plasma interactions are interesting and important, the most difficult and pressing problem is that of suppressing instabilities.

Symbols Used in Text

$\omega_0 = \sqrt{\frac{4\pi n_0 e^2}{m}}$ is the Langmuir frequency of plasma electrons;

$\omega_{0i} = \sqrt{\frac{4\pi n_0 e^2}{M}}$ is the Langmuir frequency of plasma ions;

ω is the frequency;

ω_H is the electron Larmor frequency;

Ω_H is the Larmor ion frequency;

$\delta = \mathrm{Im}\,\omega$ is the growth rate;

δ_k is the growth rate for a wave characterized by wave vector **k** ;

$\Delta\omega$ is the width of a resonance curve $\delta(\mathrm{Re}\,\omega)$;

V_{ph} is the phase velocity of a wave in the beam direction;

$k_3 = \frac{\omega}{V_{ph}}$ is the projection of the wave vector in the beam direction;

$k_{\parallel}$ is the projection of the wave vector along fixed magnetic field;

$k_{\perp}$ is the projection of the wave vector perpendicular to fixed magnetic field;

k is the wave number;

$\mathrm{Im}\,k$ is the spatial growth rate;

V_0 is the ordered beam velocity;

v^0 is the velocity of ordered motion in direction perpendicular to fixed magnetic field;

$V_{Te,i}$ is the thermal velocity of electrons or ions;
V_{dr} is the drift velocity;
V_A is the Al'fven velocity;
n_0 is the plasma density;
n_+ is the ion background density
n_- is the density of electrons not trapped by wave;
N is the number of particles in a bunch;
n_1 is the beam density;
T_{ei} is the electron temperature or ion temperature (given in degrees in tables);
$\theta_0 = kT_e$ is the plasma electron temperature at t = 0 (here k is the Boltzmann constant);
$\theta_{\parallel}$ and $\theta_{\perp}$ is the temperature of beam electrons parallel and perpendicular to the direction of beam motion, respectively;
$\Delta\theta_{\perp}$ is the change in transverse beam temperature;
E_0 is the fixed electric field;
E_k is the amplitude of the wave corresponding to a given wave vector **k**;
E_{max} is the field intensity at which stream breakup starts in the plasma;
E is the electric field intensity;
$E_e \simeq 1.5 \cdot 10^{-8} \frac{n_0}{T_e}$ v/cm is the critical electric field;
$p_{\perp}$, $p_{\parallel}$ are momenta transverse to and along magnetic field, respectively;
θ is the angle between fixed magnetic field and direction of wave propagation;
σ is the conductivity;
$n_j(\omega)$ is the refractive index;
Γ is the gamma function;
λ_D is the Debye radius;
$\mathcal{E}$ is the particle energy;
f is the distribution function;
S is the flux of runaway electrons;
a is the radius of plasma column;
λ is the wavelength in vacuum;
$\mu = \frac{m}{M}$ is the ratio of electron mass to ion mass;
r_i is the ion Larmor radius;
$L_{\parallel}$, $L_{\perp}$ are the geometric dimensions of the system.

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MAGNETIC TRAPS WITH OPPOSING FIELDS

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Introduction

In searching for systems which would be suitable for the experimental realization of thermonuclear fusion, several conceptually very ingenious devices consisting of interesting and complex technical equipment were constructed in the past few years. Striving to find the final or almost final solution to this extremely difficult technical problem, physicists were compelled to develop systems with very large dimensions which are evacuated to the maximum attainable vacuum, and to use powerful magnetic fields with complex configurations. Such devices as "Ogra," "Zeta", or the stellarator clearly show what direction was followed in the construction of such devices.

Unfortunately, the actual properties of heated plasma are immeasurably more complex than the properties given by the idealized picture. Manifestations of various types of instability were recently detected in magnetic traps with plugs as well as in toroidal systems with longitudinal magnetic fields. Hence the understandable interest in traps with magnetic fields that increase toward the periphery, which are, at least in principle, free from some forms of instability. An additional advantage of such traps is the absence of the magnetic field in the central region, i.e., the region which contains the maximum concentration of plasma. This results in the fact that magnetic radiation losses are negligible in this case. However, considering our contemporary level of knowledge, it is hardly justifiable to persist in this argument. We are still too far removed from realizing conditions under which magnetic radiation losses would become a serious hindrance in the construction of thermonuclear generators.

Of course, the enumerated advantages cannot be provided gratuitously. Traps with rising fields are very leaky. In addition to the possible escape of particles through the plugs in the vicinity of the system's axis, a ring-shaped magnetic slit exists in the equatorial symmetry plane in traps of this type. (It is assumed that the trap is axially symmetric and that it is formed by two coils which are connected in opposition, i.e., the trap constitutes a magnetic quadrupole.)

As it was with almost all main trends in solving the problem of controlled fusion, the first ideas and assumptions were stated in our country and abroad perfectly independently and practically simultaneously. The general properties of magnetic systems where the external plasma boundary has a positive curvature were determined by L. A. Artsimovich and E. Teller. Even before the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958), O. B. Firsov [1] and Grad, Berkovich, et al. [2] considered the process of the plasma drift away from the region limited by the rising field. In particular, O. B. Firsov expressed the idea of the diffusion broadening of the magnetic slit, which is essential for traps of this type. At the same time, the experimental possibilities of constructing a small stationary trap of this type were discussed and the first experiments performed at the Institute of Atomic Energy, Academy of Sciences, USSR [3, 7]. Simultaneously, there appeared papers which were devoted to the passage of the plasma blob through magnetic fields with different configurations including fields that increase toward the periphery [4], as well as papers where the behavior of weak-ionized plasma in such fields was discussed [5]. However, in general, the pace of development in this direction was rather slow, and the above-mentioned interest in traps with opposing fields abated in the period of the last one and a half to two years. In this time, approximately ten articles which were devoted to the behavior of plasma in such devices were published in our country and in the USA [6-16]. In spite of this, the total amount of the information obtained is not great, and many problems require further careful consideration, while a systematic presentation of the accumulated experimental information is rather difficult.

We shall adopt the following order in presenting the available material: We shall first consider the qualitative behavior pattern of plasma in traps, then discuss the basic experimental facts, and, in conclusion, draw certain inferences regarding the possible trends in further research.

Behavior of Plasma in Traps with Opposing Fields

We shall assume that we have a magnetic system which is formed by two coaxial coils which are connected in opposition (Fig. 1); then, near the zero point of the field, the magnetic field components increase linearly with their coordinates:

$$H_Z = aZ;\ H_r = -\frac{a}{2} r. \tag{1}$$

We shall assume that, by means of a certain still-unknown mechanism, the hot, well-conducting plasma is accurately introduced for a very short time into the trap's center where H = 0. The plasma pushes apart the lines of force and fills the weak field region. A central region where the field is absent, and a region where the field is somewhat constricted, which is free from plasma, appear in this case (Fig. 2, a and b). The pressure balance is maintained at the plasma boundary, the corresponding currents flow along the plasma surface, and the diamagnetic plasma generation has an invariable, stable form. At this initial instant of time, the plasma departs through the ring-shaped magnetic slit, whose width is 4 ρ_e; here, ρ_e is the Larmor radius for the electrons in the slit. However, simultaneously with the outflow of plasma, another process starts – the plasma immediately begins to diffuse into the field and the field diffuses into the plasma, i.e., the mutual penetration of the plasma and the field occurs. This process can be characterized as the broadening of the magnetic slit. According to the diffusion laws, the process of slit enlargement, which is initially fast, gradually slows down in time (Fig. 2, c and d). Penetrating the transition layer, plasma leaves the trap through the widened ring-shaped slit while moving along the field's lines of force. Due to the quasineutrality, the departure of plasma in this direction takes place with ionic velocity. Pressure equilibrium is established at the boundary between "pure" plasma and the transition layer, and the plasma, like paste from a tube, is squeezed out of the trap. It appears that, under equal-pressure conditions, the rate at which the slit (or the transition layer) is broadened does not depend on the magnetic field and that it coincides with the rate at which the skin-layer is formed.

In order to understand the following, it should be noted that the Debye screening radius at the plasma's boundary is much smaller than the Larmor ion radius. Therefore, the transition-layer formation, which takes place as a result of electron – ion collisions, begins with the layer whose thickness is, at the initial moment, equal to the Larmor electron diameter. Figuratively speaking, the mobile electrons tend to leave the trap along the lines of force (through the slits), but they are retained by sluggish ions. It would seem that ions with larger Larmor radii should move faster across the field; however, they are retained by electrons.

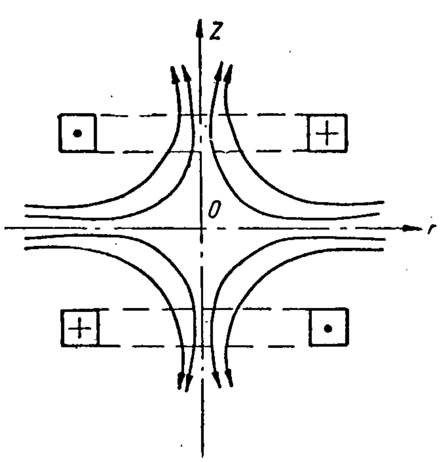

Fig. 1. Lines of force of the magnetic field in the trap.

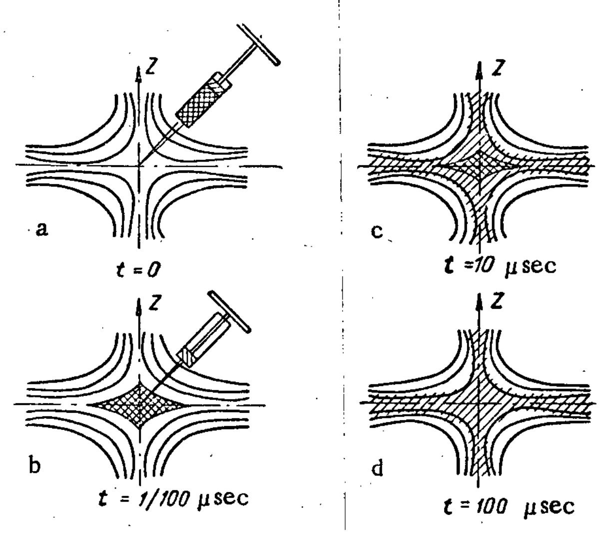

Fig. 2. "Fast" plasma injection into the trap center.

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With reference to the described qualitative picture of the situation, we can determine the time necessary for the plasma to leave the trap in dependence on the characteristic dimension R of the system, the magnetic field strength H, and the initial plasma energy W, and we can also determine the character of time changes in the plasma density.

Suitable calculations [16] show that the lifetime of plasma in the trap under these conditions is approximately proportional to the value of $(R/H)^{1/2}$, that it slowly increases with the initial energy of plasma formation, and that it is virtually independent of the plasma temperature.

In order to find the dependence of the plasma density on time, it is sufficient to solve the following equation

$$\frac{dN}{dt} = -\frac{nv_i}{4} S, \qquad (2)$$

where N is the over-all number of particles in the volume where the field is absent, n is the plasma density, v_i is the ion velocity, and S is the cross-sectional area of the magnetic slit. If we take the classical expression for the diffusion coefficient, noting that $N = nV$, where V is the variable volume of the contracting plasma, by using the condition for the equality between the plasma pressures and the field we can find the solution of the above equation.

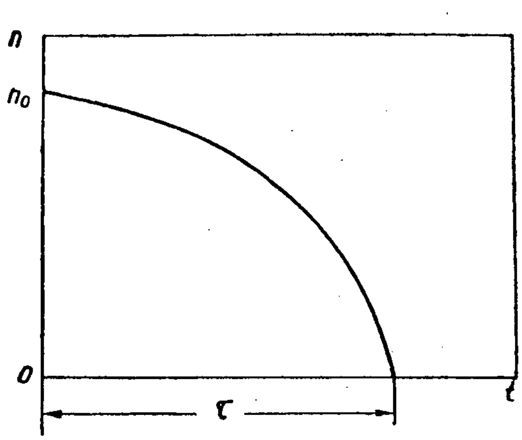

Fig. 3. Dependence of the plasma density on time. The diagram applies to a displaced-field model.

Figure 3 shows the variation of plasma density in time. The solution is characterized not by the finite time in which the plasma leaves the trap, but by the fact that the density decreases according to the exponential law.

It is understood that all that has been said above is still far from being an adequate description of the actual processes occurring in the trap. The point is that the behavior of plasma in such a trap, its stability, its lifetime, etc. are most closely related to the method used for filling the system with plasma.

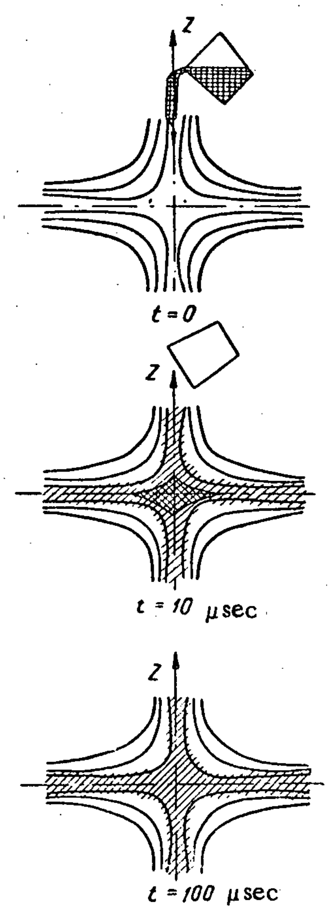

Fig. 4. "Slow" injection of plasma into the trap through an axial magnetic slit.

Various types of electrodynamic injectors for plasma injection were used in almost all experiments on traps with opposing fields. The injector types considerably differ from each other with respect to the intensity, the plasma blob velocity, and the action time. However, there is no ideal injector which would be capable of introducing very hot plasma into the trap in a very short time. Therefore, in penetrating the magnetic barrier under actual conditions, the plasma enters the trap after it has been already partially mixed with the field (Fig. 4).

The depth to which the field penetrates the plasma and the intensity of the magnetic flux, which is trapped by the plasma and which appears to be frozen in it, depend on the plasma temperature, the velocity with which the plasma moves, and the magnetic barrier magnitude. Two facts concerning the filling of traps with plasma must be mentioned. In the first place, the filling process proceeds simultaneously with the enlargement of the magnetic slit and the diffusion of plasma in all directions. In other words, the increase in the plasma density occurs simultaneously with its exit. In the second place, the presence of the macrocurrent which flows along the periphery of the plasma blob to be injected displaces to a certain extent the position of the system's center (the zero field point in vacuum).

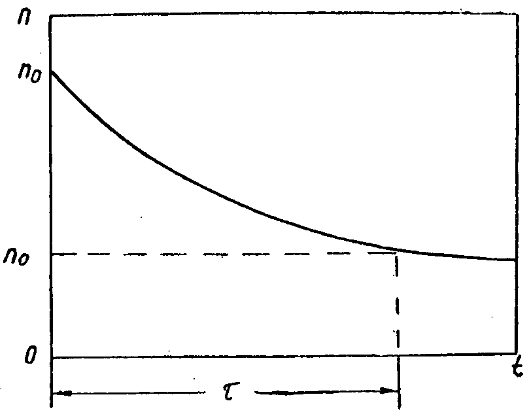

Fig. 5. Dependence of the plasma density on time. The diagram applies to plasma which is mixed with the field.

The process by which the plasma that is free from the field (if such plasma exists at all) leaves the trap will again be described by Eq. (1), but with an additional term, which depends on time and which takes into account the injector action. Also in this case, the plasma departure time remains finite.

We shall now assume that, at the end of injection, a certain volume filled with plasma that is mixed with the field will exist in the trap. We shall also assume that "pure" plasma constitutes only a small portion of the over-all quantity of plasma. Then, the process by which the trap is evacuated will be described more adequately by means of a model with a constant volume and a constant-width slit. We must remember that the slit becomes quickly enlarged at the initial stages and that, subsequently, after attaining considerable dimensions during the injection, it widens slowly. As before, the ions are not magnetized in the central region of the weak field, and their migration from one end of the slit to the other occurs without preservation of the magnetic moment. As before, the outflow of plasma takes place along the lines of force with ionic velocity, but without the displacement of plasma by the magnetic field. For such a model, the variation of the plasma density in time can be written in the following form

$$n = n_0 e^{-t/\tau}, \quad (3)$$

where τ is the characteristic departure time (Fig. 5). The value of τ is determined by the equation

$$\tau = \frac{2R}{v_i} \ln\ R/\delta + 1). \quad (4)$$

Here δ is the slit width, while the remaining notation is the same as before.

Thus, regardless of the actual pattern of processes in traps with opposing fields, the plasma must be concentrated in the central region. The plasma must depart through the annular magnetic slit. The time in which the plasma leaves the trap can be estimated for two limiting cases. In the model with "pure" plasma, the departure time is finite.

Basic Experimental Data

Table 1 provides the dimensions and the maximum magnetic field values (in the magnetic slit region) for a number of devices that have been constructed. In all except the Watteau device, plasma is injected into the trap along the axis of symmetry by means of various electrodynamic injectors. The velocity of the plasma blob is set within the range of $(0.7 \text{ to } 1.2) \cdot 10^7$ cm/sec. In the Watteau device [9], a variable magnetic field with a period of 10 μsec and with the amplitude value indicated in Table 1 was superimposed on a direct self-constricting discharge with a current intensity of 15 ka. The vacuum conditions were similar in all cases. Superhigh-vacuum techniques were not used.

Several methods were used for investigating the plasma properties in traps. By using photographic techniques including high-speed cinematography, we obtained photographs of plasma in traps at different instants of time. The use of various types of electric probes made it possible to determine the plasma density in time and its topography. Magnetic probes were used for studying the process of forcing the field out of the plasma (or the process of capturing the field) and for determining the currents in the injected plasma blobs. The use of the calorimetric method made it possible to determine the spatial pattern of plasma departure from the central regions of the trap. The spectroscopic method has been used to a very small extent until now. Partially, this is connected with the small plasma luminescence intensity under these conditions.

TABLE 1. Parameters of Some of the Magnetic Devices with Opposing Fields

Shape of the device and material of the walls	Diameter (max.), mm	Length, mm	Magnetic field, kgauss	Literature cited
Cylindrical, with rectangular insert; metal	200	1000	1.5	[7]
Cylindrical; glass	76	600	3.2	[8]
Cylindrical, with wider middle portion; glass	200	400	6.0	[11]
Cylindrical; metal	500	1500	3.5	[12]
Axially symmetric complex form; metal ("Orekh" device)	900	1200	4.5	[16]
Cylindrical; quartz	180	350	25 pulsed	[9]

We shall first consider the experimental data which confirm the capture of the plasma blob in traps and the problem of the plasma lifetime. Figure 6 shows oscillograms of the ion saturation current in the "Orekh" device [16] flowing toward an electric probe that is located in the central region. Under the assumption that the plasma temperature is constant, these curves show the variation of plasma density in time. The discharge in the injector circuit is shorted by means of a special discharger after the first half-period; thus, the injector's operating period amounts to only approximately 3 μ sec. It is obvious from these oscillograms that the plasma density attains its maximum value after the current in the injector circuit decays. The process of the decrease in density extends over a period of many tens of microseconds. Curiously, the characteristic departure time appears to be virtually independent of the magnetic field strength. Figure 7 illustrates this statement on the basis of data that were obtained by means of the same trap.

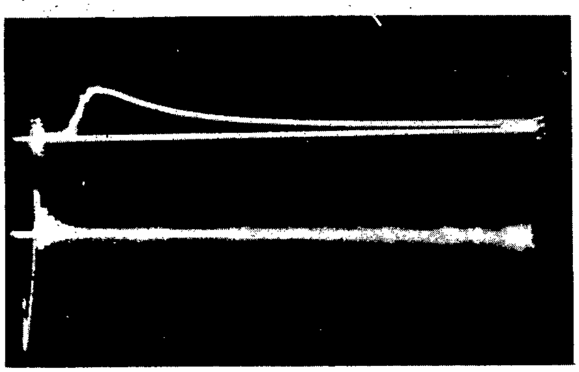

Fig. 6. Ion saturation current flowing to the probe (upper beam); current in the injector circuit (lower beam).

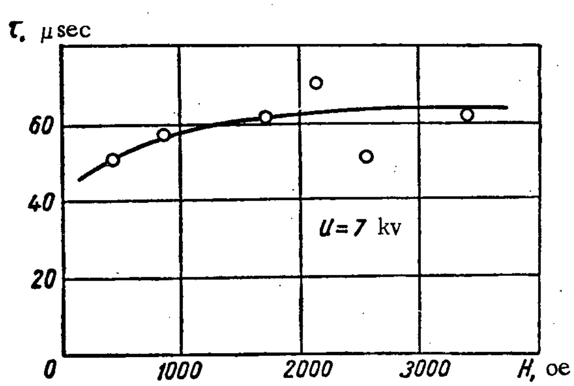

Fig. 7. Dependence of the plasma lifetime in the trap on the magnetic field strength.

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The plasma lifetimes which were measured by means of other devices are of the same order and they lie in the range from approximately 15 μsec in [9] to approximately 200 μsec in [12]. Besides, the injection process duration is very long in the latter case (approximately 150 μsec), so that it is rather difficult to separate the trap-filling stage from the stage during which the trap is vacated. Secondary ion emission from the system's walls, which places slow ions into the central region and delays the collapse of the plasma, was another complicating factor in these experiments.

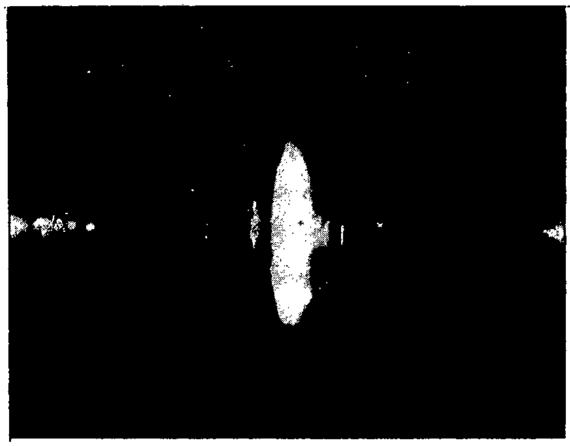

Fig. 8. Luminescence of plasma in the trap. The pulse field has a strength of 25,000 oe; the initial deuterium pressure was 0.5 mm Hg. The diameter of the quartz tube was approximately twice as large as the visible luminescence diameter.

The formation and disintegration of plasma can also be observed with respect to its luminescence by recording the radiation intensity by means of a photoelectric data transmitter. The results of photoelectric measurements are in agreement with the data obtained by using the probe method.

Superhigh-speed cinematography was used for observing the development of the process in [11]. The obtained cinematographic frames made it possible to follow the passage of plasma through the magnetic barrier as well as the events occurring while the plasma was inside the trap. In this case, the plasma lifetime was of the order of tens of microseconds.

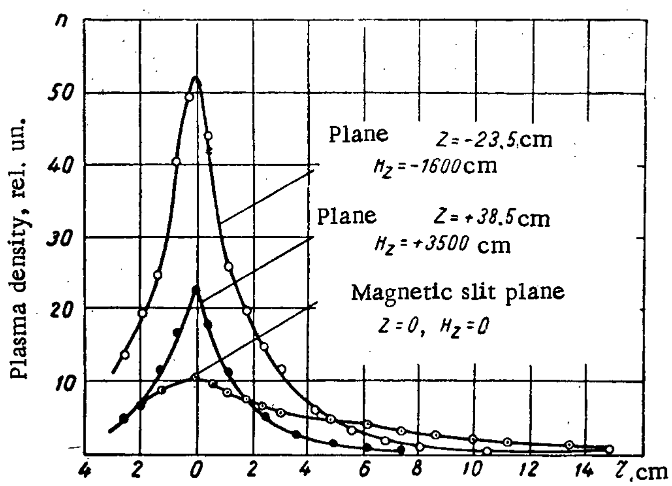

Fig. 9. Radial distribution of the plasma density at different cross sections of the trap.

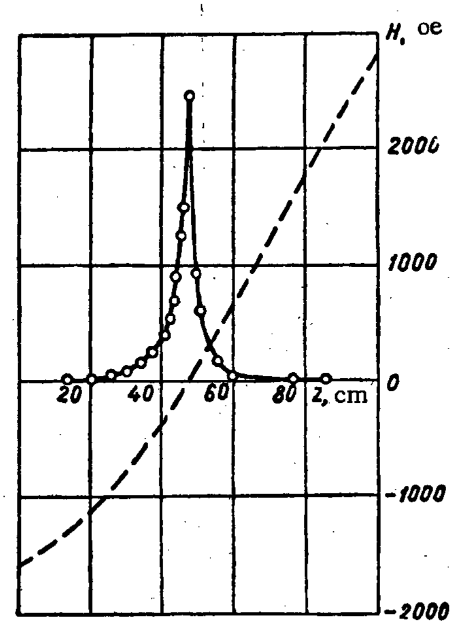

Fig. 10. Current flowing to the side wall of the trap in the magnetic slit region. The dashed line shows the variation of the H_z component along the axis.

Summing up, we can say that the totality of observations by means of probe, photoelectric, and photographic methods indicates with sufficient conclusiveness that the plasma blob is captured in the trap. The values of the characteristic plasma lifetimes are, however, discouraging; they are close to the flight times. This is not to be wondered at; as was mentioned before, plasma can flow out through slits in traps with opposing fields even in the absence of collisions between particles.

A quantitative comparison between experimental data and the above estimates would necessarily have a tentative character. However, we shall adduce a few figures. For the "Orekh" device (under typical operating conditions), a model with a displaced field leads to total departure times of the order of 20 μsec. The model with a constant volume yields a characteristic departure time (i.e., the time in which the initial concentration is reduced to 1/e of its initial value) of the order of 80 μsec. A reasonable "bracketing" of the estimated values is obtained.

The penetration of plasma by the field during the injection process was established by analyzing the readings of the magnetic probes. Such data are given in a number of papers [8, 12, 16]. The experimentally observed (see Fig. 7) virtual constancy of the plasma lifetime for wide-range changes in the magnetic field strength also indicates that vigorous mixing of the field and the plasma occurs under the above conditions. It should also be noted that the very short lifetime obtained in the experiments performed by Scott and Wenzel [8] is in agreement with the small transverse dimension of the trap.

We shall now pass to the problems connected with the spatial plasma distribution in the trap. Figure 8 shows a photograph of plasma, which was obtained by constricting a pulse discharge by means of opposing fields [9]. The flattened shape of the plasma formation, which is localized in the median plane of the system, is seen here with complete clarity. The same inference can be drawn from a consideration of the cinematographic frames given in [11]. The quantitative data on the plasma topography in a trap with opposing fields, which were obtained by Coensgen et al. [12], are given in Fig. 9. It is obvious from the graphs that the plasma is drawn closer toward the axis in moving away from the median plane of the system. The curves for the radial plasma density distribution are given in relative units; they were obtained by the integration of signals from specially constructed electric probes.

In accordance with the above-presented concepts, the departure of plasma from the trap must occur mainly through the ring-shaped magnetic slit in the median plane of the system. An ideally complete picture of the plasma departure could be obtained by measuring the plasma energy losses at the chamber walls in dependence on time by means of devices with a sufficiently good time and spatial resolving power. This ambitious program has not yet been put into effect. However, Fig. 10 shows the distribution of the number of charged particles incident on the electric probe in dependence on the coordinate (on the basis of data from the USA [12]), while Fig. 11 shows the distribution of heat fluxes flowing toward the heat receiver (for two magnetic-field values), which was obtained by means of one of the devices at the I. V. Kurchatov Institute of Atomic Energy. It is obvious that the results of thermal and electric measurements are in excellent agreement with each other, which indicates that the outflow of

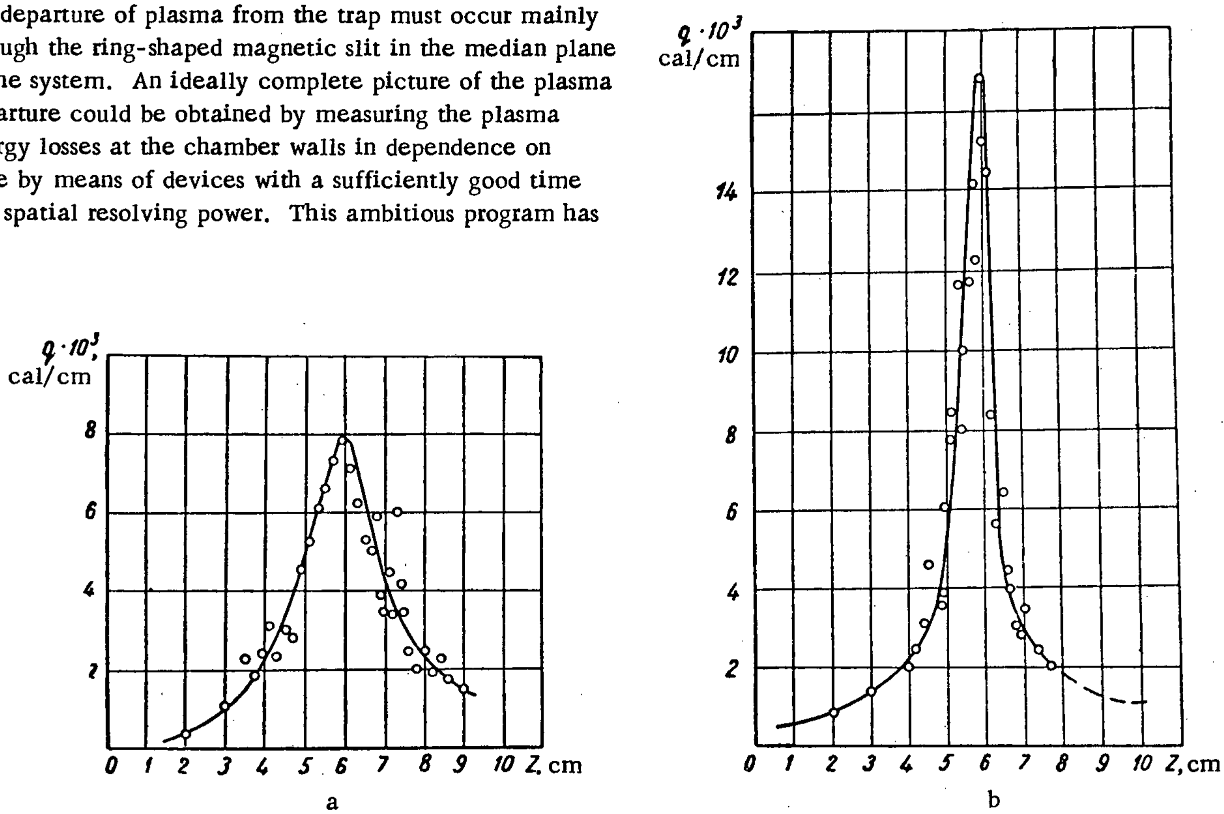

Fig. 11. Heat transfer to the trap's side wall in the magnetic slit region. a) For H = 285 oe; b) for H = 1000 oe.

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energy and particles occurs in the median plane. Finally, the thermal measurements have an integral character, while control measurements with electric near-wall probes confirm the adequacy of using thermal probes as data transmitters that characterize the departure of plasma from the central region.

The dependence of the magnetic slit width on the field strength is given in Fig. 12. The question whether the experimentally-observed dependence reflects only the effect of the magnetic field or the effect of some other additional factors remains open.

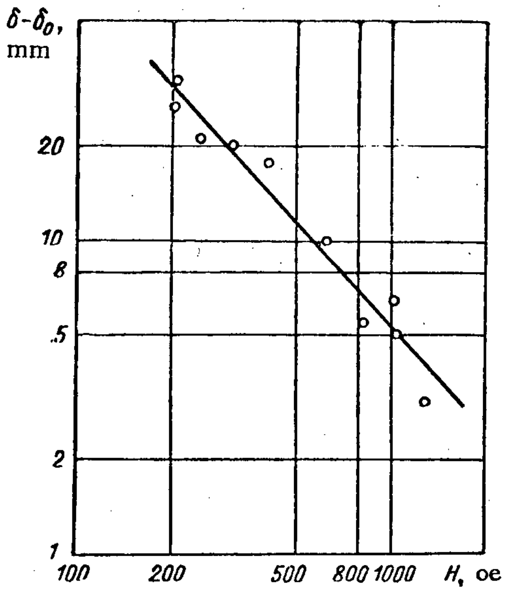

Fig. 12. Dependence of the magnetic slit width on the field strength.

TABLE 2. Density and Lifetime of Plasma in Various Devices

Density n, cm^{-3}	Lifetime τ, μsec	Literature cited
$3\cdot10^{12}$	40	[7]
10^{11}—10^{12}	100	[12]
$8\cdot10^{15}$	15	[8]
—	30	[13]
10^{-13}—10^{14}	60	[16]

We shall now consider the results of density determinations. The plasma density values in the trap's central region depend on the magnetic field strength, the injector's operating conditions, and the experimental geometry. Table 2 provides a comparison between the published values for several cases. As a convenience, the table also provides numerical values for the plasma lifetime.

The plasma density values given in the table are typical in the sense that they correspond to operating values of the magnetic field and to the conditions under which injectors operate. The plasma density in the trap increases with an increase in the field strength and an increase in the injector voltage [15].

It should be noted that the n values given in [8] are doubtful, since they were obtained by using a spectrometric method, the essence of which was presented by the authors very briefly and with insufficient clarity.

These are the main conclusions to be drawn from the investigations performed on magnetic traps with opposing fields.

Considering the prospectives of further work, we see that the efforts of experimenters will be directed toward the production of plasma with the maximum possible initial density and temperature. On the one hand, this will require improved injectors; on the other hand, it will be necessary to change the injection geometry and the geometry of the trap itself. The future will show what progress can be made in these directions and whether traps of this type will be able to compete with other systems or whether the solution must be sought in the construction of some hybrid systems.

The authors extend their thanks to L. A. Artsimovich, I. I. Gurevich, S. M. Osovets and O. B. Firsov, with whom they discussed some of the problems considered in this survey.

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All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

PHYSICAL INVESTIGATIONS IN THE CYCLOTRON LABORATORY OF THE I. V. KURCHATOV INSTITUTE OF ATOMIC ENERGY

N. A. Vlasov and S. P. Kalinin

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The cyclotron of the I. V. Kurchatov Institute of Atomic Energy was constructed in 1947. The diameter of the electromagnet's poles is 1.5 m, and the weight of the magnet is 330 t. Initially, the cyclotron was adjusted for the acceleration of deuterons and molecular hydrogen ions to 14 Mev and of α-particles to 28 Mev with extraction beyond the limits of the deflecting plate. The extraction and focusing of the beam on a target which was at a distance of approximately 12 m from the cyclotron was realized in 1950. A detailed description of the cyclotron is given in a special article [1].

Various operating conditions were secured and certain improvements were made during the utilization of the cyclotron [2]. The conditions under which the accelerated particles were brought onto a remote target are given in the table.

At the present time, the beam currents to targets having a surface area of approximately 1 cm^2 have an intensity of several tens of microamperes under any operating conditions (including conditions 5). In practice, the magnitude of the current used is limited not by the acceleration and extraction conditions, but by the target-cooling conditions and the degree of radiation safety in the working rooms adjacent to the cyclotron.

Uses of the Cyclotron Operating Conditions

Condition No.	Conventional designation of operating conditions	Particle energy, Mev			
		p	d	α	He^3
1	D-14	7	14	28	—
2	D-20	10	20	40	—
3	P-12	12	—	—	—
4	α-20	5	10	20	—
5	He^3-36	—	—	5*	36

* Accelerated by the third harmonic of the HF field.

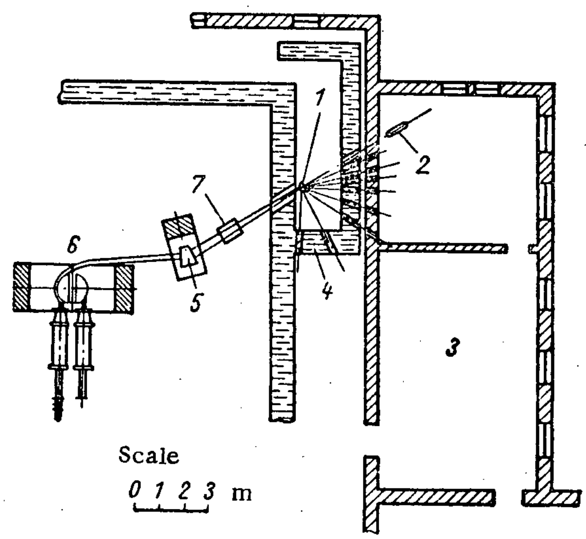

Fig. 1. Layout of the cyclotron and the recording equipment. 1) Target; 2) recording device; 3) control panel. 4) water shield; 5) focusing magnet; 6) cyclotron; 7) electrostatic focusing system.

The nuclear physics laboratory for work with the cyclotron was organized in 1953. The first projects assigned to the laboratory were concerned mainly with measurements of reaction cross sections with respect to the yield of various radioactive isotopes, where very simple methods, which did not require lengthy preparations, were used. Later, more complex and advanced methods were perfected. Among these methods, the basic ones were the method of fast-neutron spectrometry with respect to the flight time and the method where reactions which are accompanied by the generation of tritium are investigated.

The geometry of physical measurements is shown in Fig. 1. The existing rooms were provided inside the finished building after the cyclotron had been in operation over a period of several years, and, therefore, the rooms for the target, the measuring equipment, and the personnel engaged in measurements are not sufficiently spacious and convenient.

Certain Cyclotron Improvements

The use of the cyclotron as a pulsed source of fast neutrons for spectrometry with respect to flight time imposes certain specific requirements on the cyclotron. The basic requirements are the necessity of stabilizing the accelerating-voltage frequency, the stabilization of the phase with which the particles strike the target, and the constancy of the duration of the target current pulse within limits allowable from the point of view of the spectrometer's resolving power.

Frequency-stabilization methods are sufficiently well-known, and their application does not involve difficulties of a basic character. In our case, the stability of the accelerating-voltage frequency was secured by using a high-stability quartz master oscillator and automatic frequency control, whereby the reactive parameters of the cyclotron's resonance system were tuned to this frequency.

The question of phase stabilization is much less clear, and it requires special investigations, since the phase depends on many factors. One of these factors, probably the main factor, is the accelerating-voltage magnitude. Actually, by stabilizing the accelerating-voltage amplitude while stabilizing the deflecting-system voltage, a much smoother phase behavior was secured, which resulted in reliable measurements of spectra with respect to the flight time over sufficiently long time intervals.

In searching for ways of controlling the phase-interval width and for the purpose of monochromatizing the beam, an experiment was performed, where a system of diaphragms which were calculated for strict beam collimation at the beginning of the acceleration process was installed near the center of the cyclotron. This experiment was highly successful. Regardless of the strict limitations of the center geometry, the intensity of the accelerated beam did not diminish, which was due to the electrostatic focusing of ions by the diaphragms during the first revolutions. Moreover, as a result of improved ion-extraction conditions, the current to a remote target was considerably increased. Besides, the system of diaphragms freed the accelerator from ballast ions.

The installation of diaphragms made it possible to obtain an intensive beam of accelerated ions with an energy spread $\leq$ 0.2%, i.e., a beam which was highly monochromatic. This result, which is not final, shows that one of the basic disadvantages of the cyclotron – the large spread of accelerated-particle energies – can be eliminated without substantial beam intensity losses, and that, therefore, along with electrostatic generators, the cyclotron can be used for precision nuclear-spectrometric investigations.

Work on Fast-Neutron Spectrometry

Work on fast-neutron spectrometry constitutes one of the basic tasks of the laboratory. Under the perfected cyclotron operating conditions, neutrons with an energy of up to 40 Mev can be produced in (d, n) reactions at $E_d =$ $= 20$ Mev and in (α, n) reactions at $E_\alpha = 40$ Mev.

In connection with the solution of certain practical problems, fast-neutron investigations were started in the first few days after the laboratory was completed. The first projects were based on the production of monoenergetic neutrons with an energy of up to 7 Mev in the T (p, n)He^3 reaction and on detection by means of an all-wave counter and a telescope consisting of proportional counters with a hydrogenous radiator [3, 4]. The all-wave counter is hardly being used presently, but the telescope is still used as a very useful device for absolute measurements of neutron fluxes as well as for solving certain specific problems. Thus, for instance, measurements of the polarization of neutrons from the T (p, n) He^3 reaction and of protons of the back reaction He^3 (n, p) T were performed by means of this telescope [5].

Work on the development of a method for the spectrometry of fast neutrons with respect to the flight time has been in progress since 1954.

The cyclotron constitutes a pulsed source of accelerated particles and, consequently, of neutrons that are produced in the target, since the capture of ions during the acceleration process takes place in a limited interval of accelerating-voltage phases. However, for spectrometry which is based on the flight time, it is necessary that the neutron pulse duration be not greater than the resolving time of the recording equipment, i.e., it must be practically less than 2 mμsec. This means that the phase interval of the ions extracted from the cyclotron must not exceed 2% of the accelerating-voltage period. There was no sufficient reason for expecting that this condition could readily be satisfied.

In 1954, at the very beginning of experiments on the analysis of flight time, it was established that, under normal accelerating conditions, the pulse width of neutrons from the cyclotron's target did not exceed 10 mμsec. This experiment indicated the possibility of using the cyclotron directly as a pulsed source of neutrons under its normal operating conditions without any additional basic developments.

Further experiments showed that the width and shape of pulses depend on various parameters of the cyclotron's operating conditions. Under certain conditions, the pulses assume a complex doublet structure. By improving the basic parameters which affect the width, it became possible to secure conditions under which the pulse width does not limit the spectrometer's resolving power. On the whole, the spectrometer is characterized by a resolving time of 2.5 mμsec.

The first single-channel variant of the spectrometer was developed in 1956 [6]. At the present time, investigations with a multi-channel spectrometer are in progress. In contrast to ordinary analyzers for short time intervals, which transform time into signal amplitude, our spectrometer constitutes a direct time magnifier, which operates on the vernier principle. Periodic signals with a constant reference frequency are produced by a pulse generator, which operates in step with the cyclotron's accelerating voltage. The pulse from the detector for the recording of neutrons (and γ-quanta) is supplied to another pulse generator, which produces a series of pulses with a frequency that only slightly differs from the reference frequency. Due to the difference between these frequencies, the interval between the pulses from the two generators changes with each period T by an amount equal to the difference ΔT between the periods. The coincidence of pulses is recorded at the instant of time which depends on the moment when a neutron (quantum) reaches the detector. In this circuit, the time interval is directly magnified by a factor of $\frac{T}{\Delta T}$. For $\frac{T}{\Delta T} = 1000$, further time analysis of pulses can be performed by means of ordinary microsecond-range analyzers. A detailed description of this spectrometer is given in a monograph by B. V. Rybakov and V. A. Sidorov as well as in specific articles [7]. An ELA-2 [8] 256-channel analyzer with an adapter for the extraction of figure data or data in the shape of a perforated tape, which is used for processing the results in a computer, serves as the output-recording device.

Figure 2 shows the time distribution of pulses, which was recorded by means of this spectrometer in investigating Li + d (10 Mev) reactions. In our case, the target usually constituted a sufficiently intensive source of γ-rays, which accompanied various nuclear reactions. The recording of γ-rays by means of the spectrometer can be conveniently used for determining the time scale and for controlling the spectrometer's resolution. The width of γ-peaks, which is equal to 2.5 mμsec, characterizes the spectrometer's over-all resolving time.

The spectrometer was used for investigating spectra of fast neutrons which are produced in various nuclear reactions, mainly in those reactions which are widely used for the production of monoenergetic neutrons.

The results obtained in this work are important primarily for fast-neutron spectrometry as an investigation method. Hardly any neutron-spectrometry investigations in the region of energies greater than 15 Mev have been performed up to now. For the development of spectrometry in this region, it is necessary, in the first place, to obtain data on the characteristics of neutron spectra of different reactions. At lower energies, the D (d, n) He^3, T(d, n) He^4, T (p, n) He^3, etc. reactions are often used for producing neutrons by means of electrostatic generators. For the energy of particles that are produced in the cyclotron, these reactions have not yet been sufficiently investigated.

Figure 3 shows the yield of neutrons at an angle of 0° from the T (p, n) He^3 reaction for neutron energies of up to 12 Mev [9]. This reaction represents one of the best sources of high-energy neutrons, since there are no excited states in the final He^3 nucleus, while the fission of He^3 with the generation of continuous-spectrum neutrons has a rather high threshold (7.3 Mev). The polarization of neutrons from this reaction was measured in a special experiment by means of a proportional telescope using the method of back reactions [5]. It appeared that, at an angle of 40° and for $E_p = 10$ Mev, the polarization of neutrons attains a value of 30% and that it increases with an increase in energy (Fig. 4).

Investigations of the D (d, n) and T (d, n) reactions [10] showed that, along with the well-known monoenergetic neutrons, these reactions also produce groups of considerably more intensive continuous-spectrum neutrons (Fig. 5) as a result of deuteron breakup and other reactions that constitute multiparticle reactions in the final state. In the experiments performed in the Los Alamos laboratory [11], it was shown that continuous neutron spectra are formed with a considerable probability and for a lower deuteron energy, which does not greatly exceed the breakup threshold.

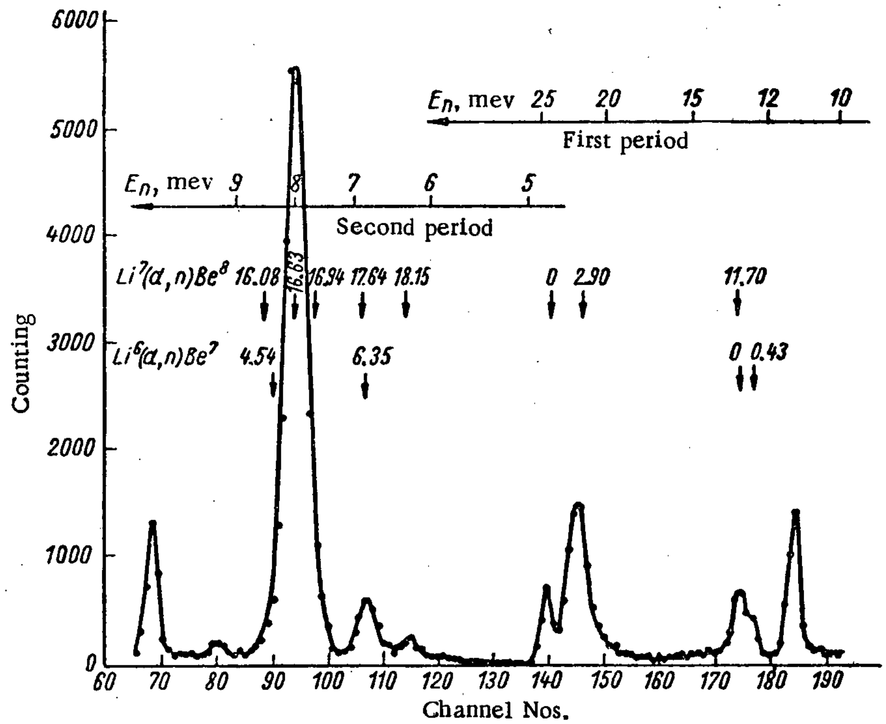

Fig. 2. Spectrum of neutrons from the Li + d (10 Mev) reaction. The channel width was 1.12 mμsec. On the extreme left and right are the γ-peaks.

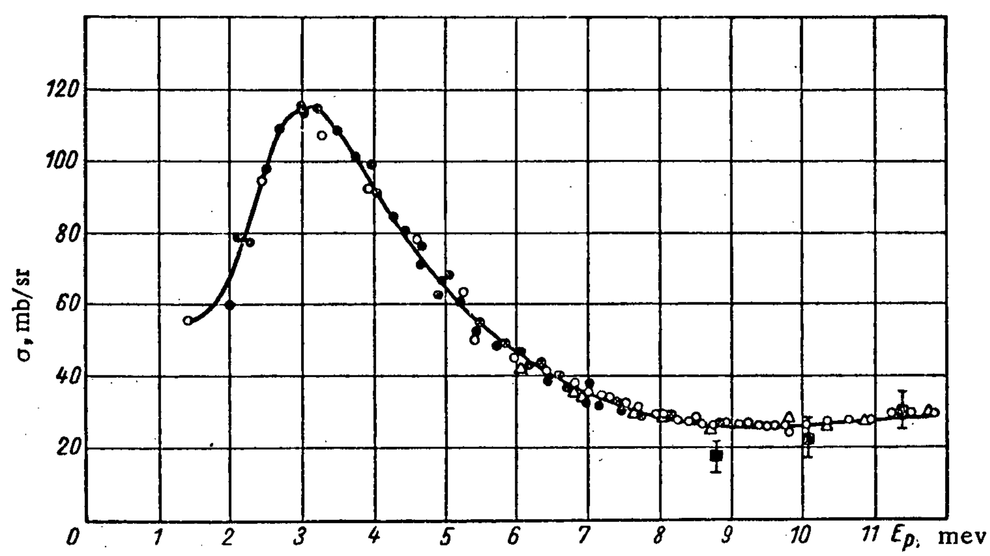

Fig. 3. Dependence of the differential cross section of the T (p, n) He^3 reaction for an angle of 0° on proton energy.

The spectra of neutrons from (d, n) reactions for a 0° angle are characterized by a maximum in the $E_n \simeq \frac{1}{2} E_d$ region and a relatively low yield of neutrons with the maximum energy.

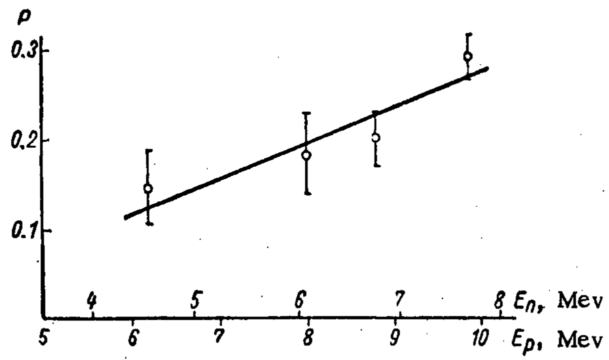

Fig. 4. Dependence of the polarization of neutrons from the T (p, n) He^3 reaction and of protons from the He^3 (n, p) T reaction for an angle of 40° in the laboratory system on the energy of primary particles.

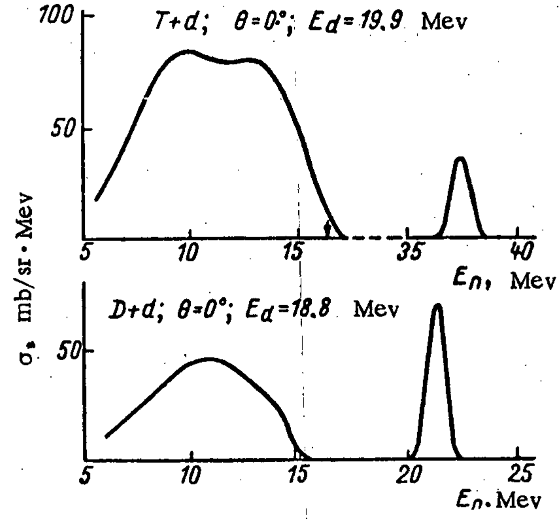

Fig. 5. Neutron spectra for a 0° angle, produced by bombarding tritium and deuterium targets with deuterons.

More detailed investigations of continuous neutron spectra showed that the shapes of spectra considerably differ from the shape usually expected in three-particle reactions for the simplest statistical energy distribution. One of the reasons for this is the interaction of the formed pairs of particles in the final state. In this respect, the spectrum of neutrons from the D(p, n) 2p reaction, which is shown in Fig. 6, is typical. Here, the maximum at the upper limit of the spectrum is connected with the formation of a virtual diproton, while the second maximum for a lower energy is connected with the formation of a virtual deuteron [12]. In the continuous neutron spectrum of the T(d, n) reaction, a broad maximum, which is connected with the formation of α-particles in the excited state, is observed near the upper limit [10].

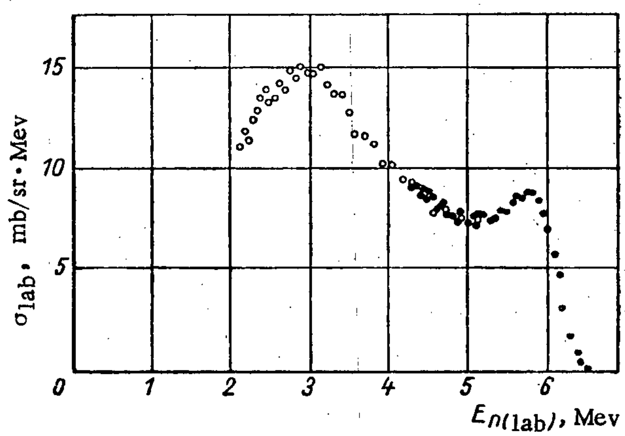

Fig. 6. Neutron spectrum for a 0° angle, produced by bombarding deuterium with protons having an energy of 8.6 Mev. ○) Flight range: 5.15 m; ○) flight range: 1.58 m.

Different types of spectra were observed in D(d,n) (see Fig. 5) and He^3 (d, n) (Fig. 7) reactions. Almost no pair interactions in the final states were observed in these spectra. The shapes of the spectra can probably be explained by the statistical distribution of energy among three particles if we take into account the possibility of their escape with orbital moments different from zero [13]. Observations of breakup protons from the He^4 + d reaction (20 Mev) showed [14] that the angular distributions of the two components of continuous spectra greatly differ from each other (Fig. 8). The group connected with an intensive pair interaction has a narrowly-directed angular distribution, which is characteristic for the stripping process. The distribution of the broad statistical group is close to an isotropic distribution (in a center-of-mass coordinate system). Besides protons, also elastically-scattered deuterons and recoil α-particles were observed in this experiment. A direct comparison between the cross sections given in Fig. 8 shows that, in the collision of 20-Mev deuterons with α-particles, the breakup of deuterons into free nucleons is observed in approximately one-half of the events.

The great probability of deuteron breakup, which was directly observed in these experiments, is one of the main causes of anomalies in the elastic scattering of deuterons on nuclei.

Continuous spectra of protons which are generated by the breakup of deuterons on medium and heavy nuclei were recently studied in a paper by Cohen et al. [15]. The Coulomb field of the nucleus apparently exerts a noticeable influence on the shape of nucleon spectra in the breakup on heavy nuclei.

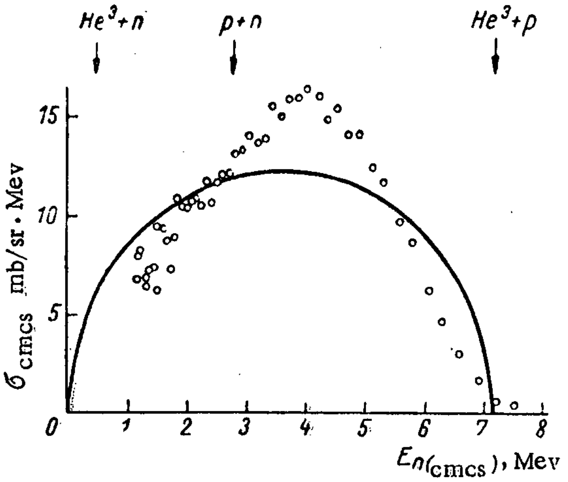

Fig. 7. Spectrum of neutrons from the He^3 + d reaction in a center-of-mass coordinate system for a 0° angle at E_d = 18.6 Mev.

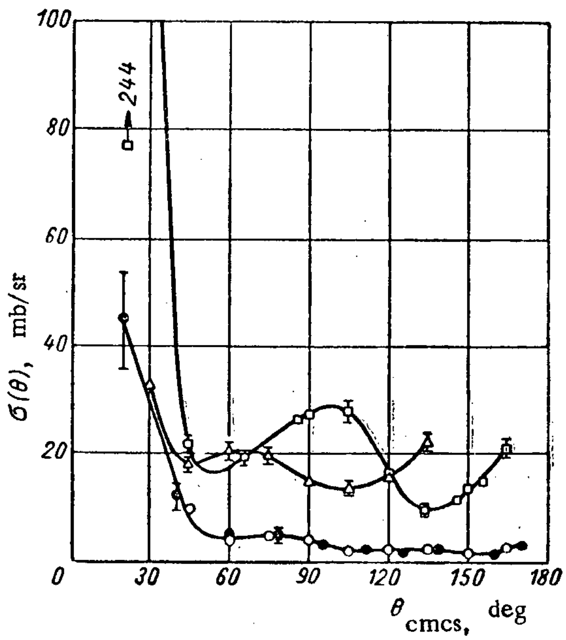

Fig. 8. Angular distribution of charged collision products from He^4 + d (20 Mev). □) He^4(d, d) He^4; △) He^4 (d, pn) He^4; ●, ○) He^4 (d, p) He^5.

The other problem for the solution of which fast-neutron spectrometry was used is connected with the statistical properties of nuclei. For statistical theory, it is very important to determine the dependence of the density of levels on the excitation energy of nuclei. Experimentally, this problem can be solved by observing the spectrum of nucleons which emanate from complex nuclei. Many spectrum investigations pertain primarily to charged particles. However, the penetrability of the Coulomb barrier greatly affects the shape of the spectra of these particles, and, therefore, the conclusions concerning the distribution of nuclear levels heavily depend on the accepted value for the nuclear radius, and therefore they are not reliable [16]. Observations of neutron spectra make it possible to determine the level distribution in a more reliable manner. However, such observations are more complicated from the methodological point of view, and, therefore, the available results are insufficiently accurate. The use of the fast-neutron spectrometer made it possible to investigate evaporation neutron spectra with sufficient thoroughness. Spectra of neutrons which are formed in (α, n) reactions for an angle of 90° and an α-particle energy of 11-20 Mev were studied for this purpose. According to the statistical nuclear theory, the shape of neutron spectra is given by

$$N(E) = \text{const}\, E\varrho(E^*),$$

where $\rho(E^*)$ is the density of the levels of residual nuclei for the excitation energy E^*. In Fig. 9, the results obtained for the V^{51} (α, n) Mn^{54} reaction are given in the shape of the dependence of $\ln\frac{N(E)}{CE} = \ln \varrho(E^*)$ on the final nucleus excitation energy. A satisfactory agreement with the distribution

$$\varrho(E^*) \sim e^{E^*/T}$$

is observed, while the temperature T increases with an increase in the energy of the bombarding α-particles.

The third possibility of using the fast-neutron spectrometer involves the measurement of fission cross sections. As is well known, measurements of fast-neutron fission cross sections are rather difficult, and, therefore, for E_n > > 14 Mev, only data on U^{238} have been published up to now [17]. Since monoenergetic neutrons with variable energies greater than 20 Mev are almost impossible to produce, spectral analysis of neutrons with respect to the

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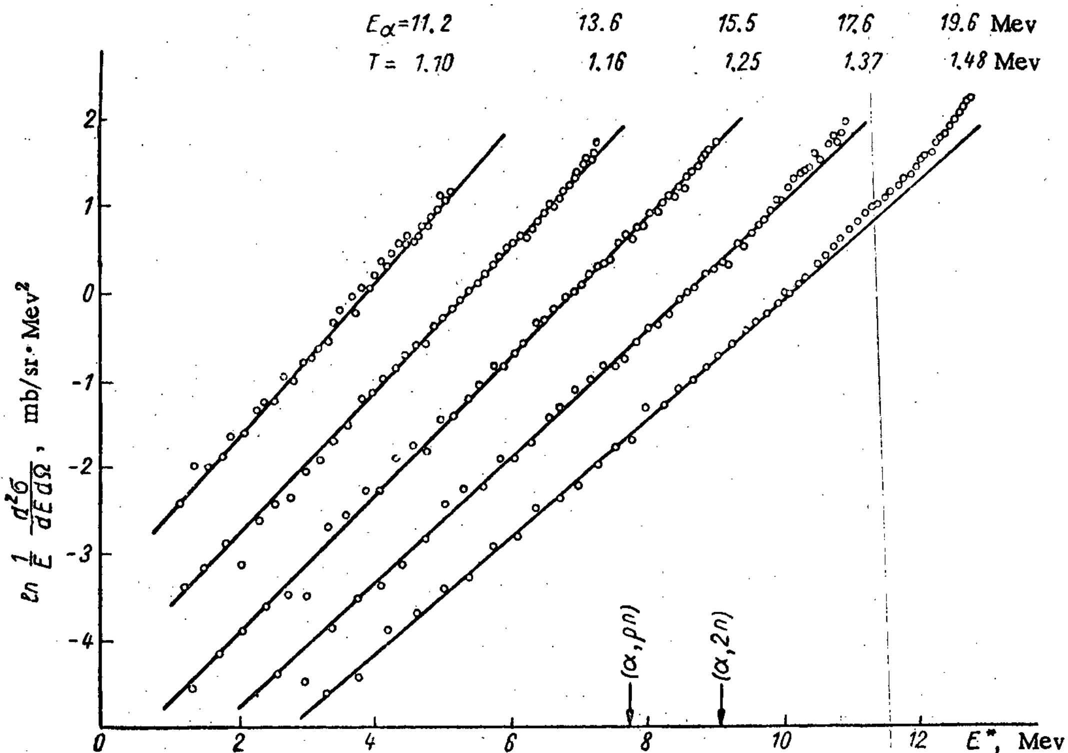

Fig. 9. Density of levels for the neutron spectrum of the V (α, n) reaction for a 90° angle.

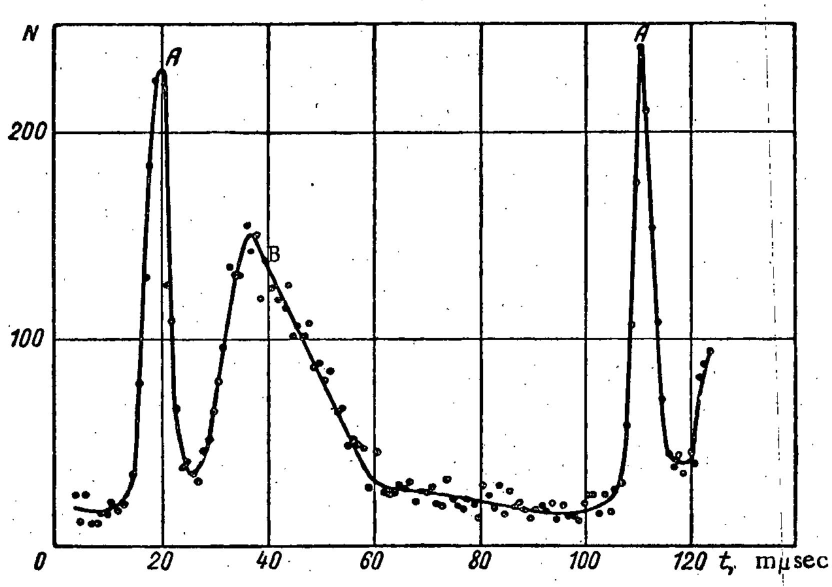

Fig. 10. Time distribution of pulses due to Th^{232} fission by neutrons from the D (d, n) reaction for E_d = 19.5 Mev. The range was 3 m. A) Fission by neutrons from the D (d, n) He^3 reaction; B) fission by neutrons from the D(d, pn) D reaction.

flight time should be used. However, this problem requires the development of fast-acting detectors capable of clearly distinguishing fission events from α-decay events. The available solid scintillators are not suitable for this purpose due to the nonlinearity of the luminescence yield. Therefore, gaseous scintillators were developed and utilized [18]. The connection of these scintillators to the circuit of the spectrometer based on flight time made it possible to observe the entire complex spectrum of neutrons that cause fission. Figure 10 shows the time distribution of pulses due to Th^{232} fission, which is caused by neutrons from the D(d, n) reaction at E_d = 20 Mev. The broad group corresponds to breakup neutrons, while the narrow group (two peaks) corresponds to neutrons from the D(d, n)He^3 reaction. Similar results were also obtained for neutrons from the T (d, n) reaction, where the relative intensity of the continuous spectrum is even greater.

Figure 11 shows the dependence of the Th^{232} fission cross section on neutron energy in the 3-37 Mev interval.

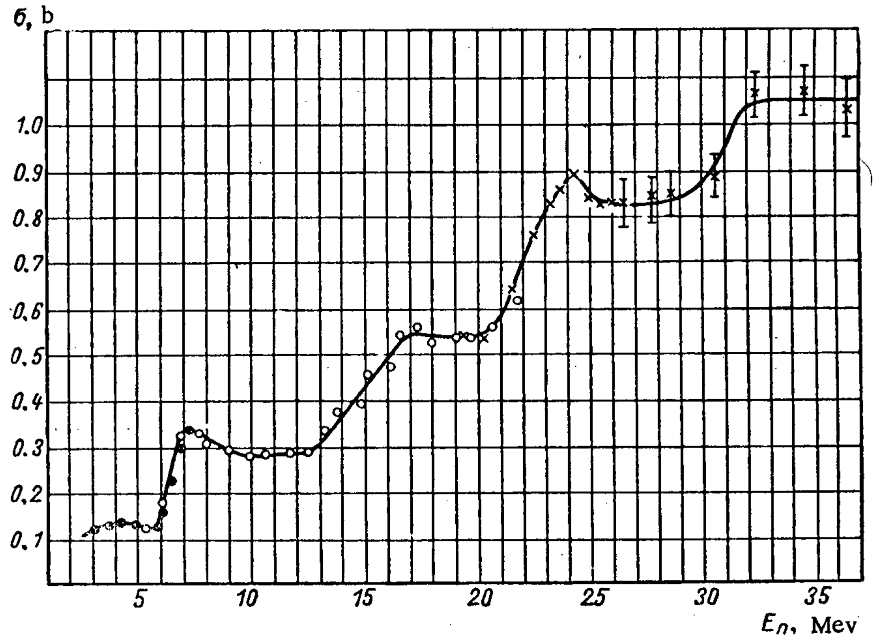

Fig. 11. Cross section of Th^{232} fission by neutrons with energies from 3 to 37 Mev. ●) With T(p, n) He^3 neutrons; ○) with D (d, n) He^3 neutrons; x) with T (d, n) He^3 neutrons.

Investigation of Nuclear Reactions That Are Accompanied by the Formation of Tritium

Tritium is one of the usual products of the very simple (p, t), (d, t), (α, t), etc. nuclear reactions. The investigation of these reactions is of interest for an explanation of their mechanism and also from the point of view of nuclear spectrometry. In connection with this, a simple but sufficiently efficient method for studying the spectra and angular distributions of tritons has been developed in our laboratory [19]. Piles of aluminum foils, which are penetrated by tritons to depths that depend on their energy, were arranged at different angles around the thin target, which was bombarded by accelerated particles (Fig. 12). After exposure to the beam, tritium was extracted by heating from each foil and was introduced into a Geiger counter. The amount of accumulated tritium was determined with respect to the measured activity, while its energy was measured with respect to the depth at which the foil was located. A single irradiation with a flux of the order of 100 μamp·hr made it possible to measure triton spectra in a wide energy interval (from 0 to 20-30 Mev) and also the angular distributions in an interval from 7° to 150°.

In spite of its relative simplicity this method is very efficient, since the recording of any other particles, except those of tritium, is precluded, and therefore, the background that limits the possibilities of other methods is absent.

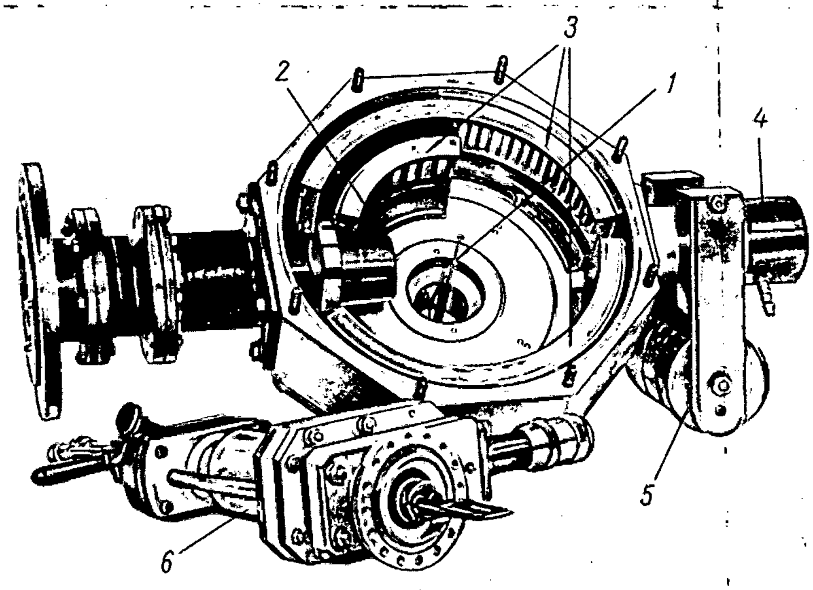

Fig. 12. Device for studying nuclear reactions in which tritium is generated. 1) Target; 2) entrance collimator; 3) holders with collecting foils; 4) Faraday cylinder; 5) magnet which prevents the escape of secondary electrons; 6) chambers for targets which are oxidizable in air.

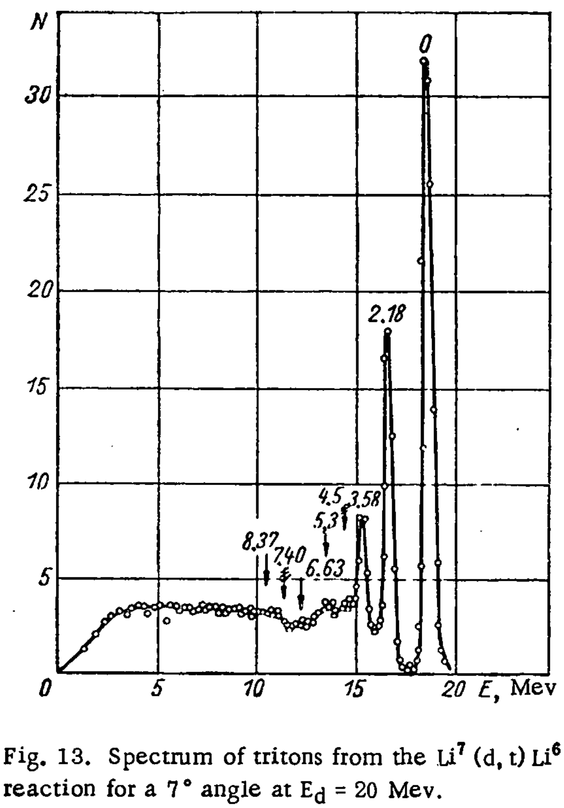

Fig. 13. Spectrum of tritons from the Li^7 (d, t) Li^6 reaction for a 7° angle at E_d = 20 Mev.

Figure 13 shows the spectrum of tritons from the Li^7 (d, t) Li^6 reaction, which was observed under a 7° angle. The monoenergetic lines near the upper limit of the spectrum correspond to the lower level of the final Li^6 nucleus. Their intensity sharply decreases with an increase in the Li^6 excitation energy, which is typical for the pick-up reaction (d, t). The angular distribution of the three groups corresponds to the extraction of neutrons with the orbital moment l = 1. The continuous triton spectrum is connected with multiparticle reactions.

The direct process of neutron extraction in the (d, t) reaction primarily leads to the excitation of hole states of the final nucleus, and it makes it possible to determine the binding energy corresponding to the single-particle state of the neutron in the target-nucleus. Thus, for instance, the investigation of the O^{18} (d, t) O^{17} and F^{19} (d, t) F^{18} reactions shows that the energies of the s and d states are interchanged in transition from O^{18} to F^{19} [20].

The possibility of knocking out deuterons from filled internal nuclear shells is very interesting. The effect of various shells is most clearly manifested in (d, t) reactions with zirconium isotopes [21]. The spectra of tritons from these reactions are shown in Fig. 14. Two groups of tritons can be observed in these spectra. The intensity of one of them is proportional to the number of supermagnetic neutrons. It is obvious that this group is formed by the knocking out of the external neutrons. The intensity of the second group is practically equal for all isotopes, including the magic Zr^{90}, the spectrum of which is not shown here. This group is connected with the extraction of neutrons from filled shells. The angular distributions of both groups are matched

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with the neutron orbital moments, which are assigned to the groups by the well-known shell scheme (l = 2 for the first group, and l = 1 and l = 4 for the second group).

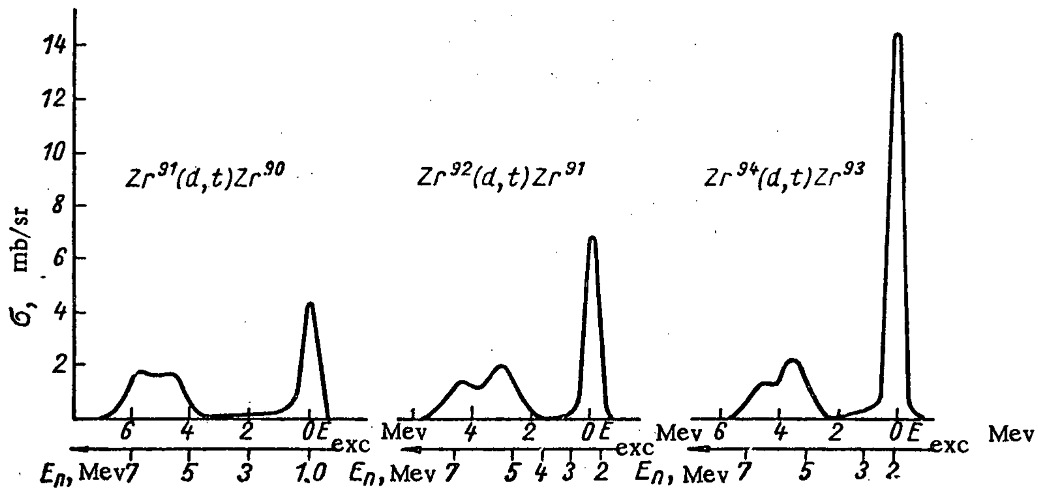

Fig. 14. Spectrum of tritons from the (d, t) reaction with zirconium isotopes.

In O^{18} (d, t) O^{17} and F^{19} (d, t) F^{18} reactions, the extraction of neutrons from closed p-shells was also observed [20]. At the present time, the problem of the extraction of nucleons from closed shells is being solved by using the method of the quasielastic scattering of fast protons on nuclear protons [22]. In these experiments, it was also possible to separate the effects of various shells.

Besides the (d, t) reaction, other nuclear reactions were also studied by means of this method [23]. An investigation of the Na^{23} (α, t) reaction showed that its mechanism sharply differs from the mechanism of the Na^{23} (d, n) reaction, although the transfer of protons to target-nuclei takes place in both reactions.

The above projects were completed by the large team of co-workers of the cyclotron laboratory with the participation of the authors of the present article.

We must mention also the large contribution made by N. I. Venikov who, since 1957, conducted work on the improvement and utilization of the cyclotron, and the important role played by M. A. Egorov and N. N. Khaldin, who supervised the preparation of the experimental equipment.

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A SURVEY OF NUCLEAR-REACTOR DESIGN METHODS

G. I. Marchuk

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October, 1961
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INTRODUCTION

The wide application of high-speed computers in calculation has brought about conditions that are favorable for the development of many regions of science and technology.

It has become possible to solve new and very complex mathematical and logical problems that were previously considered to be unsolvable in practice because of the very great amount of numerical work involved in their solution. In this connection, the questions concerned with the mathematical formulation of a problem and the derivation of an effective numerical logarithm for its solution are of particular importance.

The latest developments in numerical analysis have necessitated the review of logarithms for the solution of many problems of mathematical physics, and the derivation of new logarithms based on the application of numerical methods that are the best for the new computers available.

Analytical methods for the solution of problems have in many cases been replaced by more effective numerical methods.

The achievements in the realm of numerical analysis have had a great influence on the development of the theory and methods of calculation for nuclear reactors. After the book of S. Glesston and M. Édlund [1], in which the elementary foundations of the theory of thermal-neutron reactors were described, there appeared the monograph of A. D. Galanin [2], which was also devoted to questions on the theory of thermal-neutron reactors. The theoretical foundations of nuclear energy have been most thoroughly described in the books by A. Weinberg and E. Wigner [3], and also in the book by B. Dévison [4]. The author of the present article has studied methods of performing calculations for nuclear reactors in the monographs [5, 6]. A book has also recently appeared by R. Meghreblian and D. Holmes [7], in which questions on the theory and method of calculation for nuclear reactors are considered.

Further developments in the theory and design of nuclear reactors were also published in the reports on the First and Second International Geneva Conferences on world-wide investigations of atomic energy.

There is still theoretical value in the works of the earlier period of development of nuclear energy. These results were obtained by E. Wigner [8], R. Peierls [9], R. Marchak [10, 11], N. N. Bogolyubov [12], I. I. Gurevich and I. Ya. Pomeranchuk [13], H. Hurwitz [14, 15], A. Weinberg [16], and others.

A great proportion of the development of the theory of methods of calculation for nuclear reactors was carried out in the Soviet Union.

The main progress has occurred in the theory and design of thermal reactors, which is described by I. V. Kurchatov [17], A. P. Aleksandrov [18], A. I. Alikhanov [19], D. I. Blokhintsev [20, 21], V. S. Fursov [22], I. I. Gurevich and I. Ya. Pomeranchuka [13], S. M. Feinberg [23-25], A. D. Galanin [2, 26], V. V. Orlov [27, 28], and others.

On the basis of these works, the scientific design was carried out for nuclear reactor projects for power stations such as the First Atomic Electrical Generating Station, for the icebreaker "Lenin", and for other purposes, and a large number of experimental reactors were also planned for using various moderators and methods of heat-exchange.

The theory of and calculations for reactors for intermediate neutrons have been developed in the works of A. I. Leipunskii, A. S. Romanovich, L. N. Usachev [29, 30], V. Ya. Pupko [31, 32], V. A. Kuznetsov, B. F. Gromov, G. I. Toshinskii, V. V. Chekunov, V. V. Orlov [33], and others.

The theory of and calculations for reactors for fast neutrons have been developed and improved in the works of A. I. Leipunskii [34-36], D. I. Blokhintsev [36-37], L. N. Usachev [29, 30], O. D. Kazachkovskii [38], I. I. Bondarenko [39, 40], S. B. Shikhov [41, 42], Yu. Ya. Stavisskii [34, 35], V. S. Vladimirov [43, 44], Yu. A. Romanov [45], and others.

The works we have referred to formed the scientific foundation for the nuclear energy stations BR-2 and BR-5, the construction of which has now been completed, and which came into active operation in 1956 and 1958 respectively.

A review of the results of foreign scientific workers in reactor theory and design was given in the reports on the First and Second Geneva Conferences.

The investigation of finite-difference equations approximating the integro-differential equations for a reactor is described in the works of A. N. Tikhonov and A. A. Samarskii [46, 47]. In these works there is a very full investigation of the problems of three-point finite-difference schemes, a practical logarithm is given for the most efficient approximation to differential equations by finite differences, and the general properties of the solutions of difference equations are established. The authors introduce the idea of integral accuracy for the solution of a finite-difference equation relative to the solution of the differential equation, and prove theorems on the convergence of the solutions of the finite-difference equations. It is shown, in particular, that difference equations obtained in the class of discontinuous coefficients are of second integral order accuracy.

For the solution of three-point finite-difference equations of elliptic type, I. M. Gel'fand and O. V. Lokutsievskii (see [5]), A. S. Kronrod (see [2]), and also Stark [48] independently derived the method of linear factorization, which can be used to reduce a boundary-value problem to the successive solution of three finite-difference equations of the first order.

There is a method, interesting from the practical point of view, of solving the finite-difference equations in a two-group approximation, proposed by G. M. Adel'son-Vel'skii (see [2]). This method is based on the solution of the boundary-value problem by using a solution of the Cauchy problem. The effective application of the method is possible, due to the stability developed in the numerical scheme.

An essential advance was obtained in methods of solving the problems involved in the physical design of reactors by using statistical methods, usually called Monte-Carlo methods. These latter methods, in their turn, became feasible with the advent of computers with an even higher speed of operation.

The essence of Monte-Carlo methods, in their application to problems of nuclear physics, is the statistical modelling of physical processes described by an integro-differential transfer equation. With this object in view, certain random processes are considered, based on the elementary laws of behavior of particles, and the whole history of a particle is traced, from the instant of its generation in the system being considered to its capture by or escape from the system. The multiple repetition of this process, taking into account all possible probability situations, makes it possible to accumulate the statistics necessary for obtaining an approximate solution of the problem.

The Monte-Carlo method for determining the critical reactor mass was developed by V. S. Vladimirov and I. M. Sobol' [49].

A new approach to the solution of the above problem, based on the application of the adjoint equations for the reactor, was developed by I. M. Gel'fand, N. N. Chentsov and A. S. Frolov [50]. In these authors' work, an algorithm was given for the solution of the problem by space-energy dependent operators.

A great amount of mathematical investigation in the theory of radiation transfer in general, and in the theory of nuclear reactors in particular, was carried out by E. S. Kuznetsov [51-53] in collaboration with T. A. Germogenov [54, 55], M. V. Maslennikov [56, 57], V. A. Chuyanov [58, 59], L. V. Maiorov, M. G. Krutikov, and others.

The problems involved in the physical design of reactors and methods of solving these problems have been systematically investigated by the author of the present article in collaboration with his fellow-workers Sh. S. Nikolaishvili [60, 61], V. V. Smelov [62, 63], E. I. Pogudalin [64, 65], V. P. Kochergin [65, 66], F. F. Mikhailus [67], G. A. Ilyasov [65], and others.

The problems involved in nuclear-reactor calculations were also the object of investigations by A. S. Kronrod (see [2]), N. Ya. Lyashchenko [25], V. K. Saul'ev [68], and others.

The progress in numerical analysis has been widely discussed in scientific literature, and also at conferences and meetings.

In the present survey, we will consider certain questions on the theory and design of reactors which have generated wide interest in connection with the practical work of scientists in the Soviet Union.

The Main and Conjugate Equations

The most general mathematical formulation of the design problem for the critical regime of reactor operation is obtained from the integro-differential Boltzmann equation with the boundary condition corresponding to the outer surface S of the reactor:

$$\mathbf{\Omega}\nabla\varphi + \Sigma\varphi - \int dv' \int d\Omega' \varphi(\mathbf{r}, \mathbf{\Omega}', v')\, w(\mu_0, v' \to v) = 0; \tag{1}$$

$$\varphi(\mathbf{r}, \mathbf{\Omega}, v) = 0 \text{ on } S \quad \text{for} \quad \mathbf{\Omega n} < 0, \tag{2}$$

where $\varphi = nv$ is the flow of neutrons with velocity $\mathbf{v} = v\mathbf{\Omega}$ at the point with radius vector $\mathbf{r}$; $\mathbf{\Omega}$ is the unit vector in the direction of neutron motion; Σ is the total microscopic cross section of interaction of a neutron with matter; $\mu_0 = \mathbf{\Omega}\mathbf{\Omega}'$. The primes on the quantities v' and $\mathbf{\Omega}'$ denote that these values are for the velocity of a neutron $\mathbf{v}'$ before its collision with a nucleus. The function $w(\mu_0, v' \to v)$ is the differential cross section of the nuclear interaction of neutrons with matter.

The boundary condition (2) expresses the fact that the neutrons escaping from the reactor, the unit velocity vectors of which are related to the outer normal $\mathbf{n}$ to the surface by the relation $\mathbf{\Omega n} < 0$, do not return to the reactor. The condition (2) is equivalent to the assumption that the reactor is surrounded by a vacuum or a perfectly black body.

The space-energy and angular distributions of neutrons in a critical reactor are therefore described by the homogeneous problem given by (1) and (2). It is known that a non-negative solution for this problem is possible for completely definite dimensions of the reactor; these dimensions are called critical. In the majority of cases, the solution of the problem (1) and (2) amounts to seeking the critical dimension of the reactor. Various variations are possible, however, in the design of a critical reactor. Thus, for example, for fixed reactor dimensions, it is possible to vary the concentration of nuclei of the active isotope, or to modify the reactor to ensure a non-negative solution of the above problem. Other methods of realizing the critical regime of operation of a reactor can also be used.

In what follows, we will consider some simplifications in posing and solving the problem described by (1) and (2) for various concrete conditions of physical design of a reactor.

We will, however, first of all formulate approximate methods of solution of the reactor equations, and will begin by considering a fundamental problem in the theory of nuclear reactors, namely the application of the conjugate equations in the physical design of reactors.

To obtain the equation conjugate to the basic reactor Eq. (1), we introduce the idea of a scalar product. We consider two functions $f(\mathbf{r}, \mathbf{\Omega}, v)$ and $f^*(\mathbf{r}, \mathbf{\Omega}, v)$. Then, the scalar product of these functions is defined to be

$$(f, f^*) = \int d\mathbf{r} \int d\Omega \int dv f f^*, \tag{3}$$

where the integration is carried out over the whole region of variation of the variables $(\mathbf{r}, \mathbf{\Omega}, v)$.

Equation (1) will be written formally

$$L\varphi = 0, \tag{4}$$

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where L is the operator defined by the relation

$$L = \Omega\nabla + \Sigma - \int dv' \int d\Omega' w(\mu_0, v' \to v). \quad (5)$$

We will assume that the function $(\mathbf{r}, \Omega, v)$ satisfies the boundary condition (2), and that the operator L is finite. Under these conditions we can form the functional

$$J = (f^*, Lf). \quad (6)$$

If the functional (6) is reduced by transformation to the form

$$(f^*, Lf) = (f, L^*f^*),$$

then the operator L^* is called adjoint to L. By direct verification, we can deduce that L^* has the form

$$L^* = -\Omega\nabla + \Sigma - \int dv' \int d\Omega' w(\mu_0, v \to v'), \quad (7)$$

where it is required that the function $f^*(\mathbf{r}, \Omega, v)$ satisfies the followingcondition at the outer surface of the reactor S:

$$f^*(\mathbf{r}, \Omega, v) = 0 \text{ on } S \quad \text{for} \quad \Omega\mathbf{n} < 0. \quad (8)$$

If, for the function $f(\mathbf{r}, \Omega, v)$ corresponding to the relation (6), we take a solution of the Eq. (5), i.e., we set

$$f = \varphi(\mathbf{r}, \Omega, v),$$

and in this case we denote the function $f^*(\mathbf{r}, \Omega, v)$ by $\varphi^*(\mathbf{r}, \Omega, v)$, then the equality (7) becomes the conjugate equation of the reactor,

$$L^*\varphi^* = 0. \quad (9)$$

As a result of the above, we arrive at the conjugate problem relative to that posed by (1) and (2):

$$-\Omega\nabla\varphi^* + \Sigma\varphi^* - \int dv' \int d\Omega' \varphi^*(\mathbf{r}, \Omega', v') w(\mu_0, v \to v') = 0, \quad (10)$$

$$\varphi^*(\mathbf{r}, \Omega, v) = 0 \text{ on } S \quad \text{for} \quad \Omega\mathbf{n} > 0. \quad (11)$$

The simplest conjugate reactor equations were introduced by E. Wigner in [3]. For the single-velocity problem, the conjugate equation was formulated in a very general form by K. Fuchs [69] and N. A. Dmitriev (see [30]). The most complete conjugate reactor equation, taking moderation into account, was obtained by L. N. Usachev [30]. The latter also gave a physically illustrative interpretation of the conjugate function as the "value" of the neutrons. The theory of conjugate equations was further generalized by B. B. Kadomtsev [70] for the nonhomogeneous equations of particle transfer. In the work by the author and V. V. Orlov [27], a method was developed for obtaining conjugate equations for a wide class of nonhomogeneous linear problems, and the theory of disturbances for various linear functionals was also formulated in general form.

In the cases of the calculation of critical mass, the space-energy distribution of current, and the neutron value, the exact solution of the kinetic Eq. (1) for the boundary condition (2) is very difficult. In the majority of cases therefore, only approximate solutions are sought. Among the approximate methods that are useful in this work, an

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especially important example is the diffusion approximation. The essence of the method lies in the fact that the solution of the problem (1) and (2) can be written as a series of spherical harmonics, and the first two terms of the series can be used as an approximation [10] (the P_1-approximation).

Therefore,

$$\varphi(\mathbf{r}, \Omega, v) = \frac{1}{4\pi}[\varphi_0(\mathbf{r}, v) + 3\Omega\varphi_1(\mathbf{r}, v)], \qquad (12)$$

where the function φ_0 is the total neutron flux through the surface of a unit sphere with center at the point $\mathbf{r}$, and $\boldsymbol{\varphi}_1$ is the vector flux of neutrons at the point $\mathbf{r}$.

We expand the function $w(\mu_0, v' \to v)$ in a series of Legendre polynomials and retain only the first two terms. We then have

$$w(\mu_0, v' \to v) = \frac{1}{2}[w_0(v' \to v) + 3\mu_0 w_1(v' \to v)]. \qquad (13)$$

If we substitute the expressions in (12) and (13) in Eq. (1), we obtain the system of integro-differential equations

$$\left.\begin{aligned} &\nabla\varphi_1 + \Sigma\varphi_0 - \int dv' w_0(v' \to v) \times \varphi_0(\mathbf{r}, v') = 0; \\ &\frac{1}{3}\nabla\varphi_0 + \Sigma\varphi_1 - \int dv' w_1(v' \to v) \times \varphi_1(\mathbf{r}, v') = 0. \end{aligned}\right\} \qquad (14)$$

The boundary condition for the system of Eqs. (14) is obtained, according to R. Marshak [10], in the form

$$2\varphi_1\mathbf{n} - \varphi_0 = 0 \quad \text{on } S. \qquad (15)$$

The system of Eqs. (14), together with the boundary condition (15), form the closed system of basic equations for a reactor for the diffusion approximation.

The system of adjoint reactor equations, for the diffusion approximation, can be obtained similarly, and is

$$\left.\begin{aligned} &-\nabla\varphi_1^* + \Sigma\varphi_0^* - \int dv' w_0(v \to v') \times \varphi_0^*(\mathbf{r}, v') = 0; \\ &-\frac{1}{3}\nabla\varphi_0^* + \Sigma\varphi_1^* - \int dv' w_1 \times (v \to v')\,\varphi_1^*(\mathbf{r}, v') = 0 \end{aligned}\right\} \qquad (16)$$

The boundary condition for the system of Eqs. (16) is

$$2\varphi_1^*\mathbf{n} + \varphi_0^* = 0 \quad \text{on } S. \qquad (17)$$

The set of Eqs. (16), together with the boundary condition (17), form the closed system of adjoint reactor equations for the diffusion approximation.

Similar equations and boundary conditions that can be obtained for various more accurate approximations than the above can also be obtained by applying the spherical-harmonic method.

In connection with the fact that it is very difficult to solve the main and adjoint reactor equations in their most general form, and that the solution can be obtained only in very rare cases, the necessity arises of developing

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various approximate methods. One of the most widely-used approximate methods is the multigroup method. This method is based on breaking up the whole neutron-velocity range in the reactor into partial intervals, in each of which it is assumed that the physical parameters are constant. Then, in each of the groups, in which the physical parameters are assumed to be constant, we can integrate the Eq. (1) within the limits of the given energy group, and use as unknowns the integral neutron flux for the groups. We formally arrive at a multigroup system of equations for the reactor. Thus, for example, the multigroup system of basic equations in the P_1-approximation is [5, 6]

$$\left.\begin{aligned} &\nabla\varphi_1^j + \Sigma_0^j\varphi_0^j - \sum_l \overset{l\to j}{\Sigma_0}\varphi_0^l = 0;\\ &\frac{1}{3}\nabla\varphi_0^j + \Sigma_1^j\varphi_1^j - \sum_l \overset{l\to j}{\Sigma_1}\varphi_1^l = 0 \end{aligned}\right| \tag{18}$$

with the condition that

$$2\varphi_1^j\mathbf{n} - \varphi_0^j = 0 \text{ on } S. \tag{19}$$

The multigroup system of adjoint equations becomes

$$\left.\begin{aligned} &-\nabla\varphi_1^{*j} + \Sigma_0^j\varphi_0^{*j} - \sum_l \overset{j\to l}{\Sigma_0}\varphi_0^{*l} = 0;\\ &-\frac{1}{3}\nabla\varphi_0^{*j} + \Sigma_1^j\varphi_1^{*j} - \sum_l \overset{i\to l}{\Sigma_1}\varphi_1^{*l} = 0, \end{aligned}\right\} \tag{20}$$

where the boundary condition at the outer surface is

$$2\varphi_1^{*j}\mathbf{n} + \varphi_0^{*j} = 0 \text{ on } S. \tag{21}$$

It is necessary to use perturbation theory to obtain the system of multigroup constants Σ_0^j, Σ_1^j and functions $\overset{l\to j}{\Sigma_0}$, $\overset{l\to j}{\Sigma_1}$. For this, we require that in the transition from the problem (1) and (2), which we will call the unperturbed problem, to the multigroup perturbed problem (16) and (17), the critical dimensions of the reactor or any other characteristic parameters of the problem remain constant.

We thus arrive at the following formulas for the group constants [5, 6]:

$$\left.\begin{aligned} &\Sigma_0^j = \frac{\int\limits_{G_n} d\mathbf{r}\varphi_0^{*j}\int\limits_{v_{j-1}}^{v_j} dv\Sigma\varphi_0}{\int\limits_{G_n} d\mathbf{r}\varphi_0^{*j}\int\limits_{v_{j-1}}^{v_j} dv\varphi_0},\\ &\Sigma_1^j = \frac{\int\limits_{G_n} d\mathbf{r}\varphi_1^{*j}\int\limits_{v_{j-1}}^{v_j} dv\Sigma\varphi_1}{\int\limits_{G_n} d\mathbf{r}\varphi_1^{*j}\int\limits_{v_{j-1}}^{v_1} dv\varphi_1};\\ &\overset{l\to j}{\Sigma_0} = \\ &\frac{\Delta v_j\int\limits_{G_n} d\mathbf{r}\varphi_0^{*j}\int\limits_{v_{l-1}}^{v_l} dv\varphi_0\int\limits_{v_{j-1}}^{v_j} dv' w_0(v\to v')}{\int\limits_{G_n} d\mathbf{r}\varphi_0^{*j}\int\limits_{v_{l-1}}^{v_l} dv\varphi_0}; \end{aligned}\right\} \tag{22}$$

$$\overset{l\to j}{\Sigma_1} = \frac{\Delta v_j \int\limits_{G_n} d\mathbf{r}\varphi_1^{*j} \int\limits_{v_{l-1}} dv\varphi_1 \int\limits_{v_{j-1}} dv' w_1 (v \to v')}{\int\limits_{G_n} d\mathbf{r}\varphi_1^{*j} \int\limits_{v_{l-1}}^{v_l} dv\varphi_1}. \tag{22}$$

In the formulas (22), it has been assumed that we know the neutron-flux spectrum at every point of the reactor and the multigroup neutron value. Strictly speaking, however, neither the neutron flux or the multigroup neutron value is known beforehand, so that the exact values of the group constants, defined by the formulas (22), are unknown.

The above formulas can nevertheless be successfully applied in the approximate calculation of the group constants. Thus, for example, in the active zone of the reactor the mean of the constants can be obtained by taking into account the spectrum of the equivalent reactor without neutron reflectors, and in the reflector the mean can be obtained from the integral neutron flux obtained beforehand from the balance relations for the reactor. Such an approximate method has been developed by S. B. Shikhov [41, 42].

There are other methods of averaging that take into account more precisely the concrete features of a reactor. After the approximate neutron spectrum has been found, the algorithm for averaging the physical constants of a reactor with one-dimensional geometry is as follows. In the formulas in (22), we set $\varphi_0^{*j} = 1$ and $\varphi_1^{*j} = \mathbf{k}$, where $\mathbf{k}$ is a vector in the direction of the normal to the coordinate surface, and we obtain a simple system of group constants which can be used in the solution of the adjoint multigroup problem (20) and (21). After this, we again calculate the group constants, etc. This process converges very rapidly, so that after two or three iterations the group constants are sufficiently accurate. After this, the set of group constants that have been obtained is used in the solution of the multigroup system of reactor Eqs. (18) and (19).

If the group interval is sufficiently small for the neutron flux to vary only slightly within the limits of each group, then the averaging of the physical parameters is not essential, and in this case we can determine a universal system of group constants, independent of the neutron spectrum in the reactor. If, on the other hand, the group intervals are large, then for intermediate and fast reactors it is necessary to use the averaging method described above.

We note, in conclusion, that in spherical-harmonic methods of higher accuracy than the P_1-approximation, we can obtain group-average formulas similar to those given in (22). To obtain the mean constants from these formulas, it is necessary to know the neutron spectrum at every point of the reactor. The spectrum is obtained by using various approximate methods, among which is the P_1-approximation method.

Numerical Spherical-Harmonic Methods of Solution

Among approximate methods of solving the kinetic equations, the spherical-harmonic method occupies a conspicuous place. This method was developed by G. Vik, and improved by R. Marshak [10], L. N. Usachev [29], B. Devison [4], G. Mark [71], V. S. Vladimir [43, 44], and others. The basis of the method is to obtain the solution of the kinetic equation in the form of a Fourier series of spherical harmonics. To obtain the unknown Fourier coefficients, we have an infinite system of differential equations (with derivatives with respect to the geometrical coordinates).

We consider, for simplicity, a one-velocity kinetic equation, which is an element of the group calculations. If it is assumed that the neutron dispersion in the laboratory system of coordinates is obtained as a function g (μ_0), then the neutron-transport equation for the plane-parallel problem will have the form

$$\mu \frac{\partial \varphi}{\partial z} + \Sigma\varphi = \frac{\Sigma_s}{2} \int\limits_{-1}^{1} d\mu' g(\mu_0)\, \varphi(z, \mu') + f(z, \mu), \tag{23}$$

where $\mu_0 = \mu\mu' + \sqrt{1-\mu^2}\sqrt{1-\mu'^2}\cos\alpha$ with α as the azimuth.

We will seek a solution of the Eq. (23) in the form

$$\varphi(z, \mu) = \frac{1}{2}\sum_{l=0}(2l+1)\varphi_l(z)\,p_l(\mu), \tag{24}$$

where $P_l(\mu)$ is a Legendre polynomial. As a result, we obtain the system of ordinary differential equations

$$m\frac{d\varphi_{m-1}}{dz} + (m+1)\frac{d\varphi_{m+1}}{dz} + (2m+1)\Sigma_m\varphi_m = (2m+1)f_m, \tag{25}$$

where

$$\Sigma_m = \Sigma - g_m\Sigma_s;$$

and g_m and $f_m(z)$ are Fourier coefficients in the expansion of the functions $g(\mu)$ and $f(z, \mu)$ in the series of Legendre polynomials.

On the outer boundary of the region, we use Marshak's conditions

$$\int_{-1}^{0} d\mu\mu^{2i+1}\varphi = 0 \text{ on } S\ (i = 0, 1, 2, \ldots). \tag{26}$$

When we substitute the solution (24) in the condition (26), we arrive at the boundary conditions for the Fourier coefficients

$$\sum_{m=0}^{\infty} a_{im}\varphi_m = 0 \text{ on } S, \tag{27}$$

where a_{im} are given numbers.

For the solution of the system of ordinary differential Eqs. (25) with the condition (27), we use the apparatus of matrix calculus. With this in view, we introduce the vectors

$$\boldsymbol{\varphi} = \begin{Vmatrix} \varphi_0 \\ \varphi_2 \\ \cdots \\ \cdots \end{Vmatrix}, \quad \mathbf{J} = \begin{Vmatrix} \varphi_1 \\ \varphi_3 \\ \cdots \\ \cdots \end{Vmatrix},$$

$$\mathbf{f} = \begin{Vmatrix} f_0 \\ f_2 \\ \cdots \\ \cdots \end{Vmatrix}, \quad \mathbf{F} = \begin{Vmatrix} f_1 \\ f_3 \\ \cdots \\ \cdots \end{Vmatrix},$$

and consider separately the Eqs. (25) for even values of "m", 0, 2, 4, and for odd values 1, 3, 5, . . .

We then obtain the matrix equations

$$\left.\begin{aligned} \alpha\frac{d\mathbf{J}}{dz} + \mathbf{a}\boldsymbol{\varphi} = \mathbf{f}; \\ \beta\frac{d\boldsymbol{\varphi}}{dz} + \mathbf{b}\mathbf{J} = \mathbf{F}, \end{aligned}\right\} \tag{28}$$

where $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\mathbf{a}$ and $\mathbf{b}$ are known matrices, determined from the coefficients of the Eqs. (25). At the same time, the boundary condition can be written

$$\mathbf{A}\boldsymbol{\varphi} + \mathbf{B}\mathbf{J} = 0 \text{ on } S. \tag{29}$$

The final problem consists of solving the system of Eqs. (28) with the boundary conditions (29).

By the application of methods that are well established in the calculus of finite differences, the Eqs. (28), in the case of piece-wise continuous coefficients, can be written as the single three-point, matrix, finite-difference system of equations

$$\varphi_{k+1} - B_k\varphi_k + C_k\varphi_{k-1} = -g_k, \tag{30}$$

where k is the number of the point on the z-axis, B_k and C_k are matrices, and g_k is a vector.

The Eq. (30) is resolved by the matrix-factorization method into the three difference equations of the first order:

$$\left.\begin{aligned} \boldsymbol{\beta}_{k+1} &= \mathbf{C}_{k+1}(\mathbf{B}_k - \boldsymbol{\beta}_k)^{-1}; \\ \mathbf{z}_{k+1} &= \boldsymbol{\beta}_{k+1}(\mathbf{z}_k + \mathbf{g}_k); \\ \boldsymbol{\varphi}_k &= \mathbf{C}_{k+1}^{-1}(\boldsymbol{\beta}_{k+1}\boldsymbol{\varphi}_{k+1} + \mathbf{z}_{k+1}). \end{aligned}\right\} \tag{31}$$

The set of Eqs. (31) is supplemented by given "initial" conditions obtained from the boundary conditions [5, 6].

The matrix-factorization method is the most effective numerical method of solution of spherical-harmonic equations, and it can be used to solve any problems in one-dimensional plane, cylindrical, or spherical geometries. As an illustration, we note that the kinetic equation for an infinite cylinder in the P_3-approximation, for five zones and 60 points, can be solved by an electronic computer in 7 sec. The critical dimension of a spherical reactor, in the multigroup P_3-approximation, is obtained by a computer in only four times the calculating time needed for the P_1-approximation.

It can evidently be asserted, at least for one-dimensional problems, that the solution of kinetic equations by the spherical-harmonic method, in combination with numerical, matrix-factorization method, yields a very effective algorithm.

We should also mention another numerical method of solving the spherical-harmonic equations, developed by S. K. Godunov, and presented at the All-Union Conference on approximate methods in Moscow in 1960.

This method consists of the solution of the boundary-value problem for a system of spherical-harmonic equations, by using problems with initial values. A stable numerical algorithm is obtained by applying a special algorithm for the systematic smoothing of rounding errors arising in the calculation.

Small-Group Approximations

In the application of electronic computers in the design of nuclear reactors, certain difficulties are often encountered, connected with the limitations of the machines available. First of all, this applies to the memory of the machines and their speed of operation. In this connection, the question arises of the most convenient mathematical arrangement of a problem in given circumstances, and the arrangement that will ensure that the solution will contain the maximum possible amount of information. We note that the information must be not only complete, but also reliable.

In the physical calculations for a reactor, the multigroup operation is desirable for two- or three-dimensional cylindrical reactors, carried out with the fewest possible steps, and taking into account the various physical effects in the P_n-approximations. It is clear, however, that the contemporary numerical computers cannot carry out the solution of the problem we are considering completely, even with the program needed for the design. The solution of these problems demands such a great amount of machine time that the calculation is neither economically rational nor justified.

The physical calculations for a reactor can be broken up into several very simple problems, the solution of which is not difficult. The set of solutions of the corresponding one-dimensional problems, in conjunction with perturbation theory, can be used to yield very complete information on the details necessary in the design of a reactor. The complex problem is thus replaced by a collection of more or less simple problems, for which the solutions can be obtained by using electronic computers. This means that in each concrete case we must determine the choice of simple problems that will provide the information necessary for the design of the projected system.

In connection with what has been described, a verylive question at the present is that of the small-group system of reactor equations.

In what follows, we will consider the one-group and the three-group methods.

The critical mass of a reactor can be found by using the effective one-group theory and the formulas (18) to (31) with the assumption that all the neutrons are combined into one group. For this, we can obtain a system of effective one-group constants by solving the multigroup problem in the P_1-approximation. The resulting one-group kinetic equation will be used in the following for making more precise the calculation of critical parameters of a reactor in the P_3-approximation. The simplest method of taking the kinetic effects into account is the following. We solve the multigroup system of equations of the reactor in the P_1-approximation, then obtain the mean constants for the one-group theory, and finally solve the one-group problem in the P_3-approximation. A comparison of the calculations of the critical masses in the P_3-approximation using the multigroup method with the corresponding calculations for the one-group theory indicates a very high accuracy for the one-group calculations, which is completely satisfactory for all practical purposes.

If the one-group theory can be used only in making the value of the critical reactor mass more precise, then the three-group method will give an essential improvement in the accuracy of the energy-output field in the active zone of the reactor. In the method we are considering, the fast neutrons are combined into one group, the intermediate-energy neutrons into another group, and the thermal-energy neutrons into a third. Thus, the solution of the problem again begins with the solution of one-dimensional, multigroup, reactor equations in the P_1-approximation. The neutron flux thus obtained is subsequently used in the calculation of the effective three-group constants. By using the three-group system of equations, we can improve the accuracy of calculation of the critical mass and the energy output in the P_3-approximation and also carry out the physical calculations for the reactor in two-dimensional or three-dimensional geometry.

The one-group and the three-group methods of reactor calculation, using effective methods for averaging the constants, was proposed by the author of the present article [5, 6], and subsequently developed by him in collaboration with E. I. Pogudalin and V. P. Kochergin.

Heterogeneous Reactor Design

The theory of heterogeneous-reactor design, in the case of thermal neutrons was begun by S. M. Feinberg [23], A. D. Galanin [2], [26], G. A. Bat [72], and others. This theory can be used to carry out the direct calculation of the critical parameters of a heterogeneous reactor and the neutron spectra. The theory is based on the following assumptions [23].

The field of the thermal neutrons in the region of a core containing the active isotope is axially symmetric, so that the neutron sources and sinks can be considered to be linear. To describe the diffusion of the thermal neutrons between the cores, we can apply the elementary diffusion equation. Finally, the absorptive capacity of the uranium cores is characterized by the logarithmic derivative of the neutron flux at the core surface. When these assumptions are used, the problem of critical-mass calculation for a heterogeneous reactor, using influence functions, reduces to a system of homogeneous, linear, algebraic equations.

In the calculations of the critical mass of a reactor we can also use effective homogenization methods, including the calculation of the effective constants for fast, intermediate, and thermal neutrons.

We consider, first of all, the calculation of effective constants for the energies of the fission spectrum. In this case, it is of particular importance to calculate the capture-fission cross section for U^{238}, since this cross section can be used to calculate the multiplication coefficient of the reactor for fast neutrons. The calculation of the effective capture-fission neutron cross section is carried out, taking into account the mutual shielding of the uranium cores, by using the method of successive collisions [1]. Other constants are calculated using various homogenization methods [62, 73, 74].

Resonance effects in the intermediate-energy range are taken into consideration by using effective resonance integrals, and the cross sections, varying smoothly with the energy, are subjected to the process of formal homogenization. If the core-effect exists, i.e., if the neutron flux varies considerably between the reactor cells, then we must use effective homogenization methods.

In the calculation of the one-group constants for the thermal group of neutrons, we first of all consider the problem of finding the space-energy neutron distribution in a reactor cell, taking the thermalization into account. The calculation is carried out in the P_1-approximations. The one-group averaging of the constants is then performed. The resulting constants are used for the one-group calculation of the integral spectrum of the slow neutrons in the P_1 and P_3-approximations for the volume of a cell. The cross sections relative to a cell are finally averaged, to obtain the effective constants for the equivalent homogenized reactor. If the calculations in the P_1 and P_3- approximations, in the one-group model, lead to an essential difference in the calculations for the homogenized constants, then it is necessary to use the calculation of the space-energy distribution of the neutrons in the P_3-approximation, taking into account the thermalization.

The numerical methods of calculating the spectra of slow neutrons were developed by the author and V. V. Smelov [75, 62]. Further theoretical results on these questions can be found in the works of V. V. Smelov, L. V. Maiorov, and others.

In the results of A. D. Galanin [2, 76], some theoretical developments are given concerning the spectrum of slow neutrons in a heterogeneous medium, and important estimates are given, which agree well with the results of numerical calculations.

After the effective homogenized constants have been obtained, the calculations for a heterogeneous reactor are the same as those for a homogeneous reactor, and can be carried out with the program used for the latter.

The Calculation of the Compensating Capacity of the Controlling Rods

The calculation for the compensating system of a reactor is the most complex problem of physical design. This problem can be solved, more or less simply, only in the case when the compensating rod is completely inserted into the reactor and there are no end reflections (the latter can be replaced by effective additions to the height), and the rod coincides with the axis of the reactor. In this case, the problem reduces to a one-dimensional problem, and can be solved in the multigroup approximation by using effective boundary conditions at the surface of the compensating rods. Let the introduction of a rod change the characteristic number $\lambda = 1/K_{eff}$ of the problem by the quantity $\delta\lambda_0$. In the diffusion approximation for a cylindrical core, the formula for $\delta\lambda_0$ was obtained by L. N. Usachev:

$$\delta\lambda_0 = \frac{2\pi r_0}{\int\limits_G drQQ^*} \sum_j \frac{D^j}{\gamma^j} \varphi_0^{*j} \varphi_0^j,$$

where γ^j is the logarithmic derivative on the interval of the group [77](ν_{j-1}; ν_j); r_0 is the radius of the core, G is the reactor volume, Q (r) is the total number of secondary neutrons and $Q^*(r)$ is the neutron fission value. The quantity $\delta\lambda$ for a rod located at a distance r_j from the center can be estimated by using a formula from perturbation theory obtained by L. N. Usachev [29]:

$$\delta\lambda_j = \delta\lambda_0 \frac{Q^*(r_j)\,Q(r_j)}{Q^*(0)\,Q(0)},$$

where Q^* (r) and Q(r) are unperturbed functions, obtained in the absence of the rod. We note the point that perturbation theory yields a value for the quantity $\delta\lambda_j$ only, and cannot be used to calculate the neutron flux or the function Q(r) in the presence of a rod. The calculation of the neutron flux, even in the very simple case where the rod is located at a distance r from the center of the cylinder, involves the solution of a two-dimensional problem in the (r, θ) plane.

We arrive in a similar way at the necessity of solving a two-dimensional problem when a rod, situated at the point $r = 0$, is partly withdrawn from the reactor. The same case occurs when we consider a compensating cylinder, or a set of compensating cylinders situated symmetrically relative to the origin.

The calculation is still more complicated when a system of compensating rods in a reactor is considered for various methods of withdrawing the rods from the reactor with the consumption of the active part of the uranium. In this case, it is necessary to carry out calculations for a series of three-dimensional reactors with various rod positions.

The above two-dimensional and three-dimensional problems can be solved by an effective three-dimensional method in the P_1-approximation with effective boundary conditions at the surface of the compensating rods or cylinders.

The Problem of the Physical Design of a Reactor

The advent of high-speed computer techniques in numerical analysis has provided the necessary prerequisite for the physical calculations for nuclear reactors with any spectra, and with various complicated setups for the active elements and the moderation. Here, it is necessary to formulate a single method which can be used to carry out the calculations for a homogeneous reactor with any possible spectra from fast to thermal. Such an approach is naturally only possible when the method developed takes into account all the basic features of the moderating mechanism for various energies and also takes into account the cross sectional structure of the nuclear processes.

In the majority of cases, the calculation of the critical mass and the neutron spectrum is possible in the P_1-approximation. An exception is the type of reactor in which the mean free neutron path is comparable to the characteristic dimensions of the reactor. The calculations in the case of this type of reactor in the P_1-approximation can lead to gross errors in the determination of critical mass and of neutron spectrum. In this case it is necessary, in the calculations, to use a more accurate approximation than the P_1- approximation. For such calculations we must use, for example, the P_3-approximation.

The performance of the serial multigroup calculations for a reactor in the P_3-approximation on a computer can use considerable amounts of machine time. The calculation of critical masses can therefore be performed by using effective one-group theory, programmed for the calculations in the P_1-approximation.

It is very important in the calculations to take account of the resonance structure of the cross sections, and also the thermalization of the neutrons.

All the above particulars of the reactor must be taken into consideration in obtaining the mathematical algorithm for solving the problem of calculating the critical dimension of the reactor. In what follows, we will formulate some algorithms for the solution of the basic problems involved in the physical design of nuclear reactors with various spectra. The aim of these algorithms is to lead to programs for electronic computers.

In the USA, programs for multigroup calculation are based on algorithms developed by G. Hurwitz and R. Erlich [48, 78].

In the calculation of the critical dimension of a reactor in the P_1-approximation, the neutrons of all possible energies are divided up into groups. Neutrons with energies less than v_{gr} are combined into one group, to which effective constants are ascribed. Both elastic and nonelastic effects should be taken into consideration in the neutron-dispersion process. In the neutron moderator, we must consider the resonant character of the capture and scattering cross section. The neutrons arising during the fission process are distributed in groups corresponding to the fission spectrum. The zero-order and first-order moments must be taken into account in the neutron-scattering function.

The system of basic and adjoint equations for the reactor is solved by using the method of successive approximations [5].

In the one-dimensional and two-dimensional cases, the solution of the reactor equations is carried out for each group by using finite differences. In the calculation, it is convenient to use the simplest possible difference schemes, in which the discontinuities in the coefficients in the equations coincide with the points used in the calculations [5, 6, 46, 47]. The finite-difference equations for one-dimensional regions are solved by the factorization method, while for two-dimensional regions various relaxation methods are applied [68, 79]. A very general algorithm for the calculations arising from two-dimensional reactors was obtained by T. A. Germogenov.

In those cases where the calculation of the critical mass of a one-dimensional reactor in the P_1-approximation is not satisfactory, we can use the P_3-approximation. Multigroup systems are formulated for the basic adjoint equations for the given one-dimensional geometry in this case.

In the majority of cases, the critical mass can be satisfactorily determined by using the first two moments in the scattering function. We must mention, however, that the calculation of the neutron spectrum at large distances from the active zone should preferably include four moments, since in this case the anisotropy of the neutron flux must be taken into account more accurately.

In calculations for reactors with dimensions that are not very large, it is necessary to solve the multigroup kinetic equations. In the transport approximation, this problem reduces to the successive solution of single-velocity Boltzmann kinetic equations. For spherically symmetric regions, we have the equation

$$\mu \frac{\partial \varphi}{\partial r} + \frac{1-\mu^2}{r} \frac{\partial \varphi}{\partial \mu} + \Sigma \varphi = Q(r) \qquad (32)$$

and the boundary condition

$$\varphi(r, \mu) = 0 \quad \text{for} \quad \mu < 0. \qquad (33)$$

Here

$$Q(r) = \frac{\Sigma_s}{2} \int_{-1}^{1} d\mu \varphi + f(r); \qquad (34)$$

where f (r) is a given function.

For the solution of the Eqs. (32) to (34), we can use Vladimirov's method of characteristics [43, 44], or the S_n-method of Carlson [80]. Both these methods are based on iteration processes, in which each iteration involves the calculation of the quantity Q(r) from its value obtained in the previous calculation.

The method of characteristics uses the change of variables

$$x = r\mu; \;\; y = r\sqrt{1-\mu^2},$$

where the partial differential equation (32) is reduced to an ordinary differential equation of the first order, which is solved for y = const. In the solution of the above equation, Vladimirov applies a very original numerical scheme, which permits a very efficient use of the results of the calculation. After obtaining the solution φ (r, μ) at the points of a special grid, the function Q(r) is calculated. The process continues in the same way.

The essence of the S_n-method of Carlson is the numerical solution of the Eqs. (32) - (34) using a finite-difference method, in which the interval $-1 \leqslant \mu \leqslant 1$ is broken up into 2n equal parts, and inside the intervals (μ_{j-1}, μ_j) the function $\varphi(r, \mu)$ is assumed to be linear relative to the variable μ. This results in the problem being reduced to the solution of 2n ordinary differential equations, which can be solved successively. For the solution, finite-difference methods are used. When the solution $\varphi(r, \mu)$ has been obtained at all the grid points, a new approximation for the function Q (r) is calculated.

The methods of Vladimirov and Carlson have been well-programmed for computers, and they yield a very convenient mathematical apparatus for the solution of a wide range of problems.

In conclusion, we will describe the basic programs for the physical design of reactors. The algorithms developed for the solution of problems involved in the physical calculations for a reactor were used to write programs for the computers "BESM-2", "Ural," and others. In view of the impossibility of including the whole system of programs, written for the physical calculations, we will consider only the most characteristic programs concerned with the calculation of the critical masses of reactors which have been widely used in the scientific establishments of the Soviet Union.

Program for the 25-group calculations for reactors in any one-dimensional geometry in the P_1-approximation. The effects are taken into account of elastic and nonelastic neutron scattering, and the resonance effects in the fissionable elements. Thermalization of neutrons is taken into account within the framework of the gas model. In the scattering functions, the two first moments are used. The number of zones is up to nine, the number of points in space is up to 200. In this program the calculation begins with the determination of the critical dimension of the equivalent reactor without reflection. When the critical dimension has been found for a reactor with reflections, the physical constants are averaged for the one-group model. Further accuracy in the critical dimension is obtained in the P_3-approximation.

Program for the solution of a 25-group system of adjoint equations in the P_1-approximation for one-dimensional reactors in plane, cylindrical, and spherical geometry. The same effects are taken into consideration as in the program for the basic equations.

Program for the calculation of the critical dimension for a reactor and the neutron flux in the P_2-approximation. Number of groups – up to 25. The number of zones and points are those corresponding to the program for calculations for a reactor in the P_1-approximation. This program is used for designing shielding.

Program for the calculations for a reactor with one-dimensional geometry in the P_3-approximation. Number of groups – up to 25, number of zones, – up to six. Number of points in space – up to 100.

Program for the calculation of the compensating capacity of controlling rods. The calculation is carried out in the multigroup approximation. Number of groups – up to 25, number of reactor zones – up to nine.

Program for calculations for a heterogeneous reactor. Number of groups – up to 25. Solution obtained by the method of effective homogenization. For averaging the constants, the method of Wigner-Zeits is used in the P_3-approximation.

Program for calculating the effective resonance integral, taking into account the thermal motion of the nuclei. Number of resonance levels arbitrary.

Program for calculations for reactors taking into account the strong absorption of moderated neutrons. For 18 groups, three zones, and 50 points.

The above programs were written by the author in collaboration with V. P. Kochergin, E. I. Pogudelin, L. I. Kuznetsov, T. I Zhuravlev, V. V. Smelov, G. A. Ilyasov, F. F. Mikhailis, and others.

Program for calculating the critical mass of a fast reactor, using Carlson's S_4-method. Number of zones – up to five, number of points – up to 60, number of groups – up to nine.

This program was written by V. P. Kochergin, E. I. Zhuravlev and M. M. Antimonik.

Program for calculations for a two-dimensional cylindrical reactor in the P_1-approximation. Zones – up to 100, number of points – up to 900, number of groups – nine. Written by T. A. Germogenov and V. N. Torobtsev, under the direction of E. S. Kuznetsov.

Program for the calculations for a two-dimensional cylindrical reactor, in the diffusion two-dimensional approximation. Written by V. K. Saul'ev.

Program for the calculations for a one-dimensional reactor in the P_1-approximation. Suitable for the calculation of the critical mass and neutron spectrum in a reactor with strong absorption of moderated neutrons, taking into account the hydrogen content of the components. Number of zones – up to five, number of points – up to 100. Written by N. Ya. Lyashchenko.

In the present outline, it is impossible to describe all the programs for the physical calculations for reactors. The number of such programs is very great. In all these programs, however, there are to a certain extent the component elements that are used as fundamental components of the programs we have described. These are the programs for calculating the kinetics of reactors, the duration of operation of reactors, the compensation required during their operation, programs for calculating the dynamic processes in reactors, programs for thermal calculations, programs for calculating the protection needed against the radiation, and many others.

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All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

THE FUTURE OF FAST REACTORS

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The possibility of the full utilization of uranium for nuclear-power needs is associated with the realization of cycles which achieve expanded regeneration of nuclear fuel. As we know, this cannot be achieved by means of thermal or intermediate reactors. The regeneration coefficient in such systems proves to be less than unity for a closed uranium-plutonium cycle, and the quantity of uranium which is used in the optimum case can reach only several percent of the total amount of available uranium. Thus, the industrial development of nuclear power which is based on the use of thermal or intermediate reactors would lead to rapid depletion of natural-uranium resources and could not appreciably expand the existing power resources. A different situation obtains in the case where fast reactors are used. In such reactors it is possible to achieve high values of the regeneration coefficient which appreciably exceed unity (approximately 1.4 to 1.8). The use of fast reactors makes it possible to solve the problem of the full utilization of all the available uranium, thus satisfying the requirements of mankind for power over a prolonged period.

In principle the possibility of achieving a high regeneration coefficient in fast reactors was proved several years ago [1, 2]. Thereafter the basic research efforts were directed at solving engineering problems from the point of view of engineering realizability of industrial fast reactors.

The characteristics of the chain reaction based on fast neutrons differs substantially from the characteristics of a chain reaction for fission based on thermal neutrons. Since the corresponding fission cross sections are very small (approximately 200 to 300 times smaller than they are for thermal neutrons), the concentration of the substance which is subjected to fission and comprises the critical mass in the active zone of a fast reactor must be much higher than in thermal systems. Table 1 shows the magnitudes of nuclear fuel concentration in several power reactors for comparison purposes [3].

The second feature of a fast-neutron chain reaction is related to the fact that in the active zone of fast reactors it is expedient to use U^{238} to dilute the nuclear fuel in order to increase the regeneration coefficient; U^{238} is characterized by a relatively large fast-neutron absorption effect. The exact values of this effect depend on the neutron spectrum, but on the average it can be assumed that the ratio between the radiation-capture cross section in U^{238} and the plutonium (or U^{235}) fission cross section for fast neutrons is approximately 20 to 30 times greater than it is for thermal neutrons. This makes it necessary to use either a fuel mixture $Pu + U^{238}$ with a large plutonium content, or highly enriched uranium. Comparative data on the magnitudes of uranium enrichment in various reactors are cited in Table 1 [3].

In themselves, the indicated features do not give rise to any particular engineering difficulties if we are speaking merely of designing fast-neutron systems (for example, reactors for physics or engineering research). However, in designing industrial power reactors, whose primary purpose is to assure a sufficiently high economic efficiency, the special features governing the course of the chain reaction based on fast neutrons give rise to certain rather complex engineering problems. First of all, it is quite obvious that due to the large concentration of nuclear fuel we require intensification of the heat removal and an increase in the energy intensity in the active zone in order to reduce the relative part played by capital expenditures associated with the critical mass. From this it follows immediately that it is necessary to use liquid-metal heat carriers, since (for example) gases cannot assure the required heat removal, and water or organic liquids are inapplicable because of their moderating properties. The development of the technology for using liquid metals as heat carriers on an industrial scale is one of the most important problems which arises in designing fast reactors. Evidently, the most promising is the use of a sodium heat carrier. Comparative engineering data for certain power reactors are cited in Table 1.

TABLE 1. Comparative Characteristics of Various Types of Reactors

Characteristic of the reactor	Atomic electric power stations with thermal reactors				Atomic electric power stations with fast reactors		
	Beloyarsk (USSR)	Novo-Voronezhsk (USSR)	"Yankee Atomic" (USA)	Dresden (USA)	Bradwell (England)	"Enrico Fermi" (USA)	Projected Station (USSR)
Thermal power, Mw.	285	710	392	626	531	300	750
Fuel	U^{235}	U^{235}	U^{235}	U^{235}	U^{235}	U^{235}	U^{235}
Fuel concentration in the active zone, g/liter	5	34	94	38	2	1360	625
Enrichment, percent	1.3	1.5	3.4	1.5	Natural	26.5	21.6
Heat carrier	Water	Water	Water	Water	CO_2	Sodium	Sodium
Energy Intensity, kw/liter	1.2	43	52	29	0.6	855	600
Specific Power, kw/kg	250	1200	550	670	320	620	950

In the last line of Table 1 the values are cited for a basic quantity which characterizes the economy with which the capital expenditures for nuclear fuel are used (the specific power). It is evident from the table that in fast reactors it is possible to achieve the same high values of specific power as it is for thermal reactors. The design possibilities, generally speaking, make it possible to achieve an even higher specific power. But from the economic point of view this is impractical, for a further increase in the specific power the amount of fuel retained after emptying the reactor (before chemical processing) increases when the activity drops; this causes the economic indices of the cycle to deteriorate. The quantity of retained fuel increases as the specific power of the active zone increases. In fact, for a reactor with a specified power it follows that as the energy intensity increases, the dimensions of the reactor decrease; therefore the enrichment of the fuel must also be greater (due to the increase in neutron leakage). As a result we find that for a specified maximum depth of the fuel mixture burnout the amount of fuel extracted per unit time increases. The effect of this increase predominates over the effect involving the reduction of the critical mass for a high energy intensity. Typical curves for the dependence of the amount of nuclear fuel used in the fuel cycle are shown in Fig. 1 for a fast reactor in a projected atomic electric power station as a function of energy intensity for a specified power rating of 750 Mw.

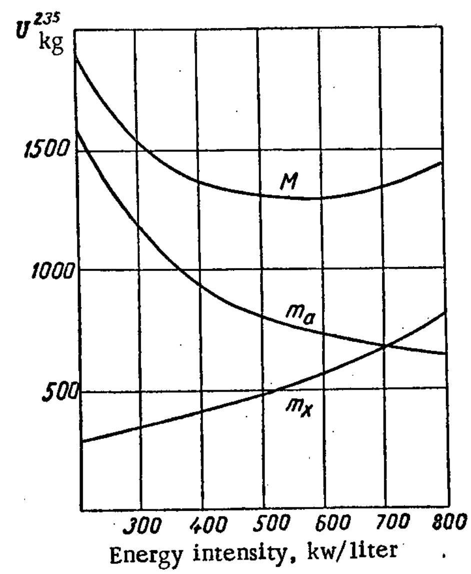

Fig. 1. Dependence of the amount of fuel in the cycle on the energy intensity of the active zone in a fast reactor: M is the total amount of fuel; m_x is the amount of fuel in the reactor; m_a is the amount of fuel outside the reactor.

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The curve M shows the presence of an optimum which lies in the region of rather large values of heat evolution. It should be noted that the magnitude of the energy intensity also affects the operating expenditures, since a change in the enrichment changes the amount of process nuclear fuel (per unit generated energy) and thus causes a corresponding change in the expenditures for chemical processing.

This effect depends on the course of chemical processing and leads to a certain reduction in the magnitude of the economic optimum.

A different engineering problem is associated with the large concentration of fuel in the fuel mixture (high enrichment). Under these conditions, it is necessary to increase the depth of burnout for the fuel mixture in order to lower the expenditure and losses for chemical treatment of the irradiated fuel. As an illustration, Table 2 shows the dependence of the amount of treated fuel on burnout depth for a fuel mixture with a 21.6% nuclear fuel content, and the corresponding decrease in the reproduction coefficient. The magnitude of the losses for each treatment is assumed equal to 2%.

TABLE 2. The Treatment and Regeneration of Fuel in Fast Reactors

Burnout depth for the fuel mixture, %	Quantity of treated fuel per 10^6 kw·hr of electrical energy, kg	Reduction of the regeneration coefficient
1	0.835	0.43
2	0.418	0.21
5	0.167	0.08
20	0.0418	0.02

In the general case for identical burnout depth of the fuel mixture the expenditures for chemical treatment of the fuel in fast reactors must be greater than it is for thermal reactors due to the high enrichment. At the same time fast reactors offer great possibilities for achieving deeper burnout. The point is that the duration of operation for the heat-evolving elements in fast reactors is determined not by the reactivity losses (as is usually the case in thermal reactors) but by the mechanical strength of these elements in the radiation field. The development of heat-evolving elements designed for deep burnout is still another important problem which arises in developing economical fast power reactors.

In order to solve the basic engineering problems which stand in the way of the industrial development of fast reactors an engineering research reactor "BR-5" has been constructed in the Soviet Union [1, 4]. This reactor has sodium cooling and is designed for a maximum thermal power of 5000 kw. The flux of fast neutrons is 10^{15} neutrons/cm^2·sec. The reactor is designed for solving a number of problems among which the basic ones are the following:

1. The complex testing of equipment for the heat-removal channel and the accumulation of experience in working with a radioactive sodium heat carrier.

2. The testing of individual specimens and prototypes of heat-evolving elements for industrial reactors at an attainable burnout depth under conditions close to operating conditions.

3. A study of the kinetics of fast reactors with a high energy intensity.

4. Performing nuclear-physics and materials-testing investigations in intense streams of fast neutrons.

From the very beginning of the process involving the design of the "BR-5" reactor we found that it was inexpedient to use it for testing power equipment since such equipment is obviously far from that required for industrial installations both in size and power. The use of a turbine would only have complicated its operation and would not have provided any substantially useful results; therefore the reactor operates without producing electrical energy and the evolved heat is dissipated (in running water and air).

The nuclear fuel used in the reactor is plutonium oxide; the expediency of using this fuel instead of metallic plutonium is due to its high melting temperature, good compatibility with the structural materials, and (as determined by preliminary tests) its resistance to a radiation field.

The plutonium oxide is confined inside stainless-steel tubes which are formed into heat-evolving assemblies. The diagrams for the assembly and the heat-evolving element are shown in Fig. 2. There are 80 such assemblies in the active zone. Moreover, this zone also contains assemblies with natural uranium, as well as special adaptors with various specimens for neutron irradiation. As we know, the reactivity of a reactor with a large K_{∞} (this is the case for the "BR-5" reactor) may be substantially affected by even relatively small variations in the geometry of the active zone (within the limits of the engineering tolerances and the temperature expansions). Here it is important that the presence of a heat-evolution gradient over the reactor radius may in principle cause the appearance of undesirable positive components in the power coefficients of reactivity. Therefore, in designing the active zone (especially in developing the system for mounting the tubes containing the plutonium in the heat-evolving assemblies and mounting the assemblies in the grid) we adopted the necessary measures to improve the system stability. The active zone has the approximate shape of a cylinder with a diameter and height of approximately 280 mm; it is located within a thick-walled central tube of stainless steel. A stream of cooling sodium flows along the tube.

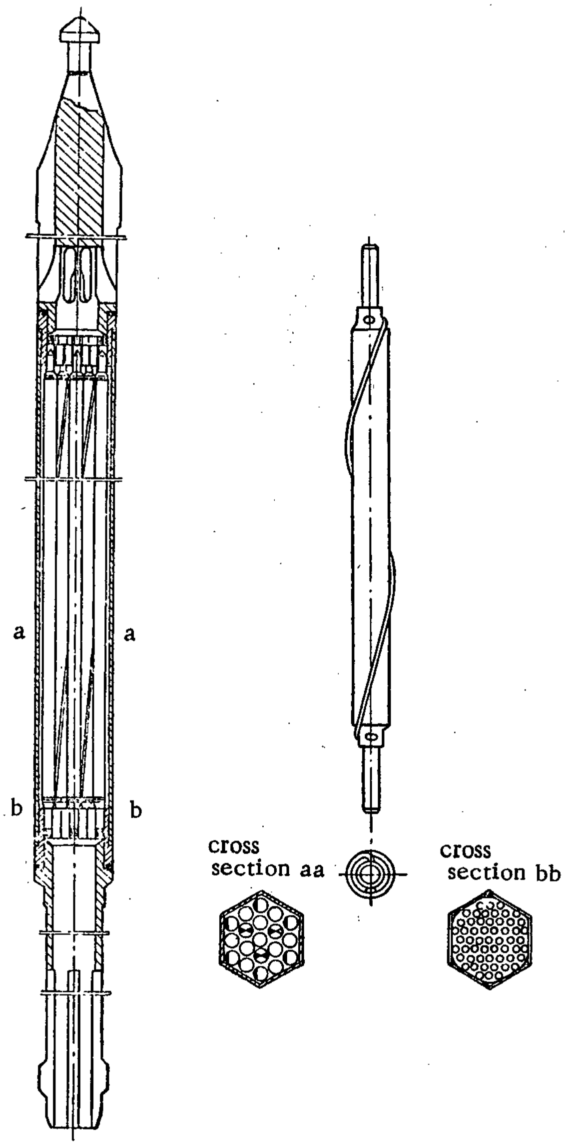

Fig. 2. Heat-evolving assembly and heat-evolving element for the "BR-5" reactor.

Since the reactor is not designed for the practical regeneration of nuclear fuel it follows that the use of uranium (natural or depleted) in the reflector is not mandatory. Moreover, here the use of uranium leads to an increase in the region of intense heat evolution and to the appearance of well-known engineering difficulties in cooling the reflector. Therefore, we chose nickel as the material for the reflector; this material has a high albedo for fast neutrons and good heat conductivity. The maximum heat evolution in the reflector is 220 kw. The removal of this heat is achieved by forced air.

The reactor is controlled on the basis of changing the reactivity of the system by shifting the inside layers of the nickel reflector. In order to reduce the reactivity the movable parts of the reflector are lowered. When it is necessary to stop the reactor quickly the supply circuit of special holding electromagnets is opened and the inner reflector is lowered by the action of its own weight. The longitudinal cross section of the reactor is shown in Fig. 3 (see insert).

The system for removing heat from the active zone has two loops (Fig. 4). It was designed while taking into account the need for obtaining the maximum diversity of experience in operating with a liquid-metal carrier. The sodium from the first main loop subdivides into two identical streams on emerging from the central tube; these streams travel around two identical sub-loops. Each loop includes a heat exchanger for transmitting heat to the second main loop and a circulation pump. The first main loop is equipped with blocking valves which permit the heat from each loop to be removed separately. The maximum sodium velocity in the active zone is 5 m/sec, and its temperature at the output from the active zone is approximately 500° C. A eutectic alloy of sodium with potassium is used as the heat carrier in the second main loop; the alloy has a melting temperature of − 12° C. Both main loops are equipped with cold traps for trapping oxides. The heat carrier expenditure in each main loop is 250 m^3/hr. The over-all quantity of liquid metal in the system is approximately 5 m^3.

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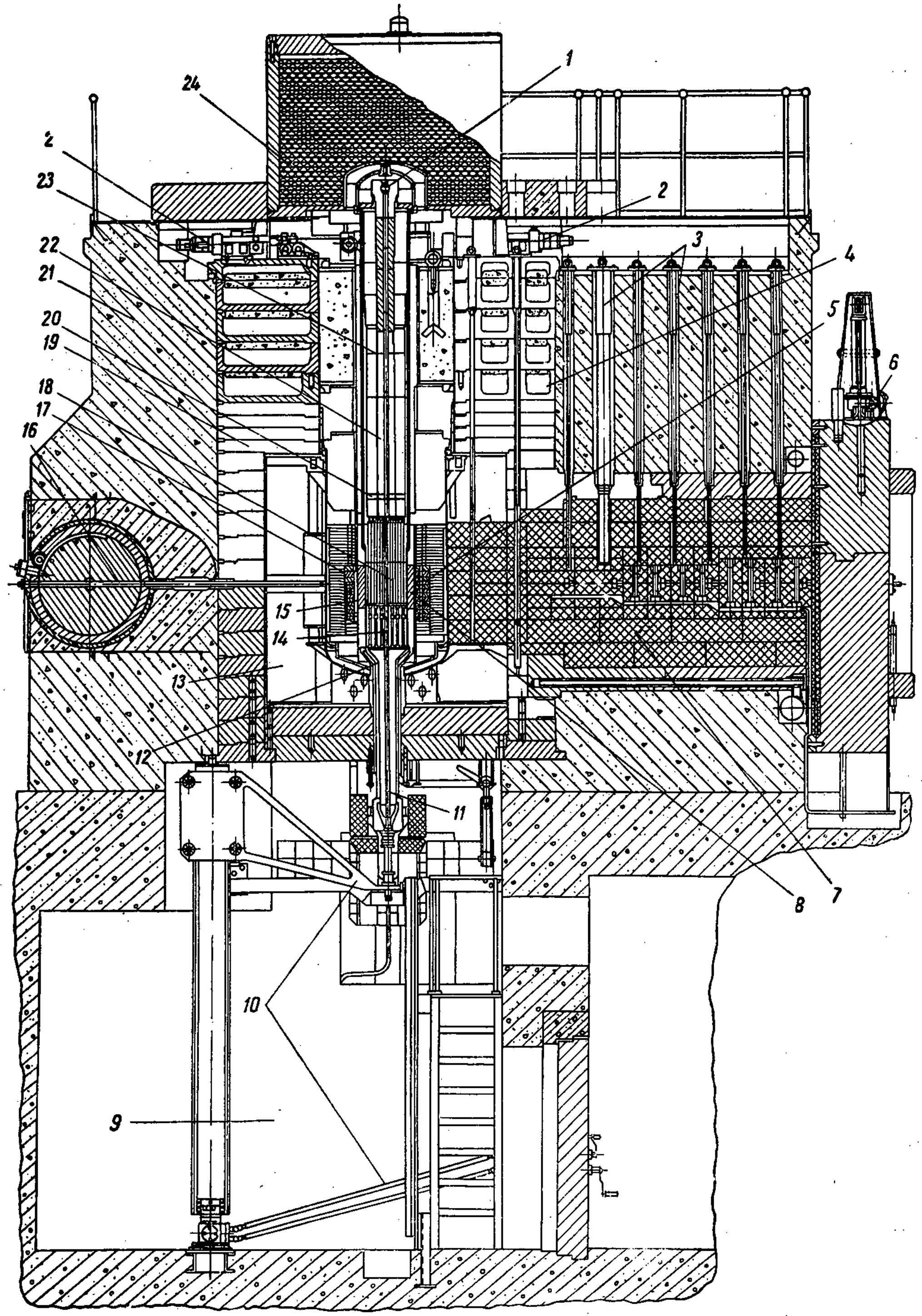

Fig. 3. Longitudinal cross section of the "BR-5" reactor. 1) Overload mechanism; 2) drives for control and protection system 3) vertical experimental channel; 4) reinforced concrete shielding; 5) compensation cylinder; 6) slide-valve of the thermal column; 7) thermal column; 8) movable shield; 9) lower reactor box; 10) device for remote reloading of specimens in the loop channel; 11) heat carrier intake; 12) reactor shell; 13) water protection tank; 14) central loop channel; 15) rod of the automatic control system; 16) slide-valve for the neutron beam channel; 17) stationary nickel channel; 18) active zone; 19) cast-iron shielding; 20) basic reactor tube; 21) basic reinforced concrete shielding; 22) rotating plugs for the system used for reloading the heat-evolving assemblies; 23) level of heat carrier in the basic tube; 24) protective plug.

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The heat from the sub-loops in the second main loop is removed in two ways. One of the loops contains an inner heat exchanger, and the heat is removed by a stream of air blown through a ventilator. The second sub-loop incorporates a steam generator. The steam which is formed is either used for engineering needs or is condensed in a refrigerator with running water. Measures are adopted to ensure heat removal for any forced stop of the reactor. The remaining heat can be removed from the active zone and transferred to the air by natural convection even when the electrical supply to the installation is completely cut off.

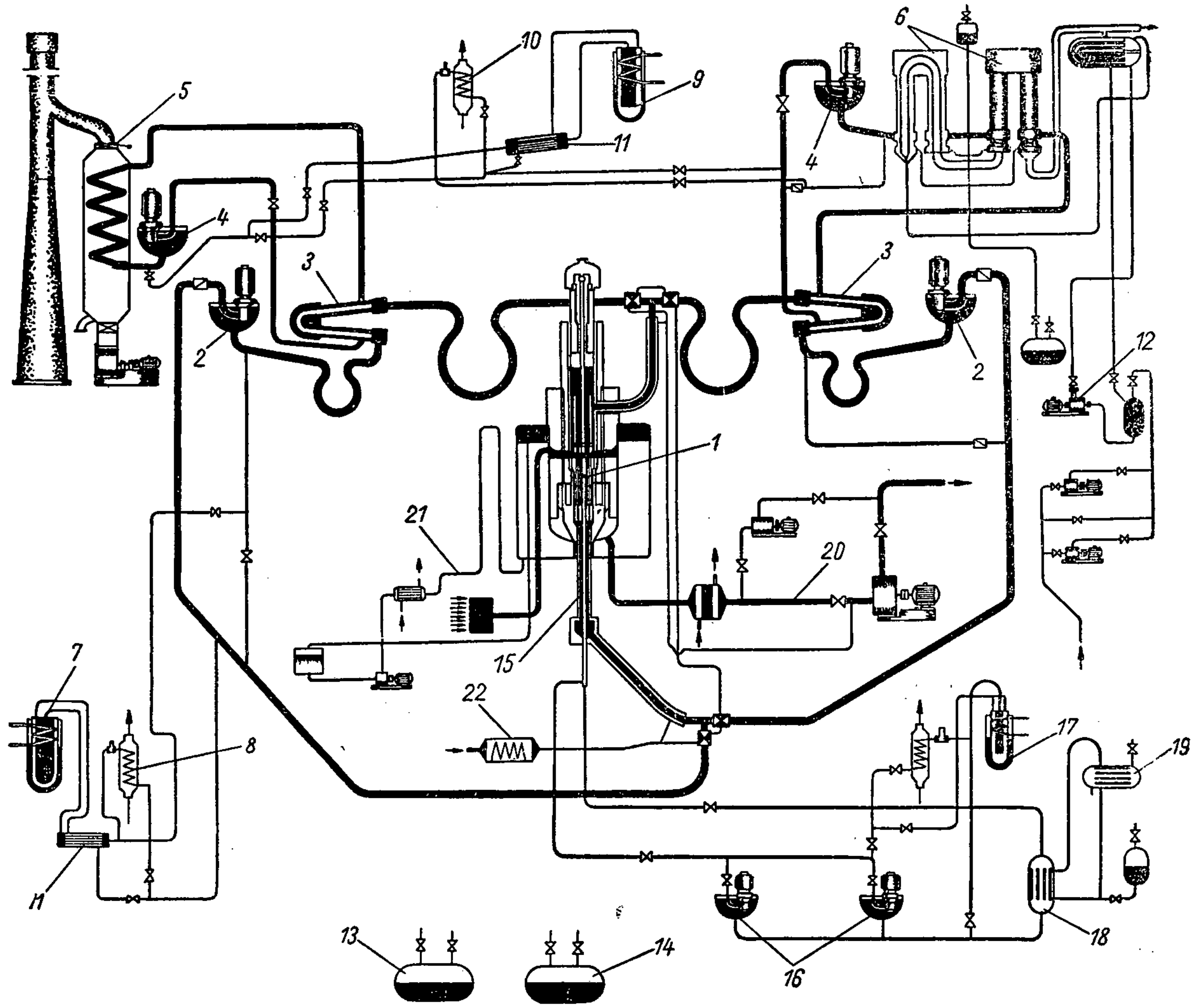

Fig. 4. Basic technological scheme for the "BR-5": 1) reactor; 2) basic circulation pump; 3) intermediate heat exchanger; 4) circulation pump for the second loop; 5) air heating exchanger 6) steam generator; 7) cold trap for oxides in first loop; 8) outside indicator; 9) cold trap for oxides in the second loop; 10) indicator for oxides in the second loop; 11) filtering system recuperator; 12) distillation pump; 13) tank for runoff of the radioactive sodium; 14) tank for runoff of the Na-K alloy; 15) central loop channel 16) circulation pumps for the loop channel systems; 17) cold trap and oxide indicator for the loop channel system; 18) "Dowtherm" evaporator; 19) unit for condensing Dowtherm vapors; 20) system for cooling the actuating mechanisms of the control and protection system; 21) system for cooling the water protection tank; 22) system for preliminary heating of the reactor.

The physical launching of the reactor without the heat carrier was performed in the summer of 1958. In January 1959 we achieved a critical state in the system when it was filled with sodium. After that the period of adjusting and refining individual sections continued for several months, and in the summer of 1959 we began using the reactor with the design parameters; the reactor continues to operate at present. The installation proved to be very quiet and convenient in operation. We should note the reliable operation of the equipment which in the majority of cases was not standard equipment and was designed especially for this system. The reactor operated in various modes in accordance with experimental requirements. During the greater portion of its operating time it maintained a maximum power of 5000 kw or close to it. The over-all time that the reactor operated at this power level during this year was in excess of 80% of the total time.

During the process of operating the installation we obtained important results in the solution of the problems posed above. We mastered the technology of operating with a radioactive sodium heat carrier on a comparatively large scale. We found that sodium is a fully satisfactory heat carrier as far as its operational qualities are concerned. For example, it is in many respects better than water, since it does not produce practical difficulties associated with corrosion effects and does not require high pressures. The convenience of sodium also is evident when we replace the equipment in the heat-removal channel. Such a replacement can be achieved quietly without draining the loop if we freeze the sodium over the required sections of the tube. In this regard sodium also has an advantage over the Na-K alloy. The cold traps assure lowering of the concentration of oxides in the heat carrier to the required value of approximately $1\text{-}3 \cdot 10^{-3}$ %.

The use of the reactor demonstrated that the design which we developed for the heat-evolving elements is fully reliable. It is sufficient to say that by June 1961 a maximum fuel burnout depth of greater than 4% was achieved. The magnitude of the integral fast-neutron flux in which the heat-evolving elements were irradiated exceeded $2 \cdot 10^{22}$ neutrons/cm^2. Here there were no signs of the appearance of plutonium in the sodium, and this indicated that sufficient mechanical strength of the heat-evolving elements was maintained. The resulting operating data verified the expediency of using a ceramic nuclear fuel. For the burnout depth which was achieved the relative quantity of treated nuclear fuel in fast reactors is comparable to the corresponding quantity in thermal reactors. At the same time the over-all volume of chemically-treated fuel is substantially lowered (due to the lowering of the amount of treated U^{238}). It is evident therefore, that the use of a ceramic fuel is more favorable than the use of a metal fuel, irrespective of a certain reduction in the regeneration coefficient (due to moderation by the oxygen nucleii) and a certain increase in enrichment (due to the reduction of the nuclear density of uranium).

We investigated the operational stability of the reactor and verified the results obtained on the basis of preliminary computations. The static power reactivity coefficient was measured experimentally and was found to be negative and of the order of 10^{-5} °C^{-1} (relative to the sodium temperature at the output). Investigations in transient modes demonstrated the absence of positive components with very short periods in the dynamic power coefficients of reactivity for the reactor. The temperature coefficient of reactivity with respect to the sodium temperature at the input also proved to be negative ($2 \cdot 10^{-5}$ °C^{-1}). As we know, in itself the temperature coefficient of reactivity does not affect the operating stability of the reactor very substantially, since this coefficient is associated with the rather great lag corresponding to the circulation period of the heat carrier. For the "BR-5" reactor this period is approximately 30 seconds.

During the entire operating time of the reactor there was not a single case of over-irradiation of personnel, notwithstanding the fact that it was necessary to perform individual repair work in the active zone and in the primary main loop with the radioactive sodium. No trace of radioactive contamination is evident in any room where service personnel work, and these rooms are quite accessible to the personnel.

After more than two years of experience with the "BR-5" reactor and after obtaining positive results in solving basic engineering problems associated with the design of fast power reactors, the problems involving the economy of such systems are becoming ever more important. It is quite obvious that in order to formulate a specific program for industrial construction of fast reactors it is necessary to acquire data on their economic efficiency. It is necessary to be able to compare the economic indices of atomic electric power stations in which fast reactors are used with the indices of other types of atomic electric power stations and with conventional electric power stations. Such a comparison must be made both on a short-range and on a long-range basis while taking into account the growth in power requirements, the change in accessible fuel resources, and the discovery of various possibilities for improving the engineering-economic indices of atomic electric power stations.

To our regret it is at present very difficult to determine the economic indices governing the operation of future industrial atomic electric power stations with a sufficient accuracy. First of all, the very method of determining these indices has not yet been adequately developed. For example, such problems as the correct consideration of the cost of nuclear fuel used in the fuel cycle, determining the price of the secondary nuclear fuel, etc. are not yet quite clear. These problems will obviously be solved on the basis of the joint efforts of economists and nuclear power specialists. The most important difficulty is the absence of the necessary experience for determining the cost of equipping and operating typical industrial atomic electric power stations. The only way to overcome this difficulty is to design experimental industrial installations of various types. As we know, it is precisely this principle which is the basis for the present nuclear-power program in the USSR. According to this program, we have launched the design of fast industrial reactors of various sizes and types.

The economy of electric power stations with such reactors depends substantially on the power of the entire station. This dependence is determined not only by the ordinary effect of the scale of the unit on the relative capital expenditures and operational expenditures, but is also caused by certain additional factors which derive from the special features and physical properties of fast reactors. We know that as the size of any reactor increases, the relative amount of neutrons leaving the active zone decreases; therefore the magnitude of the required fuel enrichment in the active zone also decreases. However, for industrial thermal-power reactors (which are comparatively large) the effect of neutron leakage is small and can practically be neglected. For fast reactors (even for the largest ones) the effective neutron leakage and its variation with a variation in reactor size prove to be noticeable. Therefore when the power (size) of a fast reactor increases, the concentration of nuclear fuel decreases substantially. In that case such important economic characteristics as the specific power and the burnout depth improve (these characteristics lead to an additional reduction in capital expenditures and a reduction in the expenditures for chemical treatment, respectively). The rough values of the indices for a fast reactor with ceramic nuclear fuel are given in Table 3.

TABLE 3. Dependence of the Characteristics of the Fast Reactors on Their Thermal Power

Thermal power, Mw.	Enrichment, %	Specific power, kw/kg	Amount of treated nuclear fuel (U^{235}), kg/10^6 kw·hr
200	32.5	485	0.27
400	26.5	690	0.22
750	21.6	830	0.18
1500	18.5	960	0.16
3000	17.2	1060	0.14

It should be noted that a still greater lowering in the concentration of nuclear fuel in the active zone can be achieved by using inert diluents [5] instead of U^{238}. However, it will be possible to orient ourselves to the use of inert diluents only after proving that this will not lead to excessive losses in the regeneration coefficient. As a whole, it can be said that the increase in the economic efficiency of atomic electric power stations with fast reactors is more rapid as the reactor power increases than is the case for stations with thermal reactors or conventional thermal electric power stations.

The possibility of producing economically favorable atomic electric power stations with fast reactors is supported by our experience in operating the "BR-5" reactor. It is a very important fact that using the "BR-5" reactor we were able to achieve and consistently maintain fundamental engineering indices which approach those of a typical power reactor. Below we shall cite certain of the most important parameters of the "BR-5" reactor and the parameters of an atomic electric power station with a fast reactor rated at a thermal power of 750 Mw for comparison purposes.

	"BR-5"	750 Mw Reactor
Electrical density, kw/liter	360	600
Temperature of the heat carrier at the reactor output, °C	500	550
Fuel burnout depth, percent	> 4	~ 5

After equipping a semi-industrial or industrial fast-power reactor and obtaining sufficient operational experience we shall determine the necessary economic data for formulating a specific program for the future and defining the exact place that fast reactors will take in the over-all program for the development of nuclear power. However, we can already cite a number of serious qualitative arguments in favor of fast reactors. These arguments indicate the important role and economic feasibility of such systems.

First of all we should note that data on conventional power resources and forecasts of the growth of power requirements leave no doubt of the need for industrial atomic energy in the nearest future. Here, we must first of all make use of fission atomic energy, since investigations in the field of producing energy on the basis of synthesis have not yet emerged from the state of laboratory experiments and it is early to make any prognoses in this field.

Of all the reactors which have been developed at present fast reactors have the advantage in that they have a large regeneration coefficient. This advantage is decisive if we are speaking of using uranium. The problem of the optimal type of reactor operating with thorium is not yet clear, although even here it must be said that fast reactors have definite advantages. Thus, fast reactors are the only type of reactor which permits practical utilization of all the uranium for power purposes. Therefore,the practicality of constructing such reactors leaves no room for doubt.

The economic advantages of fast reactors are associated with a number of factors. First of all the large regeneration coefficient produces a tendency toward a substantial lowering of the fuel component of the electrical-energy cost. However, it is of course true that in computing the fuel component, it is necessary to take into account the expenditures for the entire fuel cycle. A very substantial contribution to the fuel component may be made by expenditures for chemical treatment of the fuel material in the active zone and in the reflector.

The chemical treatment of the irradiated fuel which is emptied from fast reactors can be performed by conventional hydrochemical methods. However, the optimum possibilities are offered here when new and more progressive methods of chemical treatment being developed at present are used; these methods do not require water or aqueous solutions. (They include pyrochemistry, electrochemistry, etc.). These methods are especially advantageous when used for the waste produced by fast reactors; this follows for two reasons: 1) the relatively small volumes of treated substances provide greater possibilities for creating simple compact engineering installations, and 2) the allowable amounts of material that can be treated simultaneously are appreciably increased (due to the absence of a hydrogen moderator).

It is significant that the use of such methods as pyrochemistry and electrochemistry evidently makes it possible appreciably to reduce the time for which the fuel is exposed before treatment in order to allow for heat evolution and a drop in activity. This leads to a drastic reduction of the over-all amount of fuel used in the cycle and to a corresponding lowering of expenditures. Rough data on the relative amount of fuel used in the cycle of an atomic electric power station with a fast reactor (for various treatment methods) is given by the following table:

	Hydro-chemistry	Pyro-(Electro-)chemistry
Amount of fuel in the reactor, %	100	100
Amount of fuel exposed before chemical treatment, %	100	20
Total amount of fuel in the cycle, %	100	55

The cost of manufacturing the heat-evolving elements is also included in the fuel component. For fast reactors the number of heat-evolving elements used relative to the amount of energy produced is small due to the possibility of achieving deep burnout in them; this possibility is determined by the physics of the chain reaction based on fast neutrons. Therefore, the cost fraction assigned to the manufacture of the heat-evolving elements in the fuel components will be small. Moreover, fast reactors require less uranium for operation. The rate of accumulating new nuclear fuel in an atomic electric station with a fast reactor (especially when the newest methods of chemical treatment are used) proves to be very high and goes up to a value of the order of 12 to 15% in a year. Therefore the nuclear-fuel requirements of fast reactors will basically be determined only by the initial load of U^{235} or Pu^{239}. It is possible to use waste uranium as the nuclear raw material used in the reflector and in the active zone.

The specific program, scale and building schedules for fast power reactors as well as their economic indices will be determined in the near future after further operation of experimental units. However, at present we can already speak of the promise offered by such systems.

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All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

SOME RESULTS AND PERSPECTIVES OF NUCLEAR RADIATION AND ISOTOPE USE IN RUSSIAN SCIENCE AND INDUSTRY

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The achievements of nuclear physics are beginning to be used ever more widely in the most diverse fields of science and engineering. It is difficult to enumerate even the most important results which have been obtained at the present time by the application of those achievements. The sum total of the work of Soviet scientists and engineers in this field can be considered to amount to the creation of a new branch of science – applied nuclear physics – the foundations of which consist of such developments as the application of stable and radioactive isotopes and nuclear radiations in industry and scientific research, the use of atomic reactors and charged-particle accelerators in research work and also for studying the effects of ionizing radiations on the properties of materials and technological processes. A brief account is given in this paper of only some results of the use of isotopes and nuclear radiations in scientific research and industry.

The radioactive tracer method, which is based on the use of stable and radioactive isotopes, has had wide dissemination in physical, chemical, geological, and other investigations. It is used to obtain important results more quickly, and more precisely, than by other methods, and in many cases can be used where other means are inapplicable. With radioactive isotopes, it is possible to investigate the kinetics of rapidly-occurring processes, something which cannot be accomplished by using other methods.

The chief distinction of methods which are based on the use of radioactive and stable isotopes as tracers is high sensitivity together with the capability for studying very small quantities of matter with their help. For example, it is possible to determine the percent concentration of impurities of phosphorus, cobalt, and many other elements to a precision of about 10^{-10} % by means of radioactive isotopes.

Isotope methods make it possible to study the nature of impurity distributions in various materials, the conditions for achieving equilibrium distribution of elements among various phases, the mobility of atoms in solids and liquids, the behavior of various materials in technological processes, and make it possible to achieve control over the status of the separate units of a metallurgical plant, etc.

Scientists and industrial workers must determine the most effective direction for future expansion in the practical use of the achievements of nuclear physics. New methods and principles of investigation, control, regulation, and speeding-up of technological processes based on the use of isotopes and nuclear radiations, as a rule, are developed and applied with prime consideration for the solution of the most pressing and complex technical problems.

The widespread use of the methods of nuclear physics in Russian industry began in the forties. With the passage of time, tens of radiometric laboratories were created in many enterprises and research institutes which were occupied with fundamental research, with working out routine problems, and with work on the control and perfection of technological processes. Radioactive isotopes were first used under industrial conditions at the Novo-Tul'sk metallurgical plant and by the Kuznets metallurgical combine. At the present time, isotopes are successfully used in such important enterprises of the country as the Kuznets and Magnitogorsk metallurgical combines, the "Azovstal," F. É. Dzerzhinskii and Ilich metallurgical plants, plants at Stalino and Makeev, the "Yuzhuralnikel'" combine, the Volkhov aluminum plant, the southern ore-concentrating combine (YuGOK) at Krivoi Rog, and many others.

At the present time, the following basic trends in the use of isotopes and nuclear radiations are taking shape in the fields of engineering, science and industry.

1) For scientific and technological investigations whose purpose is a more-thorough study of the properties of matter, for revealing the mechanism of various physico-chemical processes, for analysis of impurity content in pure and high-purity materials, for the investigation of atomic displacement mechanisms, the structure of matter, etc.;

2) in geophysical work, for exploration and production of oil, gas and other minerals (ore, coal, etc.);

3) for inspection, indication, automation, mechanization of technological processes and for their control;

4) for the creation of new industrial processes (polymerization, sulfochlorination, oxidation, sterilization of materials, removal of electrical charge, etc.) which are initiated or accelerated by the action of radioactive radiations;

5) for nondestructive testing of products.

We shall consider the principal results of some work that has been carried out in this field.

1. Exploration, Prospecting, and the Exploitation of Mineral Resources

Methods and instruments which are based on the use of isotopes and nuclear radiations are used for exploration, prospecting, and the exploitation of oil, gas, coal, and ore deposits. Millions of linear meters of test and operating wells have been inspected by the geological sections of those individual economic councils which have put into practice exploration and exploitation of oil and gas deposits by these methods.

In such cases, nuclear radiation and isotopes are used for studying the geological profile of a well, for inspecting its technical condition, and for studying and checking the various processes connected with the exploitation of oil and gas deposits. Recently, radiometric surveys have begun to be used for gas and oil deposit exploration.

The γ-logging method, which consists of measurements of the γ-ray intensity from rocks lying in the depths of a well, is used, as a rule, for defining more precisely the geologic characteristics of the rocks. An important advantage of this method, and of other radiometric methods also, over other geophysical investigation techniques is the capability for making measurements in wells cased with metal pipe. In some districts, this makes it possible to obtain important new data about the geological structure of old wells drilled before the advent of geophysical methods, or to obtain this same data for wells for which geological documentation is missing. From the γ-logging plot, it is possible to select gas- and oil-bearing levels for testing. As a result of such work in Azerbadjian and the Western Ukraine, it was possible to return hundreds of idle wells to operation, producing several hundred thousand tons of oil.

The neutron-γ logging method, based on the detection of the results of neutron interactions with atoms of the rock surrounding the well, like the γ-logging method, is usually used in wells bored for the purpose of exploring gas and oil deposits. In conjunction with other methods (electrometry, γ-logging, well-profile plots), it permits a substantial increase in the reliability of logging-diagram interpretation both for picking out prospective oil-bearing layers, and for defining the geology of a cut more precisely. At the present time, about 50 % of the bores of exploratory wells drilled for oil and gas exploration are examined by the neutron-γ logging method.

Neutron-neutron logging, where the drilling equipment detector registers the intensity of thermal and epithermal neutrons attenuated in the rocks around the well, has great promise for the quantitative determination of the porosity of surrounding rock. In connection with this, the measured results for epithermal-neutron backscattering in comparison with those for thermal-neutron backscattering, depend considerably less on the mineralization (mineral salt content) of perched water and drilling fluid.

It should be noted that a combination of thermal-neutron, neutron-neutron, and neutron-γ logging makes it possible to determine reliably the water-oil separation boundaries in deposits containing water with a mineral salt concentration of 150 g/liter and above, in the case of a layer uniform in porosity and geologic composition.

The γ-γ logging method, based on the measurement of scattered γ-radiation intensity, makes it possible to keep track of openings because of changes in rock density. Thus, γ-γ logging is of great interest both for studying the geology of a section and for interpreting gravity-survey data. This method has received its widest dissemination in the exploration of coal deposits and makes possible not only the revealing of coal veins but also the determination of their thickness and structure. Explorations by the γ-γ logging method were conducted in borings in the Chelyabinsk and Pechorsk coal basins, in the central and western parts of the Don Basin, in the Primor and Eastern Ural coal beds. Part of the borings in the Kuznets, Karagandinsk, Moscow, Southern Yakutsk basins, and in other coal deposits of the country, were explored by this method.

While only several hundred meters of exploratory borings were examined by γ-γ logging in 1955, the volume of this work exceeded 1,600,000 linear meters in 1959.

Radioactive isotopes (usually Zn^{65}, Fe^{59}, and Zr^{95}) have had a widespread distribution in the oil industry for inspecting the technical condition of wells and for the solution of some geological problems of the industry associated with wells and their maintenance.

With the help of isotopes, there are determined such things as the position of a break in a casing string, the location for water inflow in a cased well, the region of fluid circulation outside the casing, the height of cement after well-plugging, the thickness of the cement cap in the space outside the casing; isotopes pinpoint the depth for column perforation; they make possible the selective perforation of double- or triple-string casings; they pick out the permeable strata in uncased wells; they establish the location of high fluid absorption zones during the well-drilling process.

In a number of oil-producing regions, γ-γ logging has been successfully used for determining such things as the height of cement, eccentricity of the casing position in boreholes, the quality of cement distribution around the casing, and the depth of casing shoes in multi-string well construction. The Volga-Ural branch of the All-Union Institute for Geophysical Exploration has developed, manufactured, and successfully introduced a special instrument for these purposes — the cementometer VUF-1.

The radiometric method is beginning to be used also for investigating the geological profile of borings drilled for the purpose of exploring deposits of boron, lead, iron, bauxite, copper, beryllium, and a number of other elements, and for solving a number of geophysical ore problems.

The photo-neutron logging method, based on the (γ-n) reaction, has been used since 1958 as an experimental method for beryllium-ore prospecting and exploration. This method makes it possible to uncover all ore bodies that are penetrated by the boring with a beryllium content close to commercial levels. The photo-neutron method is an effective means for inspection and revaluation of previously explored ore bodies. This method can also be used for beryllium-ore prospecting.

The induced-activity method for the detection and evaluation of the content of copper, aluminum, silicon, cobalt, and manganese in rock has been tested in boreholes. Separation of the elements listed is not always simply accomplished by other logging methods. Quantitative evaluation is, in the main, possible only by activation analysis.

The activation method is used also for the analysis of rock samples (core samples). The advantages of its application here lies in the opportunity for rapidly determining the content of several elements in a rock sample (for example, indium, manganese, aluminum, silicon, vanadium, etc.), and in the opportunity for determining very small quantities of a number of elements which would be impossible to detect by any other means whatsoever.

In prospecting for copper, lead, and other heavy elements, selective γ-γ logging has been developed and introduced wherein qualitative and quantitative composition of an element of interest is determined by the intensity and spectral composition of the scattered γ-radiation.

Experimental work in ore drilling shows that radiometric-logging methods are most effective in comparison to other geophysical methods for studying boreholes. One of the most important future problems in this field should be the problem of the improvement of radiometric methods and of the broadening of the opportunities for studying ore borings.

The basic purpose of the work which has been carried out in the ore-extraction and mining industries in isotope application has been directed toward such things as expanding raw material supplies, getting new raw materials and fuel supplies into production, increasing output, and making working conditions in mines and mining enterprises healthier and less rigorous. In the coal and mineral industries, radioactive isotopes can be used mainly in control and automatic equipment. Studies and the results of industrial tests of the application of radioactive isotopes and nuclear radiations in the coal and mining industries have shown that, with them, it is possible to do such things as control and automatically regulate changes in bunker coal level (without contact), establish the time when clogging of a chute or hopper occurs, accomplish the charging of a skip, check the presence of coal or ore on a conveyer belt, separate lumps of worthless rock from coal, count cars, determine the percent of ash content in coal, the density of suspensions and pulps, study the motion of various gas and liquid flows, determine their volumes, and the gas- and water-permeability of surrounding rock.

Work on the creation of a γ-electronic relay was begun in the Soviet Union during the fifties. Experimental lots of these relays were tested by the Kemerov, Sverdlovsk, and Chelyabinsk economic councils. A production line of instruments for mining use which were designated GR (gamma-relay) was set up in the "KIP" plant of the Kharkov economic council. YuGOK, a unit of the Dnepropetrovsk economic council in the Ukranian SSSR which had considerable experience with the operation of GR instruments, was one of the first large-scale industrial enterprises initiating a wide-spread introduction of automation based on the use of γ-relays. At the time, the combine suffered certain losses associated with ore plugging the loading hoppers of the coarse crushers,which led to cutting of the conveyor belt and to considerable ore spillage. In order to clean up the spillage, it was necessary to bring the operation of the machinery to a halt, and to call in an additional working force.

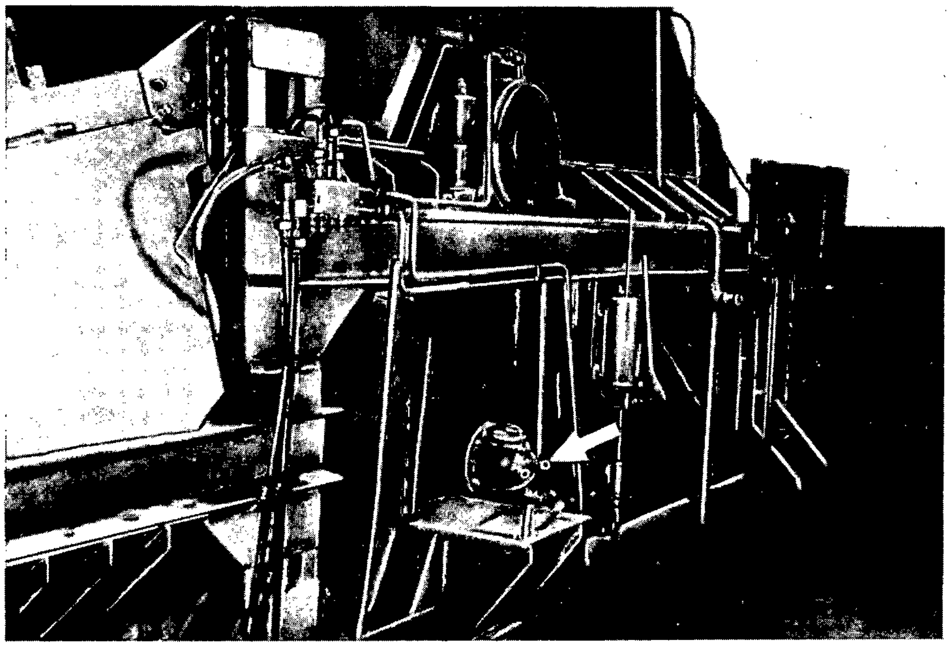

Fig. 1. Container with the radiation source of a γ-electronic relay on a loading hopper (indicated by the arrow).

In 1957, type GR-1 γ-relays (Fig. 1) were mounted on the loading hoppers of coarse crushers, completely eliminating the aforementioned defect, and then similar devices were mounted on the loading hoppers of all medium and fine crushers (Fig. 2) which assured an increase in trouble-free functioning and completely eliminated conveyor-belt loss resulting from clogged hoppers.

At the same time, γ-electronic relays were used as the sensors of an automatic switch for ore wash water which was turned on at the time the ore began to be moved by the conveyor belt. The charging of medium and fine crushers (according to their filling level) was regulated by γ-relays, which completely prevented breakage of crushing machinery in that section.

In YuGOK, the iron-ore concentrates are characterized by fine-grain structure. Therefore, three stages of crushing and two stages of pulverizing precede the concentration process with magnetite grains having dimensions less than 0.1 mm being produced as a result.

In the bar and ball mills of a concentrating plant, the ore is moved by a conveyor system from two parabolic bunkers of 40,000 ton capacity (each of the bunkers is divided into 18 compartments). Loading of the ore into the bunkers is accomplished by two transfer cars which are controlled by operators.

After fine crushing, the ore proceeds along a conveyor to the highest level of the concentration machinery. Here the stream is divided and falls into two transfer cars which dump ore into the bunker compartment above which they have been halted by the operator. Naturally, the great depth of the bunker (10 m) and the dustiness makes a determination of the necessary ore level difficult and leads to unsystematic bunker filling.

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Fig. 2. γ-Electronic relay detector mounted on the hopper of a medium crusher (indicated by arrow).

The output of the ball mill and the quality of the concentrate depends, to a considerable degree, on the homogeneity of the crushed ore with respect to all its parameters (size, iron content, etc.). Homogeneity of the ore is realized by uniform loading into the bunker and uniform discharge from it. This can be solved by the creation of an automatic system which would permit an uninterrupted raw-material supply for the bar and ball mills, and a high bunker-filling factor.

A system for regulating the loading of the parabolic bunkers was built by YuGOK based on the use of GR-type instruments. The bunkers are filled in shuttle fashion by operation of the transfer cars. In the first instance, those compartments are loaded in which the ore level is below 4 m. In a situation where all the compartments are filled to this level, the bunkers are continuously loaded by the transfer cars to the 10 m mark. Thus, the automatic bunker-loading system consists of the following principal parts: 1) indicators of medium and high ore levels in the bunker (4 and 10 m, respectively); 2) indicators of transfer-car position over a compartment; 3) actuating relay circuits of the radiation detectors; 4) an indicator panel showing filled compartments, car positions, and operating state of the equipment; 5) a program- selecting arrangement.

Stopping the car at a predetermined point above the bunker compartments is accomplished through position sensors. Each sensor consists of a type STS-5 counter. The sensors are mounted on an enclosure along the entire path along which the cars travel. The mounting position of the sensors was chosen so

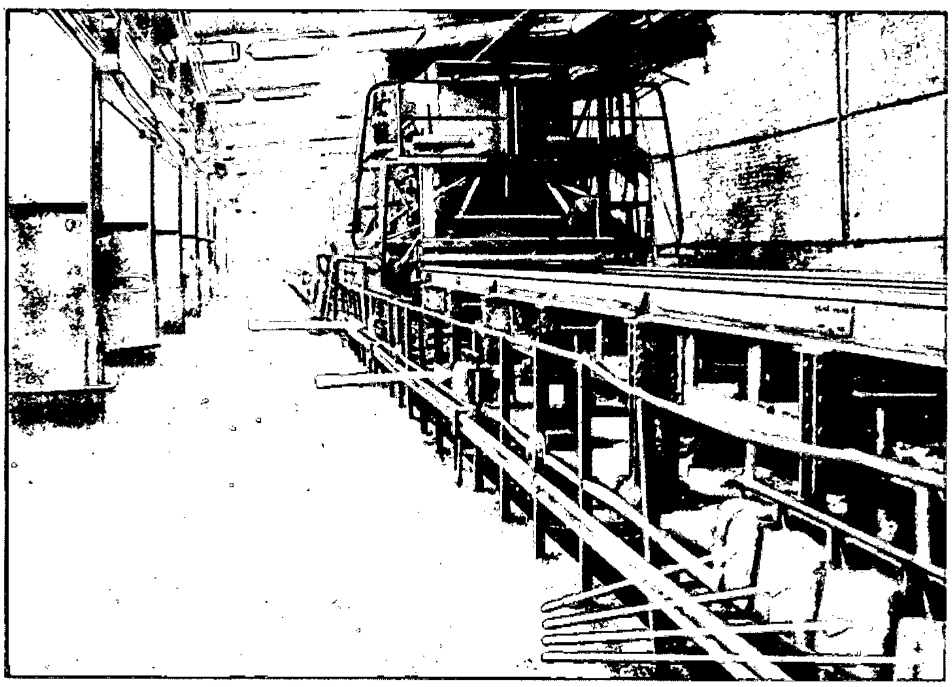

Fig. 3. γ-Electronic relay detectors mounted on the wall of a parabolic bunker for controlling the transfer car (indicated by the arrows).

that compartment loading was symmetric in cross section. For uniform loading, the cars are stopped at two points above a compartment, and four symmetrically located cones of ore are formed as a result. Such a system insures uniform bunker filling and creates the necessary conditions for ore homogeneity. Ball mill feeding is accomplished by bunker compartment feeders; the feeder motor is run by type KEP-12K electropneumatic control equipment which turns on the motors only when there is ore in a bunker compartment; if there is no ore, the feeder is shut off.

In the sintering plant of a combine, γ-relays are also used for checking the presence of a protective layer on a conveyor belt. The absence of a protective layer means that recovery material at a temperature of approximately 600° falls on the belt and burns a hole in it. The use of γ-relays brings about the elimination of such events.

In the USSR, studies have been carried out which are directed toward the creation of radiometric equipment and instruments which could be used for solving the complex problems associated with checking mine atmospheres. Thus, for example, the Central Research Laboratory of the State Mine Inspection Service in the RSFSR has developed a portable methane meter which is used to determine explosive concentrations of methane in a mine atmosphere.

2. Metallurgy, Machine Production, and Chemistry

Radiometric methods and instruments, as well as a variety of radioactive isotopes and sources of nuclear radiations, are used for the solution of various problems in metallurgy such as increasing the volume of metal produced and raising its quality, finding methods for increasing the durability of metal structures, developing new metallic materials, automating processes and plants, and controlling production.

In ferrous metallurgy, radiometric methods are used for checking such things as movement of charge materials, erosion of a refractory lining, charge level, and density of coke and agglomerate. In several plants, studies which employed radiometric methods made possible improvement in the regulation of blast-furnace operation. The use of radioactive isotopes gave positive results in work on finding more effective means for the desulfurization of cast iron by metallic magnesium and line-alumina slags. Isotopes are used for studying the operation of a blast-furnace tuyere region.

Radiometric sounding of the charge portion of the furnace makes it possible to observe the movement of charge materials (at the present time, an electrically-operated sound is used). The results of tests at the F. E. Dzerzhinskii plant on radiometric equipment for checking blast-furnace charge levels demonstrated the advisability of using this equipment in other metallurgical plants as well. Such a method of charge-level control can be used in the over-all scheme for blast-furnace charging.

The output from blast furnaces is determined, to a considerable extent, by the preparation of the raw iron ore, an important element of which is control of the ore concentration process and of the agglomerate sintering. The use of radioactive isotopes has also proven to be effective for this. A radiometer for the determination of agglomerate density has been developed by the Kuznets metallurgical combine. Tests of the instrument by a sintering plant showed that, according to tentative calculations, the introduction of automatic control of the degree of agglomeration can effect a saving of about 0.2 million rubles per year in the Kuznets combine.

In a number of plants, blast-furnace lining wear is checked by the means of radioactive inserts which make it possible to keep a watch on the state of the lining during furnace operation. Where several years ago such work was done only for investigative purposes, now metallurgical enterprises (Kuznets and Magnitogorsk metallurgical combines, and others) use the radiometric method for checking on the wear of a refractory lining. The results of these investigations made possible important improvements in the construction of blast-furnace shafts and hearths. A plan for placing radioactive isotopes in the hearth of a blast furnace of the F. E. Dzerzhinskii metallurgical plant is shown in Fig. 4. The principal results of this work have been a prolongation of blast-furnace operating time and a large saving in general overhaul costs.

In steel-smelting production, radioactive isotopes are most widely used in work which has the improvement of technology as its ultimate goal. A number of results of such work have been introduced into practice and are of considerable use. In the Magnitogorsk combine, the process of slag formation was studied by means of the radioactive isotopes of iron, sulfur, and phosphorus, permitting a selection of the most effective order for loading the charge materials into a 380 ton open-hearth furnace. In the Kuznets combine and the "Azovstal" plant, the hydrodynamics of a steel melt were studied by means of radioactive isotopes. A possibility for shortening the smelting time was discovered as a result of which the steel output of operating open-hearth furnaces was increased by tens of thousands of tons without additional expense.

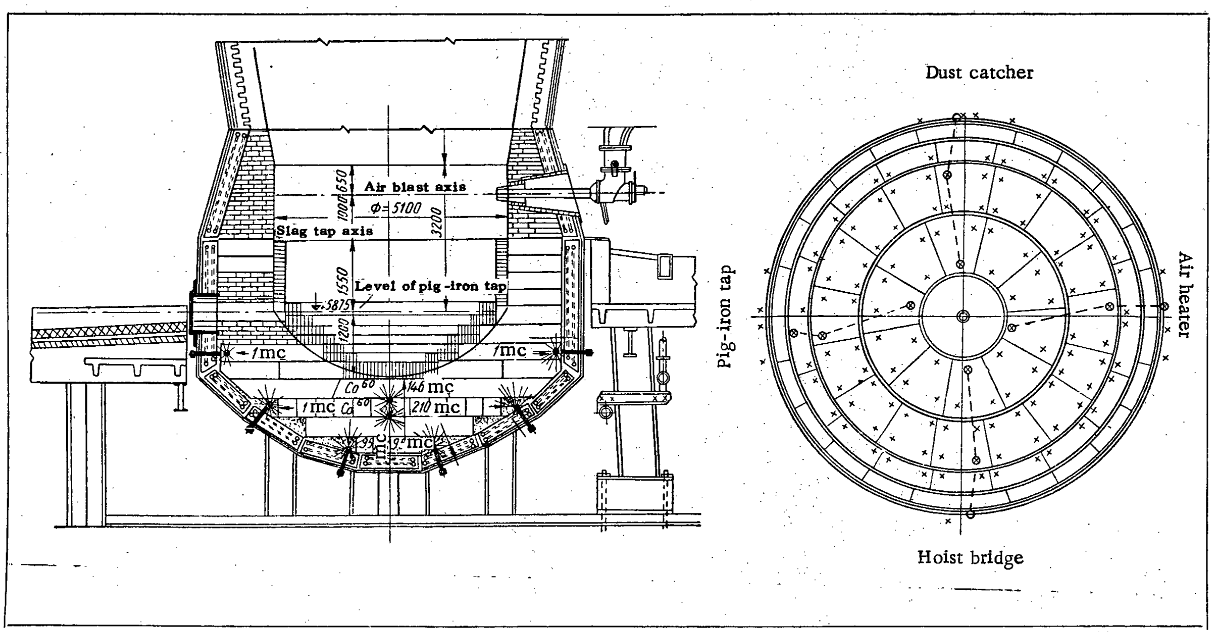

Fig. 4. Location of isotopes in the blast-furnace hearth.

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In the Kuznets combine, the Makeev metallurgical plant, and the "Azovstal" plant, radiometric methods for checking the wear of the refractory lining in open-hearth furnaces were developed which made possible a reduction of furnace down time.

Work carried out in the Kuznets combine and at the Stalino metallurgical plant on a study of the flow processes in rolled metal is of great interest. For this purpose, radioactive zones were created in metal ingots by the introduction of radioactive isotopes into the mold at different stages of metal crystallization. By contact autoradiography, it was possible to determine the contour of the crystallization zones in the ingot and the depth of distribution of deformation foci, and also to determine the features of metal flow in rolling which is important for efficient standardization of rollers and for establishing a rolling technology which would bring about an increase in the strength of rolled metal. An autoradiograph of a rail cross section which was taken in order to study the nature of metal deformation in the rolling process is shown in Fig. 5.

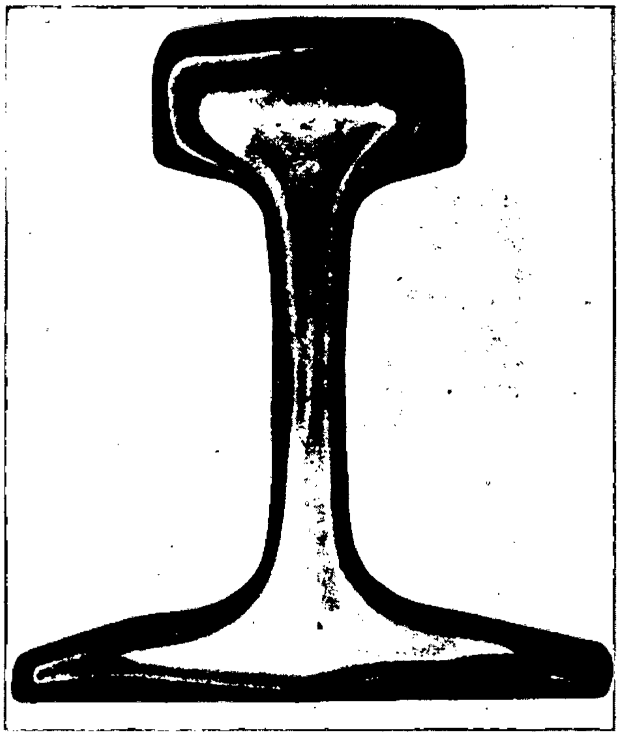

Fig. 5. Autoradiograph of rail formed by rolling.

In the future lies the use of radioactive isotopes in the chemical laboratories of metallurgical plants for the purpose of improving analytical methods.

In ferrous metallurgy plants, many instruments whose action is based on the use of radioactive isotopes have been introduced for control and automation.

A system for regulating the liquid metal level in the crystallizer of a semi-continuous casting machine was developed and introduced in the "May 1" plant in Kalanin. At the present time, machinery for the continuous steel pouring of small cross section shapes is getting ever wider distribution, and planning organizations are already including similar level regulators in the operating plans for the machinery. Without the use of such a regulator, it would be impossible to carry on high-speed pouring of liquid metal since an operator would not have the time to keep track of the metal level in a crystallizer and to control it.

A similar regulatory system was introduced in equipment for the semi-continuous casting of cast-iron pipe at the Sinarsk pipe factory.

A liquid-metal level regulator has been developed and tested in the crystallizer of a continuous steel-pouring machine of the conveyor type (URU-6), making it possible to carry on casting completely automatically.

In ferrous metal plants, radiometric thickness gauges are used for cold- and hot-rolled metal. The use of thickness gauges for measurement of sheet thickness during cold rolling contributes to an increase in finished product quality, a reduction in rejected material, a saving of metal, an increase in rolling speed, a decrease in lost time, and effects great savings. Thus, according to incomplete data, a saving of about 70 thousand rubles per year was obtained in a single twelve-roller mill merely because of rolling to smaller tolerances. The widespread introduction of thickness gauges for hot-rolled sheet can produce a large saving. At the present time, such instruments have been introduced in the Izhorsk plant and the Kuznets metallurgical combine.

The method of flaw detection with γ-rays, which permits the inspection of welded joints in difficult-to-reach places, and under working and assembly conditions as well, has had wide dissemination in ferrous metal plants. In 1952, the first γ-testing sections were organized in the Kuznets and Magnetogorsk metallurgical combines. At the present time, the welded seams of steel-casting-ladle bottoms, boilers, pipelines, blast-furnace shells, etc., are subject to inspection in tens of plants. Production quality is systematically checked in boiler-repair shops and foundries.

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The use of electro-optical converters which make possible a considerable increase in output when checking such products as welded large-diameter pipe etc., opens up a great future for the field of γ flaw-detection. Work carried out in recent years gave results which satisfy basic industrial requirements.

In nonferrous metallurgy, radioactive isotopes are used for developing methods of inspection, for studying the mechanism and kinetics of processes, and for studying the distribution of micro-impurities in metals and alloys.

The use of radioactive isotopes made possible, in a short time, the development and improvement of the technology for obtaining a number of high-purity nonferrous and rare metals. Thus, by the use of radioactive isotopes, techniques for obtaining zinc, tin, nickel, and other metals in high purity were developed and introduced in the "Ukrtsink" plant and several other enterprises.

Studies were conducted and suggestions made for improvement in the technology for electrolytic refining of copper with minimum drift of precious metals to the copper cathode, in the technology for electrolytic extraction of zinc by maintenance of high current, and in the technology for the separation of rhenium and molybdenum. With the help of radioactive isotopes, the interaction of metal with electrolyte was studied in connection with aluminum electrolysis, and the reasons for the reduction of current in magnesium electrolysis were established (because of anodic dissolution of the cast-iron block). Methods were developed for controlling the dispersion of indium during hydrometallurgical reworking of the dust deposits produced in nonferrous metallurgical plants.

The use of radioactive isotopes permitted an increase in the precision of existing methods, and the development of new methods, of chemical and spectral analysis for determining very small amounts of impurities (zinc, lead, antimony, tin, arsenic, phosphorus, germanium, thallium, indium, cadmium, gallium, selenium, tellurium, nickel, cobalt, iron, sulfur, and a number of other metals) in pure metals.

Radioactive isotopes have been used as tracers in the study of the sintering mechanism in alumina-containing mixtures, and of the kinetics of several reactions; they have been used in studies of the distribution of the various components in pit-smelting, electro-fusion, conversion, and pyro-refining of nonferrous metals, and also in studies of the distribution of the different components in electrolytic processes and in processes for the extraction and purification of metals and alloys.

As a result of scientific studies which used radioactive isotopes, considerable theoretical and practical data was obtained which allowed a more correct appraisal of the technological processes used in nonferrous metallurgy, a realization of their control, and a determination of possible ways for their improvement.

In machine production, radioactive isotopes have found their widest use in work connected with flaw-detection in metal products. In many plants, γ-flaw-detection has become an integral part of the technological processes. It has been introduced in more than 1000 enterprises in our country where about 2000 γ-flaw-detectors are operated. The use of this method in industry makes for large savings. Thus, for example, because of the introduction of the γ-flaw-detector, the Taganrogsk boiler plant achieved a yearly saving of 22.9 thousand rubles through the reduction of rejects, the Dnepropetrovsk plant for metallurgical equipment, 68.6 thousand rubles, and the "Russkii Dizel' " plant, 14 thousand rubles.

Considerable economy can also be achieved by widespread use of radioactive isotopes for inspection and automation. Many instruments and methods developed for the metallurgical industry can be used in foundry production at machine-tool plants.

A number of suggestions have been made for the introduction of isotope-using instruments in forging. For example, radiometric interlock equipment, in which a strontium beta-source mixed in enamel is used, has been developed for press interlocking in automatic sheet-metal stamping by the Likhachev automobile plant in Moscow, by the Physics Institute of the Latvian Academy of Science, by the Moscow machine-tool instrument institute, and by the Tallin control- and measuring-instrument plant.

Radioactive isotopes are used for such things as studying the wear of materials, machines, and mechanisms, observing the transfer of metal from one frictional surface to another after wear occurs, establishing the actual contact area of adjoining surfaces, studying the role of lubricants in friction, etc.

A series of studies on the wear of cutting tools was carried out in various research institutes. Tracer techniques are very sensitive, require little time for completing such studies, and make it possible to select cutting-tool materials quickly.

The use of radioactive isotopes and nuclear radiations has broadened the bounds of practical possibility in chemistry and physical chemistry very considerably. The study of the action of nuclear radiations on chemical materials and processes forms the basis for a new field in chemistry – radiochemistry. An opportunity, which has practical value for a number of processes, has been created for directing the course of chemical transformations by means of radiation effects.

High-efficiency radiochemical processes (polymerization, halogenation, etc.), which require the expenditure of energy for excitation only, can be achieved on an industrial scale by the use of powerful sources of ionizing radiation.

By radiation vulcanization of raw rubber, rubbers are obtained, including that for tires, which differ from the usual rubber both in structure and in properties. They are characterized by increased resistance to various types of ageing, high resistance to the effects of elevated temperatures, oil, and chemically deleterious media, and they maintain their strength better under repeated deformations. From studies carried out in the Karpov Physico-Chemical Institute and other laboratories, the possibility of achieving vulcanization of raw rubber by radiation effects without the addition of sulfur has been demonstrated. The resulting rubber has a high heat-stability, which is an important feature of thiocol rubbers. In the future lie radiation methods for the growth of copolymers and radiation cross-linking of various polymers.

No less important is the radiation halogenation process, i.e., the introduction of chlorine, bromine, boron, and iodine atoms into the molecular make-up of various materials which are widely used in chemical technology for producing weed- and insect-poisons.

The radiochemical method for producing hexachlorane has a number of advantages over the photochemical method.

Nuclear radiations make possible increased efficiency in catalytic processes. Radiothermal methods for cracking hydrocarbons have been developed in order to increase the yield of end products. Radiothermal cracking of petroleum and chemical raw materials can proceed at considerably lower temperatures than those used for ordinary thermal cracking, and it is carried out without a catalyst. It is possible to achieve significant savings by such, still quite prospective, techniques.

The introduction of new types of synthetic fibers and rubbers, the increased speed of machines in textile factories and other industries which work on dielectric materials, together with the considerable build-up of electrostatic charge on these materials, all give rise to technologic waste and danger, since they can lead to fires and explosions.

Air, ionized by radiation, becomes a conductor – a fact which is important for the prevention of electrostatic-charge formation in artificial-fiber production, in the textile, movie-film, paper, rubber, and printing industries, and in several other industrial fields.

Radioactive isotopes and nuclear radiations find wide application in the chemical industry in instruments for control and automation. Serial density-gauges are used for the automation of a number of processes; automatically controlling the concentration of hydrochloric acid produced by the absorption of hydrogen chloride in water, regulating the concentration of neutral alkalis and caustics, in the evaporation of electrolytic alkalis, controlling the drying or gaseous chlorine, etc. In order to control the movement of petroleum products through pipe lines by sequential pumping, γ density-gauges are used.

The use of radiometric methods as a means of control in chemico-technologic processes simplifies the solution of various technological problems and shortens the time required for studying the characteristics of technological processes.

The radioactive-tracer method is widely used in tests to estimate the quality of fuels and lubricants. The ability of fuels and oils to form deposits and the mode of action of oil additives have been studied. Of practical interest is the possible use of tracer methods for estimating oil, additive, and fuel quality under factory conditions, for determining the effectiveness of neutralizing oil additives, the varnish-forming properties of oils and additives and their corrosion resistance. The development of an activation-analysis method for determining the content of ultra-small amounts of various elements was achieved.

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Quite in the future is the use of radioactive isotopes for the purification of industrial gases. By ionizing industrial exhaust gases through radioactive radiations, it is possible to create the conditions for precipitation and consequent separation of the very fine dust fraction, making it possible to utilize the dust and to purify the air both in the plant and in the surrounding populated area.

3. Physical and Engineering Research

The importance of the use of advances in nuclear physics in science and engineering lies chiefly in the fact that we have obtained, in essence, a new means for investigating the various processes that occur in matter, and their properties. Thus, new possibilities have been revealed for more fundamental study of the various laws which determine the behavior of matter under different conditions. This, in its turn, opens the way for more accelerated technological progress. From the standpoint of growth in a number of scientific fields, the possibility of a broad application in the research plans for atomic reactors and charged-particle accelerators appears important. There is a whole series of research reactors at the disposal of physicists and engineers which have been built especially for this purpose at many scientific engineering centers of our country (Moscow, Leningrad, Kiev, Tbilisi, Tashkent, etc.). The programmed work at these reactors envisages investigation of many of the most pressing scientific problems. In various scientific fields, important studies have been carried out, and are being carried out, with the use of radioactive and stable isotopes.

Fig. 6. Autoradiograph of a Zr-C system (x 56).

Radioactive isotopes are widely used for the solution of problems connected with the investigation of new types of steels and alloys, and with the explanation of their basic heat treatment mechanisms. New facts have been obtained by the study of diffusion, distribution of elements, and atomic interactions in metals and alloys.

Through diffusion studies, results were obtained which permitted the establishment of mechanisms dealing with diffusion mobility surfaces in various metals, boundary diffusion, and donor-acceptor atomic interactions in solid solutions. The results dealing with the microdistribution of impurities and alloying elements in titanium and zirconium alloys, which are widely used in the atomic energy industry, are of fundamental importance. For example, it has been shown that thermal stability and corrosion resistance in zirconium alloys are determined, to a considerable extent, by the presence of large inhomogeneities concentrated along sub-boundaries which arise as a result of the $\beta \rightarrow \alpha$ transformation. Data on the distribution of different elements in high-fusing metals was obtained by radiography. An autoradiograph of the distribution of carbon in cast zirconium is shown in Fig. 6.

Work is proceeding on the determination of the saturation vapor pressure of various alloy components at the institute for metal working and the physics of metals of the Central Scientific Research Institute for Ferrous Metallurgy, at Moscow University, at the Moscow Steel Institute, and at other scientific institutes. Iron-carbon, iron-chromium, nickel-chromium, and other systems have been studied. Data obtained about vapor tension made possible the carrying out of detailed thermodynamic analyses and the explanation of some features of atomic interactions in solid solutions. Successful development of the aforementioned thermodynamic studies was due to radioactive isotopes, the use of which in this field considerably expanded experimental possibilities. Radioactive isotopes of iron, chromium, nickel, and many other elements were used in the studies.

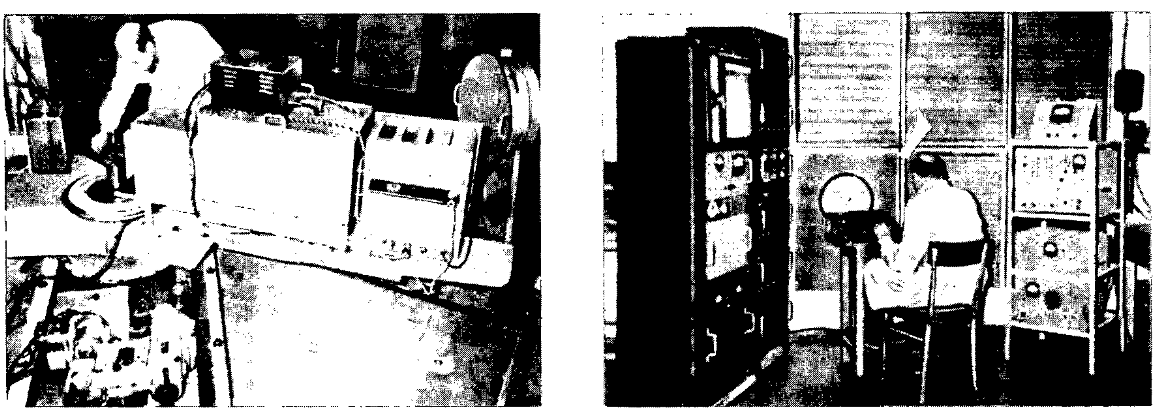
In the field of radiation physics, there have been delineated such important trends as the study of nuclear-radiation effects on construction and semiconductor materials, the explanation of the physical nature of radiation effects, the study of the mechanism of radiation interaction with matter, and the radiation treatment of solids for studies whose purpose is to obtain more precise ideas about the mechanism of radiation effect on the properties of solids (stability, conductivity, plasticity, electrical and magnetic properties). Detailed work has been carried on in a number of institutes of the USSR Academy of Science and in the academies of the republics. Results of the most important studies have been published in the literature and reported at international conferences on peaceful uses of atomic energy. These studies promote the development of atomic energy and other important engineering fields. Important individual details of the mechanisms of processes occurring in metals under radiation treatment were explained as a result of work done in the USSR Academy of Science. Data on high-energy charged-particle irradiation effects on metals are of practical interest, as is data from the study of semiconductor and magnetic materials.

The feasibility of hardening metals by radiation treatment has great importance in the physics of solids. In connection with this, the practical use of the effects of metal hardening by radiation does not appear as a primary objective, but rather the new opportunities for studying the physical nature of the state of high-strength metals.

At present, there are several well-known methods for hardening metals. In particular, the hardness of pure metals and alloys can be substantially increased by thermomechanical working. According to present ideas, plastic deformation leads to the hardening of metals as a result of the formation of defects chiefly along the slip planes of individual crystals. Severe break-up of grain structure and a series of other accompanying phenomena occur at the same time which makes the study of metal hardening and softening processes difficult.

Defects in crystal structure are also created by radiation treatment although they differ in their nature from the defects caused by plastic deformation. Radiation defects appear under certain conditions with no break-up of the metal crystals, and, in general, are similar to the finely dispersed aggregates formed by ageing. Hardening of metals by radiation treatment depends on the fact that dislocations undergo additional resistance to their movement as a result of their interaction with radiation defects. On the basis of these ideas, attempts have been made to explain such properties of metals as changes in the degree of internal friction and in the modulus of elasticity, increases in the yield point, and a number of other effects which are peculiar to irradiated materials. However, all these ideas are of a very general nature because of our lack of knowledge about the physical nature of radiation defects and the mechanism of their interaction with dislocations and other structural disturbances.

It should be noted that much data from the studies of radiation disturbances in solids has appeared in the literature in recent years. However, this data has not always made it possible to construct a clear representation of the nature of radiation effects and their behavior in solids. This can be explained, in part, by the fact that radiation treatment of metals occurs in complex fields (neutrons, α- , β-, γ-rays) where large doses of radiation are used. In the past year, therefore, the effect of small doses of a single radiation has been studied, using such sensitive investigative techniques as the measurement of internal friction.



a b

Fig. 7. Neutron-crystal spectrometer. a) Spectrometer detector; b) control panel.

Extensive data regarding the effect of preliminary fast-neutron irradiation of austenite on the martensitic transformation in steel was first obtained in our country.

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The Institute for metal working and the physics of metals of the Central Scientific Research Institute for Ferrous Metallurgy, together with the Institute for Theoretical and Experimental Physics, has carried on an extensive experimental program for the study of metal alloys by neutron diffraction (the investigation of atomic interactions, atomic arrangement in magnetic alloys, changes resulting from the effects of high pressure, etc.). A neutron-crystal spectrometer is shown in Figs. 7a, 7b, and the arrangement of the apparatus for structural analysis by neutrons is shown in Fig. 8. Work in this field has shown that large single crystals of iron-nickel alloys grown from a melt, both in the binary state and alloyed with a third element, consist of fragments disoriented with respect to one another to approximately the same degree as in a mosaic block. Moreover, different fragments from one and the same single crystal can differ considerably from one another in the degree of mosaic appearance. The results obtained in the work mentioned have a definite interest both for the theory of crystal growth and for the development of the methods of structural analysis with neutrons.

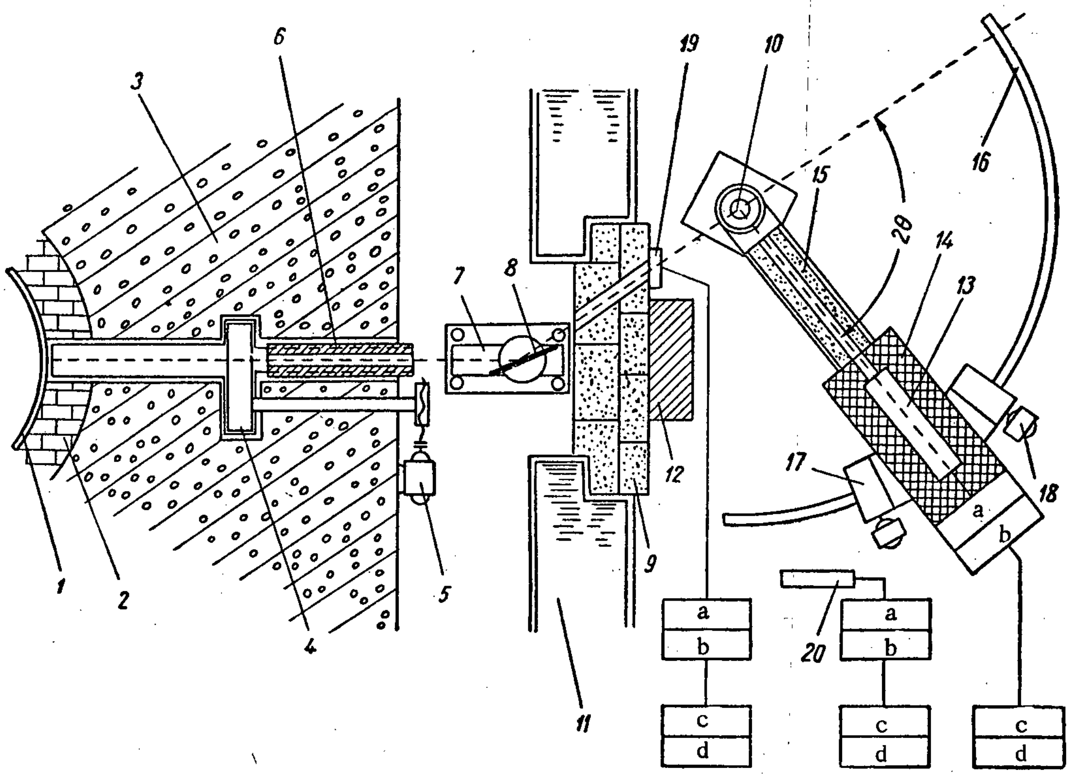

Fig. 8. Experimental arrangement for structural analysis by neutron diffraction: 1) Wall of reactor tank; 2) graphite reflector; 3) concrete shield; 4) shutter; 5) shutter drive mechanism; 6) plug with collimating slit; 7) crystal monochromator unit; 8) lead crystal; 9) shield of boron-containing material; 10) sample; 11) shielding tank containing water; 12) steel shield; 13) spectrometer detector; 14) detector shield; 15) collimator; 16) spectrometer support rails; 17) motor and reduction gear; 18) selsyn-sensor for remote indicator of angular position; 19) monitor counter; 20) background counter; a) linear pulse amplifier; b) pulse-height discriminator; c) counting equipment; d) mechanical counter (last two units are located on the panel).

The study of atomic arrangement in solid solutions has great value in the development of new magnetic alloys. By studying the magnetic portion of neutron scattering, the phenomenon of atomic ordering has been investigated in detail for the permalloy types of nickel-iron alloys. Direct data was obtained for the existence of the hyperstructure compound Ni_3Fe, and the various effects of the addition of a third element (copper, chromium and molybdenum) to this hyperstructure were noted. Analysis of the research results led to more precise phase equilibrium diagrams for iron-nickel alloys, and led to important conclusions about the special ferromagnetic nature of the atomic-ordering energy in these alloys.

Other systems where atomic ordering plays a large role in heat treatment are the iron-cobalt magnetic alloys which also have great practical value because of their high magnetic saturation. The facts obtained from neutron diffraction by these alloys made it possible to establish the presence of anomalously broad concentrated regions for the existence of the equal-atom hyperstructure state Fe – Co, and led to the conclusion that the order-disorder transformations in the iron-cobalt system are related to phase transitions of the second kind. A neutron-diffraction diagram of an iron-cobalt alloy is shown in Fig. 9.

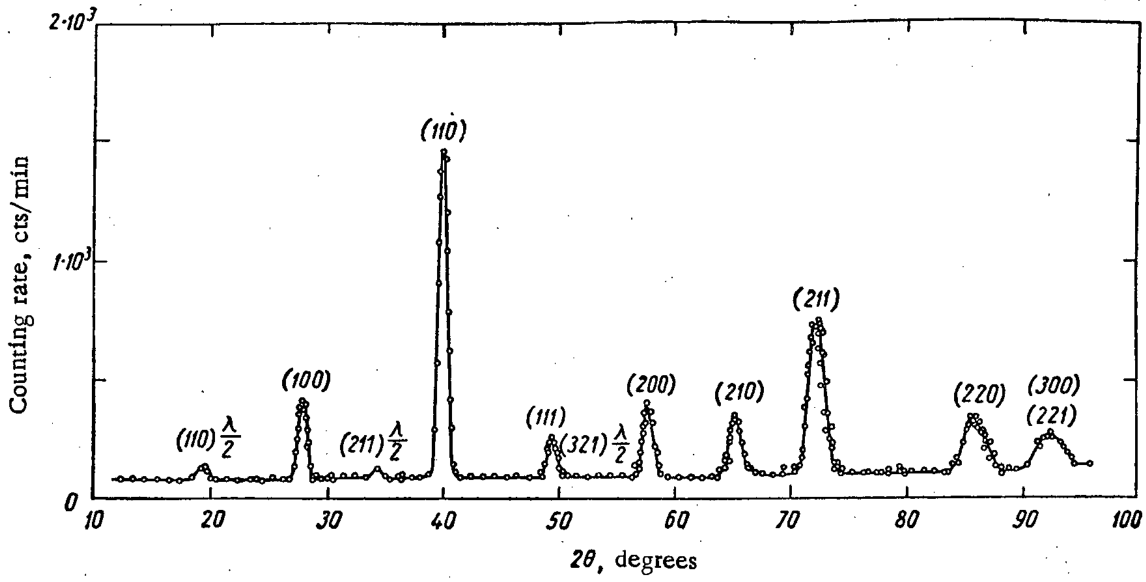

Fig. 9. Fe-Co neutron-diffraction spectrum.

In the Central Scientific Research Institute for Ferrous Metallurgy, theoretical work on the calculation of neutron diffraction by austenite crystals has been completed. Despite the opinion of some foreign investigators, the possibility of determining the position of carbon atoms in an austenite crystal lattice has been demonstrated. The experimental portion of this work was completed at the first atomic power station (USSR). The results which were obtained confirmed the hypothesis concerning the octahedral version of carbon atom disposition in an austenite crystal.

In conclusion, it should be noted that the possibilities for efficient use of isotopes and nuclear radiations in science and engineering are still far from exhausted. The study of new fields for the application of isotopes in scientific research and in industry is a present-day problem for the physicist. It is to be expected that new results will be obtained in the field of applied atomic physics in the near future which will have great scientific and practical value.

LETTERS TO THE EDITOR

THE ELASTIC SCATTERING OF NEUTRONS WITH AN ENERGY OF 15 MEV BY NUCLEI OF COPPER, LEAD AND U^{238}

B. Ya. Guzhovskii

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The differential cross sections of elastically-scattered neutrons obtained by Bjorklund and Fernbach [1] on the basis of the optimal model of the nucleus reliably reproduce the experimental data over a wide range of nucleus sizes. However, for scattering of neutrons by strongly-deformed nuclei we find that the discrepancy between the computed and experimental curves for definite scattering angles appreciably exceeds those deviations from experimental results which are associated with the inaccuracy of the theory [2]. In this paper we obtain the differential cross sections for 15 Mev neutrons which are scattered by spherical nuclei of copper, lead, or by a strongly-deformed U^{238} nucleus. The experimental data are compared with computed results obtained on the basis of the optimal model of a nucleus with a spherical potential.

The angular distribution of the neutron was measured on the basis of ring geometry. The scheme illustrating the experiment is shown in Fig. 1. Neutrons with an average energy of 15 ± 0.4 Mev were formed from bombardment of a thick zirconium-tritium target with deuterons that had been accelerated up to an energy of 290 kev in an electrostatic generator. The copper and lead scattering media were prepared in the form of thin-walled cylinders. In order to perform measurements at large scattering angles we also used toroidal scattering devices. The specimens of U^{238} which produced scattering were shaped in the form of rings with a rectangular cross section. The dimensions of the copper protecting rods were chosen in each specific case while taking the geometry of the scattering and the conditions governing the minimum background into account. The scattering angle was varied by shifting the specimen which produced the scattering and the neutron detector along the axis of the source-detector system which coincides with the direction of the deuteron beam. The neutrons were detected by means of small scintillators made of plastic and stilbene. The spectrum of the scintillator pulses was recorded by a 50-channel amplitude analyzer. The data was manipulated by the method described in the paper by Coon et al. [3]. This method, which is based on the use of an organic scintillator as a coarse neutron spectrometer, assured an energy resolution equal to approximately 500 kev; thus it permitted us to a considerable extent to exclude the effect produced by inelastically-scattered neutrons and γ-rays.

The angular distributions were measured for copper in the range 16-80° and for lead in the range of angles 10-122° with an angular resolution ranging from ± 1 to ± 3°; for U^{238} they were measured in the range of angles 10-155° with an angular resolution of from ± 2 to ± 7°.

The differential cross sections for elastically-scattered neutrons were determined from the expression

$$S(\theta)=\int\frac{R_0^2}{R_1^2R_2^2}\frac{I(\theta_1)}{I(0)}\sigma(\theta)\bar{N}\frac{\varepsilon(\bar{E}')}{\varepsilon(\bar{E}_0)}P(\theta)\left[\exp\left(\frac{r_1+r_2}{\lambda_{\text{inel}}}\right)\right]^{-1}dv, \quad (1)$$

where $S(\theta)=\frac{N-N_b}{N_0}$ is the experimental ratio between the number of scattered neutrons and the number of incident neutrons; $\bar{N}$ is the number of atoms in the specimen which produces the scattering; R_1, R_2, R_0, r_1 and r_2 are the dimensions shown in Fig. 1; $I(0)$, $I(\theta_1)$ is the neutron yield in the reactions T (d, n) at the angles 0° and θ_1°, respectively; $\epsilon(\bar{E}')$, $\epsilon(E_0)$ are the detector sensitivities for scattered and direct neutrons, respectively; $P(\theta)\left[\exp\left(\frac{r_1+r_2}{\lambda_{\text{inel.}}}\right)\right]^{-1}$ is a correction for attenuation and multiple scattering.

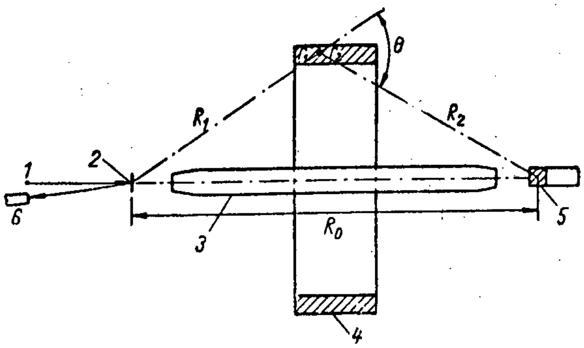

Fig. 1. Diagram of the unit for studying the elastic scattering of neutrons: 1) beam of 290 kev deuterons; 2) tritium target; 3) protective rod; 4) annular specimen producing the scattering; 5) scintillation detector; 6) α-monitor.

Figure 2 shows the experimental values for the differential cross section σ(θ) computed from formula (1) in a first approximation by replacing the integrands with their average values. Corrections for attenuation and multiple scattering are also taken into account only in the first approximation. A full consideration of all corrections will be taken after the corresponding computations have been completed.

The results obtained for copper and lead are in good agreement with published data [4]. The differential cross section for U^{238} was obtained over a wide range of angles for the first time. The experimental values of the cross sections in the range of angles 10-55° are in agreement with known data [3] for natural uranium at a neutron energy of 14.1 Mev. The solid curves in Fig. 2 depict computed angular distributions obtained on the basis of the optical model with a spherical Bjorklund-Fernbach potential for 15 Mev neutrons. The agreement between the experimental and theoretical curves is quite satisfactory. A detailed comparison of the curves for the purpose of detecting divergences associated with the nonspherical nature of the U^{238} atom proves to be possible only after corrections have been introduced for the angular resolution, the attenuation, and the multiple scattering. However, it is already possible to note that the expected discrepancy will be significantly greater only in the region of the first minimum.

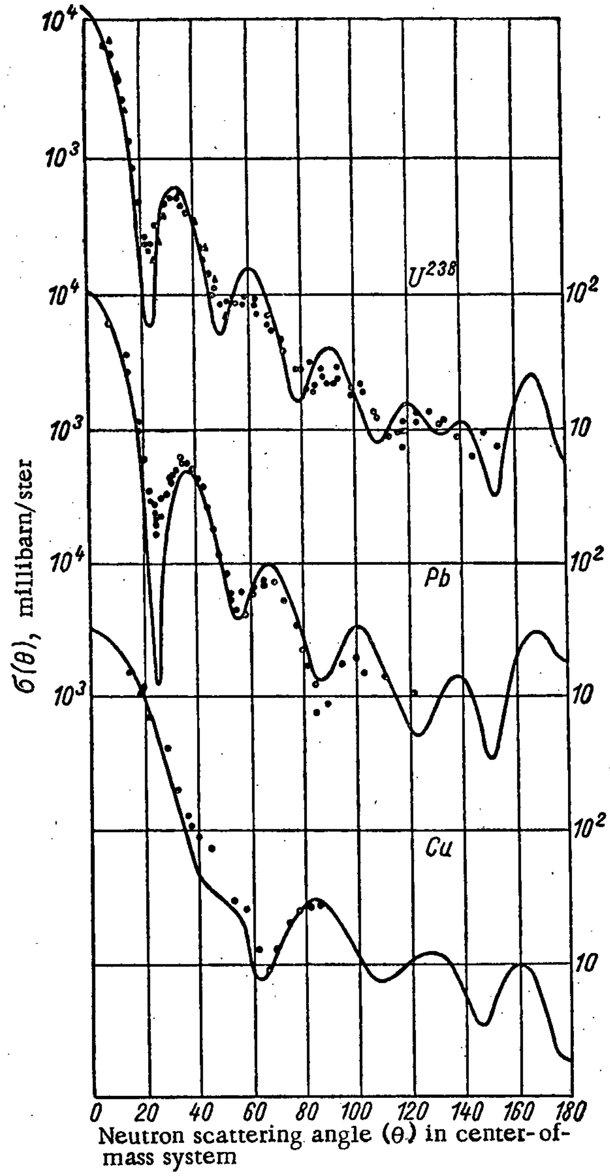

Fig. 2. Differential cross sections for elastic scattering of 15 Mev neutrons (▲ represents the data from [3]).

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MEASUREMENT OF THE CROSS SECTIONS FOR INELASTIC INTERACTION OF NEUTRONS WITH AN ENERGY OF 13 TO 20 MEV USING CERTAIN ISOTOPES

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This paper was written for the purpose of filling the "blank spots" which remained in the values for the cross sections of inelastic interaction even after the publication of numerous papers. First of all, known data [1-3, et al) do not touch on U^{235} and Pu^{239} at neutron energies of 13 to 20 Mev. Besides performing measurements with these isotopes, it would also be useful to repeat and expand measurements on specimens of U^{238}, aluminum, iron, copper and lead in order to compare our results with results cited previously in the literature.

Measurements were performed by the well-known [4] method of inverse spherical geometry. The special feature of the method resides in the fact that the neutron source is outside the sphere and the detector is inside it. This makes it possible to use nonisotropic neutron sources and thus appreciably expands the range of neutron energies accessible to measurement. At the same time, due to the reciprocity of the neutron paths in the direct and inverse geometries the physical relationship between the inelastic-reaction cross section and the experimentally measured coefficient of neutron passage through the sphere is retained:

$$T = e^{-\sigma_{ne} x n},$$

where T is the ratio between the fluxes of neutrons with a primary energy at the point D with and without the sphere; σ_{ne} is the inelastic interaction cross section; x is the thickness of the sphere; n is the density of the nuclei in the substance making up the sphere.

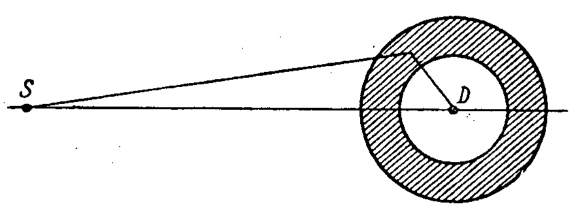

Diagram illustrating the experiment: S) neutron source; D) neutron detector.

From this formula we determined the inelastic interaction cross sections from the measured transmission coefficients T. Multiple scattering was not taken into account. The estimate of the cross section inaccuracy associated with this demonstrated that it is comparable to the errors cited in the results.

In order to measure the transmission coefficients we used conventional experimental techniques. Neutrons with energies ranging from ~ 13 to ~ 20 Mev were obtained at various angles in the reaction T (d, n) He^4 using a Van-de-Graaf generator. Spherical specimens of aluminum, iron, copper, lead, U^{238}, U^{235} and Pu^{239} (the lead specimen had the largest diameter – 14 cm) were mounted at a distance of 40 cm from the target; therefore the angular difference associated with the energy and intensity of the neutrons incident on the sphere was insignificant. The neutron flux at the point D (see figure) with the sphere and without it was detected by a circular scintillation crystal 15 mm in diameter which was made of plastic and connected through a light channel to the photocathode of a "FÉU-29." The recoil-proton spectrum from the "FÉU-29" was analyzed by a 50-channel amplitude analyzer after amplification.

The transmission coefficient T was determined as the ratio of the above-threshold integrals of the recoil-proton spectra with and without the sphere. For high thresholds we observed a range where the coefficient computed in this manner for various thresholds remained constant for all the measurements performed with lead, U^{238}, U^{235} and Pu^{239}. This proved the absence or insignificance of the contribution by inelastically-scattered neutrons to the portion of the spectrum above the threshold. The average value of T over such a range was used to compute σ_{ne}. For copper and iron specimens, and especially aluminum specimens, a drop appeared in the value of the transmission coefficients at high thresholds. This drop was caused by a reduction of the neutron energy as a result of elastic collisions. In this experiment we introduce the corresponding correction into the measured value of T.

Inelastic Interaction Cross Section, σ_{ne}, millibarns

Isotope	Neutron energy, Mev								
	13.4	14.3	15.4	16.1	16.8	17.5	18.4	18.7	19.7
Al	—	0.88±0.04	0.965±0.04	0.92±0.04	—	—	—	—	—
Fe	—	1.33±0.04	1.32±0.04	1.28±0.04	—	—	—	—	1.2±0.02
Cu	—	—	—	1.38±0.04	—	—	—	—	1.48±0.04
Pb	2.62±0.1	—	2.45±0.05	—	—	2.72±0.2	—	—	2.56±0.06
U^{238}	2.79±0.1	—	2.68±0.06	—	2.62±0.06	—	2.66±0.06	—	—
U^{235}	2.64±0.06	—	2.58±0.04	—	2.71±0.04	—	—	2.74±0.07	—
Pu^{239}	—	—	—	—	2.87±0.1	—	—	—	—

The average inelastic interaction cross sections obtained as a result of repeated measurements are shown in the table along with the equipment errors. Cross sections for aluminum, iron, copper, lead and U^{238} are in good agreement with previous data [1-3]. The results obtained with U^{235} and Pu^{239} filled the gap left in the neutron energy range 13 to 20 Mev.

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THE INELASTIC SCATTERING OF 14 MEV NEUTRONS BY SODIUM, IRON, NICKEL, AND LEAD NUCLEI

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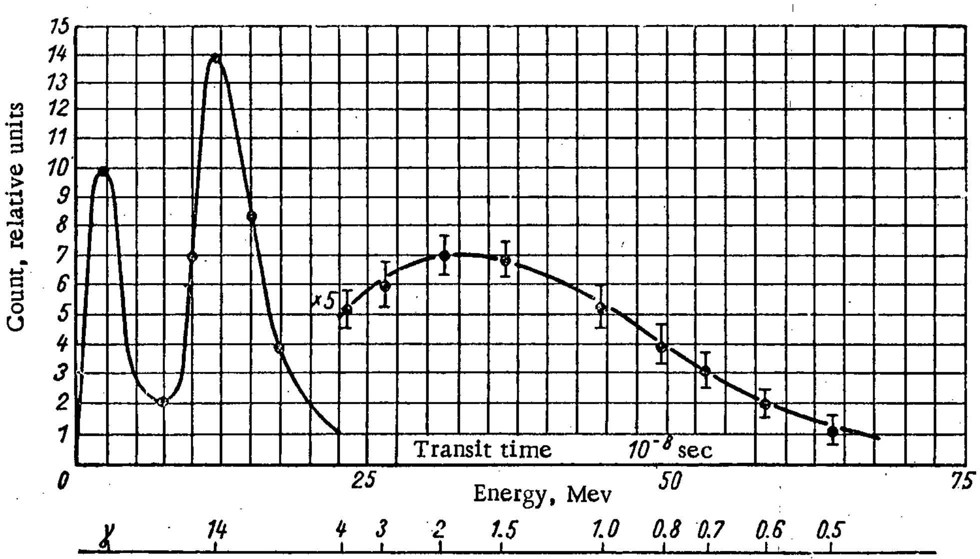
In this paper the transit time method was used to measure the spectra of inelastically-scattered neutrons in the energy range 0.6 to 4.0 Mev for bombardment of a natural mixture of sodium, iron, nickel and lead with 14 Mev neutrons. The unit consisted of a pulsed neutron source, a neutron detector, and electronic equipment for measuring the transit time of the neutrons. The neutron source [1] operated at a repetition frequency of 500 cps for a neutron pulse duration of $2.5 \cdot 10^{-8}$ sec. The transit distance for the neutrons was 6 m. We used a liquid scintillator based on xylene (5 g/l terphenyl and an admixture of "ROROR") with a volume of 150 cm^3 and a photomultiplier "FÉU-33" as the detector. In order to reduce the background from scattered neutrons the detector was placed behind a water shield 1 m thick. In performing the measurement the target was surrounded by a layer of the investigated substance approximately $^1/_3\ \lambda$ thick (where λ is the mean free path of 14 Mev neutrons in the substance). The transit time was measured by the "time to amplitude" conversion method. The conversion circuit was similar to the Weber circuit [2]. The spectrum obtained at the converter output was analyzed by means of a 128-channel amplitude analyzer. The conversion linearity was verified by means of a random coincidence curve. The maximum deviations from the average value did not exceed ± 3%. The time scale was graduated according to the known time between peaks corresponding to the γ-rays which accompany inelastic scattering of neutrons in the specimen and 14 Mev neutrons (for a base of 6 m). The time-resolving power of the unit was determined from the half-width of the γ-peak and was equal to $3 \cdot 10^{-8}$ sec. This time includes both the duration of the neutron pulse from the source and the resolution of the electronic circuit.

The Values of T and σ Obtained in Experiments on the Inelastic Scattering of 14 Mev Neutrons

Element	σ, barns	T, mev: In the present paper	T, mev: the Graves data [3]	T, mev: from the Zamyatnin data [4]
Na	0.45±0.1	0.97±0.09	—	—
Fe	0.96±0.2	0.80±0.08	0.76±0.08	0.7±0.07
Ni	0.90±0.2	0.79±0.08	—	—
Pb	1.8±0.3	0.75±0.08	0.76±0.08	0.73±0.05

As an example the figure shows the spectrum obtained for iron. For all of the investigated elements we determined the temperature T of the residual nucleus from the spectra which we obtained. The computations were performed for the segment of the spectrum 0.6 to 4 Mev by making use of the relationship

$$\frac{dN}{dE} \sim E e^{-\frac{E}{T}}.$$



Spectrum for neutrons which are inelastically scattered by iron.

No correction for the presence of neutrons from the reaction (n, 2n) was introduced. The table cites temperatures obtained in the described experiment and temperatures obtained by means of photoplates [3, 4]. The same figures shows values of the inelastic-scattering cross section σ for neutrons corresponding to the formation of a residual nucleus in the upper (10 to 14 Mev) excited states.

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THE ATTENUATION OF NEUTRON FLUX IN THE REINFORCED-CONCRETE SHIELDING OF A SYNCHROCYCLOTRON

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In order to calculate the magnitude of the protective shielding from the radiations arising during the operation of an accelerator, it is necessary to know the magnitude of the half-attenuation layer $\Delta_{1/2}$ for neutrons. The parameter $\Delta_{1/2}$ has been thoroughly studied for neutrons which arise in nuclear fission [1, 2] and the bombardment of a beryllium target with 16 Mev protons [3]. The energy of such neutrons is in the range 0.5 to 15 Mev. At high neutron energies (up to 300 Mev) the quantity $\Delta_{1/2}$ has been studied in less detail and in a geometry which is not standard [4]; this limits the field of applicability of the results obtained in [4]. For neutrons with energies above 300 Mev no experimental data at all on the thickness $\Delta_{1/2}$ is available. In order to fill this gap we performed the work described in this

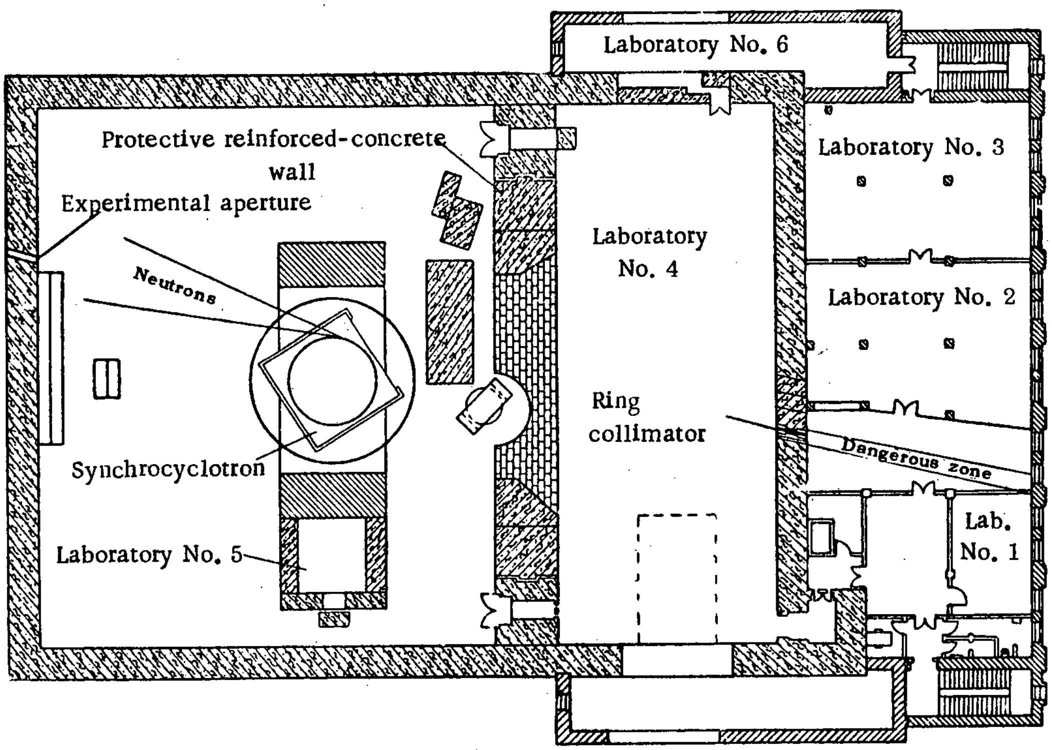

Fig. 1. Diagram of the synchrocyclotron building.

paper in the Laboratory of Nuclear Problems of the Combined Institute of Nuclear Studies. A cylindrical channel was cut through the two-meter reinforced-concrete wall of the synchrocyclotron building (Fig. 1); neutron detectors were mounted at different depths in the channel. Reinforced-concrete plugs which were adjusted to the channel diameter were placed between detectors; these plugs had a weight per unit volume equal to that of the wall (the density of the concrete was $\rho = 2.35$ g/cm^3). The magnitude of the neutron flux was determined from the activity of the threshold detectors or from the quantity of products due to various nuclear reactions caused by neutrons in the emulsion. Data on the detector parameters and the methods of recording the reaction products are cited in the table. The foils and the emulsion were irradiated under conditions close to the conditions of standard geometry.

Characteristics of the Detectors

Neutron detector	Neutron energy	Reaction products	Recording instrument
Indium foil ~ 300 μ thick	Resonance and thermal	β-radiation	Geiger counter with a thin mica aperture
Indium foil in a cadmium jacket	Resonance	"	Ditto
Foil consisting of copper C^{12} in a scintillator	Thermal	"	"
	> 20.5 Mev	"	Scintillation counter
A thick-layer photoemulsion	≥ 50 Mev	Fission	Microscope

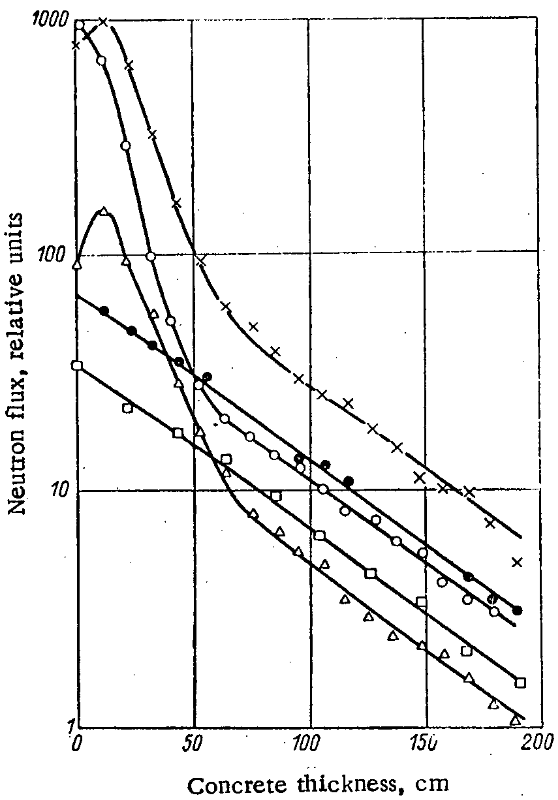

Fig. 2. Density of the neutron flux at various depths in an ordinary reinforced-concrete wall. Detector: ×) In ($\Delta_{1/2}$ is equal to 42 ± 1 and 8 ± 0.3 cm); ○) In + Cd ($\Delta_{1/2}$ is equal to 41 ± 1 and 6.5 ± 0.5 cm) △) Cu ($\Delta_{1/2}$ is equal to 41 ± 1 and 9 ± 0.5 cm); ●) photoemulsion ($\Delta_{1/2}$ = 43 + 2 cm); □) C^{12} ($\Delta_{1/2}$ = = 42 ± 2 cm).

The flux of neutrons incident on the wall was constant over an area 2 m in diameter with a center coinciding with the center of the experimental aperture. The angular divergence of the neutron beam was 3°.

The curves obtained under these conditions for the attenuation of the neutron flux density (Fig. 2) provided the necessary information on the thickness $\Delta_{1/2}$. These curves demonstrate the presence of two groups of neutrons for which $\Delta_{1/2}$ is equal to 6-9 and 41-43 cm; this corresponds to neutrons with energies of several or several hundred Mev, respectively. The equilibrium between the fluxes of these two groups of neutrons is established after passing through approximately 90 cm of ordinary concrete. The experimentally-measured magnitude of the half-attenuation layer ($\Delta_{1/2}$ = 41-43 cm) for neutrons with high energies is in good agreement with the value computed on the assumption that the basic part in the attenuation of the neutron beam is played by inelastic processes of interaction between neutrons and nuclei. The computation was performed using the relationship

$$\Delta_{1/2} = \frac{\ln 2}{\sum_i A_i \sigma_i},$$

where A_i is the number of nuclei per 1 cm^3 of a concrete element; σ_i is the cross section for inelastic interaction between the nuclei and 650 Mev protons [5].

In conclusion the author takes this opportunity to thank V. P. Dzhelepov for his help in performing the experiment and his consistent interest in this paper, and V. P. Afanas'ev for his help in performing the measurements.

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THE LONG-LIVED ISOTOPE Al^{26} IN THE ALUMINUM USED IN THE CONSTRUCTION OF A NUCLEAR REACTOR

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Of all the known aluminum isotopes [1, 2] only Al^{26} [3], which in its basic state has a half-life of $(7.83 \pm \pm 0.29) \cdot 10^5$ years [4], can be used as a radioactive tracer. However, the large value of the half-life imposes well-known limitations on the use of Al^{26} in research which is performed by the method of tracer atoms.

The isotope Al^{26} is formed as a result of nuclear reactions that occur due to the action of charged particles, fast neutrons, and hard bremsstrahlung [5-8]. One of the methods of obtaining it from the reaction (n, 2 n) consists of irradiating Al^{27} with fast neutrons in a reactor. Under these conditions the specific activity of the long-lived Al^{26} formed in the irradiated material is very small (12 decays per min per g of aluminum oxide [5]). It is of interest to determine the content of long-lived Al^{26} which is formed as a result of the reaction (n, 2 n) in the aluminum which is included in the structural elements of a reactor and is in the closest contact with the fissionable material over prolonged periods; this is all the more true since the cross section of the indicated reaction increases rapidly as the neutron energy increases (see data from [6]). In that case we can expect that treated structural aluminum will contain a greater quantity of Al^{26}.

We used treated structural aluminum which had first been purified from surface radioactive contaminations produced by the fission products. Identification was made from the lines of the γ-spectrum for Al^{26} with $E_\gamma = 1.83$ Mev, since its decay is accompanied by this line in 98% of the cases. Due to the small radiation intensity of Al^{26} the specimens had to be thoroughly purified from radioactive admixtures, chiefly from admixtures of the elements having the isotopes $Sr^{88} \rightarrow Y^{88}$, Nb^{92}, Ru^{106}, Cs^{134}, $Hg^{194} \rightarrow Au^{194}$, $Os^{194} \rightarrow Ir^{194}$ whose radiation contains γ-lines close to the γ-line of Al^{26} with $E_\gamma = 1.83$ Mev. It was especially important to exclude yttrium [1, 9]. The measurement of the γ-spectrum was performed using a scintillation spectrometer consisting of a NaI (Tl) crystal, a "FÉU-29" photomultiplier, and a multichannel analyzer with a stability no worse than plus or minus one channel per working day. The verification of the linearity and calibration of the spectrometer scale was achieved on the basis of the γ-radiation from Hg^{203}, Cs^{134}, Zn^{65}, Na^{22} and Co^{60}.

Figure 1a shows a sector of the γ-spectrum in the energy region 1.83 Mev for structural aluminum before its chemical purification. It is evident from this figure that the γ-radiation spectrum from treated structural aluminum is rather complex; it consists of a large number of lines which are of approximately identical intensity and possibly contains the line with $E_\gamma = 1.83$ Mev. Moreover, the spectrum contains lines with an appreciably smaller energy but with a greater intensity. The measurements performed in the control experiment after chemical elimination of yttrium from the treated structural aluminum showed that γ-radiation with a line corresponding to $E_\gamma = 1.83$ Mev is inherent in an addition of aluminum oxide. In order to free structural aluminum from impurities we used various radiochemical methods [5, 10]. Figure 1c shows a segment of the γ-spectrum in the energy region near 1.83 Mev, which belongs to the aluminum fraction obtained for chromatographic purification of aluminum. An analogous

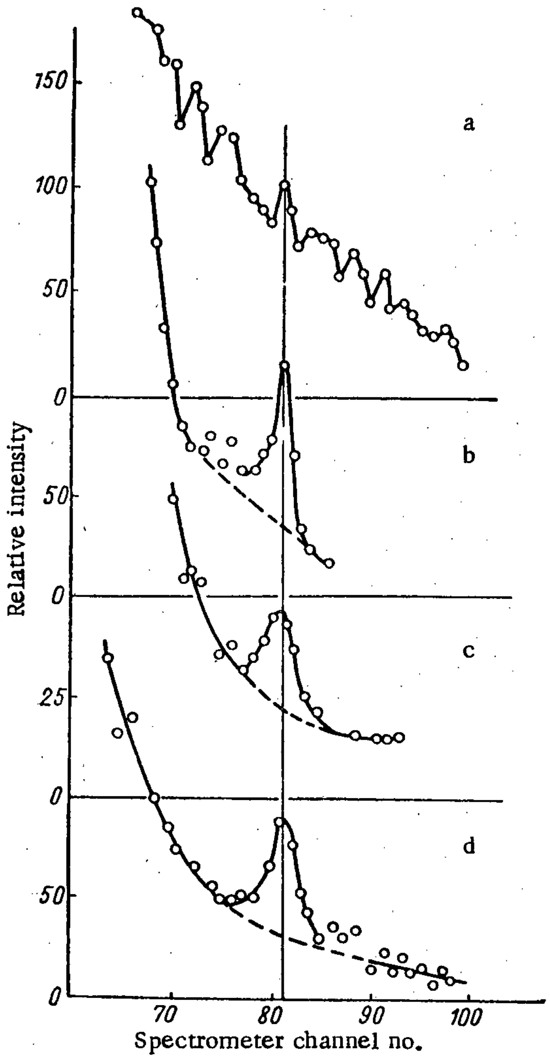

Fig. 1. Sector of the γ-spectrum in the energy region 1.83 Mev for treated structural aluminum: a) before chemical purification; b, c, d) after chemical purification by various methods.

section of the spectrum caused by radiation from the aqueous phase containing aluminum is shown in Fig. 1b. In that case the purification of the aluminum from radioactive impurities is achieved by the method of depositing hydroxides and extracting impurities. Figure 1b shows the γ-radiation spectrum for an admixture of aluminum oxide when the aluminum is purified by the method of depositing impurities in the form of hydroxides. Analogous results are also obtained when other purification methods are used. A comparison of the sections of the γ-spectra shows that for various chemical operations which must be performed in purifying structural aluminum by various methods the source of γ-radiation with one clearly delineated line having an energy E_γ = 1.83 Mev is aluminum. Therefore, the structural aluminum which we used must definitely contain the long-lived isotope Al^{26} which decays with the emission of a γ-quantum for which E_γ = 1.83 Mev. For all the purification methods the line with E_γ = 1.83 Mev is at the tail of a much more intense line of lower energy. The development of methods for purifying aluminum from the impurities which induce this line continues.

The estimate which we made of the content of long-lived Al^{26} in the investigated specimens yields a value of $2.5 \cdot 10^4$ decays/min per g of the treated structural aluminum extracted from the reactor; this is three orders of magnitude higher than the results obtained in [5] for an aluminum specimen which was irradiated in a reactor over a period of approximately one year.

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REVIEW OF GOSATOMIZDAT* (STATE ATOMIC PRESS) PUBLICATIONS FOR 1960 AND 1961

Below, we present a review of the literature on nuclear power and related subjects in science and engineering released by Gosatomizdat (State Atomic Press) during 1960-1961. However, bearing in mind the high scientific and practical value residing in the wealth of material appearing in the form "Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy" (1958 Geneva conference), we decided to include these items in the review.

The literature covered in this review is classified in terms of five permanent thematic aspects: "Nuclear Physics," "Nuclear Power," "Nuclear Fuel and Materials," "Nuclear Radiation Shielding," and "Radioactive and Stable Isotopes."

Some instances justify deviation from this arrangement. For the convenience of the reader, publications on problems of shielding at nuclear power facilities, for example, are included in the section "Nuclear Power." The review ends with a discussion of three books in popular science style which are distinguished by the broad scope of the topics treated in them and their manner of presentation.

PROCEEDINGS OF THE SECOND GENEVA (1958) CONFERENCE ON THE PEACEFUL USES OF ATOMIC ENERGY

(These sets are available in a six-volume set of papers by Soviet scientists and a ten-volume set of selected papers by foreign scientists).

Nuclear Physics. Papers on nuclear power physics are published in volume 1 of the reports by Soviet scientists, Yadernaya fizika [Nuclear Physics] and in volumes 1 and 2, Fizika goryachei plazmy i termoyadernye reaktsii [Physics of hot plasmas and fusion reactions] and Neitronnaya fizika [Neutron physics] of the selected papers by foreign scientists. The first part of the volume Yadernaya fizika is devoted to plasma physics and controlled fusion, and begins with a review paper by Academician L. A. Artsimovich on Soviet research in this field. Subsequent papers present results of investigations on high-current pulsed discharges. A series of papers is devoted to plasma stability problems, stabilization of a plasma with the aid of nonuniform magnetic fields, and plasma confinement by a high-frequency electromagnetic field. A paper on plasma radiation in a magnetic field is also interesting. One of the papers presents a theoretical examination of problems of simple and shock magnetohydrodynamic waves. Particular attention is given to experimental techniques for investigating plasma parameters. The second part of this volume includes reports on nuclear physics and some aspects of charged-particle acceleration: on the commissioning of the Dubna proton synchrotron, rocket and satellite cosmic ray studies in the USSR, nuclear reactions on heavy ions, asymmetry in fission of nuclei, radiative capture cross sections of neutrons, etc.

* State publishing house for literature in the field of atomic science and engineering. Formerly known as the Publishing House of the State Control Board on the use of Atomic Energy, under the USSR Council of Ministers.

The volume Fizika goryachei plazmy i termoyadernye reaktsii assembles texts or abstracts of papers. Review papers present a picture of the development of fusion research in the capitalist countries. Most of the papers relate to the problem of stability of plasma configurations, the theory of plasma heating by electromagnetic fields and shock waves. Many of the papers present a detailed description of plasma devices and the results of investigations on experimental fusion machines with different approaches toward plasma heating and plasma confinement (toroidal systems, stellerators, magnetic traps, etc.). Some papers undertake a review of measurements techniques used in controlled-fusion research in the USA and in Britain.

In the volume Neitronnaya fizika, some of the papers are reviews of the fundamental aspects of neutron physics. Reports in this volume may be classified under the following topics: structure and properties of neutrons; interaction cross sections with matter, including reactor structural materials; fission of nuclei, fission products, and radiations; resonance capture; slowing-down of neutrons; thermalization of neutrons; sophisticated techniques and equipment for measuring neutron cross sections, neutron fluxes, and neutron spectra. A wealth of theoretical and experimental material is offered under any one of these topics.

Nuclear Power. This heading includes: volume 2 of the papers by Soviet scientists, Yadernye reaktory i yadernaya ẽnergetika [Nuclear reactors and nuclear power engineering] and volumes 3 and 4 of the reports by foreign scientists Fizika yadernykh reaktorov [Nuclear reactor physics] and Yadernye reaktory i yadernaya energetika [Nuclear reactors and nuclear power engineering].

The first part of volume 2 is devoted to Soviet nuclear power facilities, while the second part describes experimental and research reactors, pile experiments, and work on reactor improvement. The third part, in large measure theoretical, illuminates problems in reactor physics. Here are included problems relating to reactor design and technology.

Volume 3 is in three parts. The first part considers experiments on studying the properties of various types of reactor lattices, several reactor types, and reactor systems. The second part is devoted to problems of reactor physics for various reactor types, plus some problems in theoretical physics, reactor physics, neutron physics, and mathematical physics. The third part describes reactor kinetics, calculations of fuel cycles, and reactor safety problems.

Volume 4 contains a description of the basic types of foreign power reactors and nuclear power stations. Economics and costs problems in nuclear power projects and uses of nuclear reactors not related to exploitation of the chain reaction for power generation are discussed here.

Nuclear Fuel and Materials. This heading embraces volumes 3 and 4 of the papers by Soviet scientists: volume 3, Yadernoe goryuchee i reaktornye metally [Nuclear fuel and reactor metals], and volume 4, Khimiya radioẽlementov i radiatsionnykh prevrashchenii [Chemistry of radioelements and of radiative transmutations] as well as volumes 5, 6, 7, and 8 of the selected papers by foreign scientists, vol. 5, Khimiya radioẽlementov i radiatsionnykh prevrashchenii (see above), vol. 6, Yadernoe goryuchee i reaktornye materialy [Nuclear fuel and reactor materials], vol. 7, Tekhnologiya atomnogo syr'ya [Technology of nuclear raw materials], and vol. 8, Geologiya atomnogo syr'ya [Geology of nuclear raw materials].

The first part of volume 3 takes up contributions on geology, mineralogy, prospecting, beneficiation, and processing of nuclear raw materials. The second part is devoted to such fields as metallurgy, metals science and technology of both nuclear fuels (uranium and uranium compounds, thorium, plutonium), and a variety of structural materials (zirconium, beryllium, and alloys). Here we also find results of studies of the physical and corrosion properties of reactor metals and effects of neutron irradiation on the structure, properties, and dimensional stability of fuel, i.e., results of investigations of many of the outstanding questions in modern metals and materials science.

Volume 4 of the reports by Soviet scientists considers advanced techniques in the processing of spent nuclear fuel, and presents the results of research on the chemistry of ruthenium, thorium, uranium, plutonium, and americium. Such problems as sorption and burial of radioactive wastes are also taken up. Some of the reports deal with particular problems in radiation chemistry.

The papers in volume 5 of the second set (papers by foreign scientists) throw light on aspects of chemical processing of irradiated materials, analytical methods of control, methods for removal and disposal of radioactive wastes, and some aspects of the radiation chemistry of polymers, gases, aqueous solutions, solid and liquid organic compounds.

Volume 6 of the second set presents a selection of papers on the metallurgy of uranium and its alloys, the metallurgy of niobium, and of structural materials, uranium metal studies, research on uranium alloys and plutonium, the thermodynamical,and corrosive properties of uranium, plutonium, their alloys and compounds. Effects of neutron bombardment on nuclear fuel and on structural materials are also discussed, as well as the technology of fuel element manufacture.

Volume 7 includes selected papers by foreign scientists on the technology of nuclear raw materials. This volume has five sections: leaching of uranium and thorium from ores and precipitation from leach liquors; sorptive methods of uranium extraction from leach liquors and pulps; extractive methods for winning uranium and thorium from leach liquors and pulps; isolation of pure uranium and pure thorium compounds; isolation of uranium hexafluoride and its reduction to uranium tetrafluoride.

Volume 8 of selected papers by foreign scientists contains five sections. The first section is devoted to general problems in the geology, geochemistry, and mineralogy of uranium and thorium; the second section presents ten regional reviews of the status of the raw materials base in uranium and thorium; the third section presents a description of individual uranium and thorium deposits; prospecting and exploration techniques in uranium and thorium operations are described in the fourth section; the fifth section examines the geology of beryllium and zirconium.

Radiobiology. Volume 5 of the reports by Soviet scientists, Radiobiologiya i radiatsionnaya meditsina [Radiobiology and radiation medicine] takes up four groupings of problems. The first group constitutes an investigation of the details of biological effects of ionizing radiations, remote sequela of low-dosage exposures and genetic effects of radiation, and discussions of therapy of radiation sickness. The second set of papers is devoted to the uses of radioactive isotopes in biological and medical research; the third group deals with applications of nuclear energy to medicine. The fourth group includes reports elucidating problems of absorption of several uranium-fission products into soils and uptake and storage of such fission products in plants and food products.

Volume 9 of the selected papers by foreign scientists, appearing under the same title as volume 5 of the reports by Soviet scientists, contains papers covering six headings: biological effects of radiation, shielding against radiation effects; health physics and work safety at nuclear facilities; uses of tracer atoms in biochemistry and physiology; applications of nuclear energy in medicine; radiation genetics.

Radioactive and Stable Isotopes. Volume 6 of the papers by Soviet scientists is opened up by a paper entitled "Applications of radioactive isotopes in the USSR," in which a detailed survey is presented of the status of research using isotopes in the USSR national economy. Two papers appearing in this volume elucidate such questions as preparation of materials for radiation exposure, irradiation of specimens, processing of irradiated materials, development of remote-control techniques in radiochemical laboratories.

Six subsequent papers are devoted to the uses of radioisotopes in industry and engineering. Five papers go into special problems in radiation dosimetry. The last 11 papers are devoted to different aspects of the use of radioactive isotopes and ionizing radiations in agriculture. These papers present results of photosynthesis research using quantitative radiometric techniques in the study of translocation, distribution, and transformation of several physiologically active substances in plants, phosphorus uptake by agricultural crop plants as a function of resistance to frost, applications of radioactive isotopes in studying plant protection, etc.

Volume 10 of the selected papers by foreign scientists, Poluchenie i primenenie izotopov [Isolation and applications of isotopes], consists of four parts. The first part goes into several techniques for isolating stable and active isotopes, methods for synthesizing labeled organic compounds, and a description of radiochemical facilities for isotope production from uranium-fission products. Techniques for producing radioisotopes of high specific activity are also dealt with in this section. The second section is devoted to the design of facilities and instruments using radioactive isotopes; a series of interesting examples in uses of radioisotopes is presented. The third part is devoted to a description of equipment and recording methods for ionizing radiations; the fourth part describes laboratories and equipment for handling radioactive materials.

NUCLEAR PHYSICS

NUCLEAR PHYSICS, NEUTRON PHYSICS, AND NUCLEAR RESEARCH TECHNIQUES

A book by P. Ė. Nemirovskii, Sovremennye modeli atomnogo yadra [Contemporary models of the atomic nucleus], 1960, 300 pages, is based on recent research by Soviet and foreign scientists, leaning heavily on original contributions by the author. As the title indicates, the book takes up the topics: shell model, generalized or collective model of the nucleus; optical model of the nucleus; and their interrelations. Radiative transitions in the first two models and the application of the collective model to alpha-decay theory are discussed at the conclusion of the book. The author avoided any cumbersome mathematical involvements, with the result that the book's contents are readily accessible to a comparatively broad audience of readers. The bibliography appended to this interesting text on nuclear processes at low energies contains 300 titles.

N. F. Nelipa's Vvedenie v teoriyu mnogokratnogo rasseyaniya [Introduction to multiple-scattering theory], 1960, 159 pages, is an outgrowth of a lecture course given by the author at MIFI, the Moscow Engineering and Physics Institute. Despite the book's small size, the author met with success in his presentation of methods for solving the problem of transmission of gammas, electrons, and neutrons through matter with multiple scattering taken into account. The book considers sources of different geometric shape and offers numerical examples. The book is a very timely one now, especially because of the great practical need for calculation and design of biological shielding facilities.

The symposium of contributions Apparatura dlya yadernoi spektrometrii [Nuclear spectrometry equipment] edited by S. S. Kurochkin and V. V. Matveev, 1961, 134 pages, is an interesting item. The first part of the symposium contains four articles dealing with spectrometer sensors now being produced on a mass scale (scintillators, phototube multipliers, light pipes). The second part (seven articles) describes electronic equipment and components used in spectrometers; a nonoverload linear pulse amplifier, a precision mean count rate meter, a single-channel spectrometer with 0.3 μsec resolving time, etc. The material furnished in the symposium can also be used in other branches of science and engineering in the design of various lines of control and measuring hardware.

Details of the design of equipment for nuclear research in cyclotron laboratories are studied in detail in the book Oborudovanie dlya yadernykh issledovanii [Nuclear research equipment] by L. F. Kondrashev and N. N. Khaldin, 1961, 148 pages. This book generalizes experience acquired by a team of designers and physicists of the cyclotron laboratory of the I. V. Kurchatov Institute of Atomic Energy under the Academy of Sciences of the USSR. This is the first book in which some problems which have barely received attention in the literature are given ample treatment: such problems as the design, fabrication, adjustment, and operation of special-purpose equipment used for nuclear investigations on cyclotrons and for adjustment and operation of the cyclotron. Many components described in this book could find useful applications in laboratories not equipped with a cyclotron.

A symposium of contributions under the title Neitronnaya fizika [Neutron physics] edited by P. A. Krupchitskii appeared recently: 1961, 371 pages. It contains original papers by various authors. The four sections of the symposium are addressed to the topics: slowing-down, resonance absorption, and neutron diffusion (six articles); fission, fragments, and secondary neutrons (18 articles); interactions between fast neutrons and nuclei (12 articles); and gamma radiation in response to neutron capture (four articles). This book is of great interest to theoretical physicists and engineering physicists, particularly for those engaged in the calculation and design of reactor installations and facilities.

Among the textbook family, we may single out Sbornik zadach po atomnoi fizike by I. E. Irodov, 1961, 239 pages [Problem and answer book in nuclear physics]. This serves as a manual for advanced undergraduates and has already gone through two editions. The book contains about 850 problems with generous hints for the solution of the toughest ones.

Another textbook aid for students in physics and engineering-physics departments is provided by Fizika atoma [Physics of the atom] by M. Wehr and J. Richards, translated from the English [Addison-Wesley, USA, 1960], 1961. This textbook is an introduction to modern atomic physics. It discusses the atomistic concepts of matter, electricity, radiation, the Rutherford and Bohr models of the atom, the fundamentals of relativity theory, natural and artificial radioactivity, nuclear reactions, nuclear energy, elementary particles, and cosmic rays. The appendices include tables of isotopes, atomic constants, and other reference material. The book examines the fundamental aspects of atomic physics without employing any complex mathematical tools, and fulfills to a considerable degree the need for books covering this ground.

From the translated literature on nuclear physics, we mention the book by B. Davison Teoriya perenosa neitronov [Neutron-transport theory, Oxford University, 1957] translated from the English, 1960, 520 pages; and A. H. Wapstra, G. J. Nijgh, R. Van Lieshowt Tablitsy po yadernoi spektroskopii [Nuclear spectroscopy tables] translated from the English, 1960, 178 pages. B. Davison's book is the first monograph to appear in the world literature giving a full treatment and review of modern mathematical techniques developed outside the USSR for solving problems of neutron propagation in various media. Some of the techniques appear for the first time in this book. G. I. Marchuk, who edited the translation, added a bibliography for Soviet readers, notes and comments reflecting parallel investigations by Soviet scientists to the degree possible for a translated work. The book Nuclear Spectroscopy Tables was put out by the authors as a brief handbook on α-, β-, and γ-spectroscopy. Most of the data therefore appear in the form of graphs and tabulated data. Some explanations lighten the task of the reader. General-purpose mathematical tables, atomic constants, and a description of the methods used in reducing experimental results are added at the beginning of the book, and calibrated standards for spectrometers are added at the end. Theoretical information is also included. The chapters on nuclear models and angular distributions and correlations are particularly interesting.

Among books on nuclear physics, a special place is occupied by P. A. Yampol'skii's Neitrony atomnogo vzryva [Neutrons from an atomic explosion] 1961, 132 pages; and the book Operatsiya "Argus" [Operation "Argus"] translated from the English, 1960, 117 pages. The first of these discusses the physical picture of processes induced by neutrons from an atomic explosion. After an introductory description of the fundamentals of neutron physics, the spatial distribution of neutrons in air and ground explosions, the role of delayed neutrons, gamma radiation from neutron captures in air, activation of the ground, and residual radiation from fission fragments are discussed. Dosimetry of neutrons originating in an explosion is treated in the last chapter.

"Operation 'Argus' " is the code name given to the experiment conducted by the USA in late 1958 to study the behavior of electrons originating in the explosion of nuclear bombs at a height of 480 km in the earth's magnetic field. The explosions led to the formation of an artificial electron belt circling the earth and were conducive to the appearance of polar aurorae, variations in radio-wave transmission, and other sundry effects. Observations of the electrons introduced into the geomagnetic field were carried out by means of artificial satellites and probe rockets launched to heights of 800 km. The book Operation 'Argus' contains the materials of a special symposium held in 1959 on the results of scientific observations of the effects of man-made radiation at high altitudes. The material published in this book is of theoretical and practical value for many branches of science and engineering.

Neitron [The neutron], a book in popular style by M. A. Bak and Yu. F. Romanov, 1960, 82 pages, provides an opportunity for a broad variety of readers to get acquainted with the history of the discovery and the basic properties of the elementary particle known as the neutron. The book convincingly shows the reader that the neutron is actually an important constituent of all nuclei, which has been the center of stormy advances in nuclear physics. It played the deciding role in the successful unleashing of the chain reaction of fission of nuclei and in harnessing the energy within the nucleus for industrial purposes.

In looking at the series of translated popular-style books on nuclear physics, the one that attracted the most attention was the book Fizika atomnogo veka [Physics of the atomic age], 1961, 205 pages, by H. Semat and H. White. The book was written in line with a closed-circuit TV course of lectures carried on in the USA for a wide audience. The first half of the book takes up the atom and its structure, properties of atomic particles, and the history of their discovery. The second half contains a detailed description of the history of the discovery of the atomic nucleus. Several chapters are devoted to natural radioactivity, radioactive disintegration, and splitting of nuclei, in particular with the aid of charged-particle accelerators. The concluding chapters describe the latest achievements of nuclear physics ensuing from the solution of the problems involved in liberation of nuclear energy by fission and fusion. The book is a substantial aid in finding out facts about the history and development of the science of the atom and nucleus. It will be useful to the reader regardless of his state of knowledge in a particular area of nuclear science.

Two translated books covering essentially the same ground are Metody izmerenii v yadernoi fizike [Measurements techniques in nuclear physics] by W. Braunbeck, translated from the German, 1960, 87 pages; and Izmereniya yadernykh izluchenii [Measurements of nuclear radiations] by J. Sharpe, translated from the English, 1961, 78 pages.

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Both books are outgrowths of a series of popular-style articles appearing in the periodicals Atomkernenergie and Nuclear Engineering, respectively. The books present concise but substantial surveys of the methods used in measurements of nuclear radiations. A popular style book by J. Johns, J. Rotblat and J. Wirrow, Atomy i Vselennaya [Atoms and the Universe], translated from the English, 1961, acquaints the reader with the fundamentals of nuclear physics and its application to studies of the structure of the universe. The history of the discovery of elementary particles and their properties, the splitting of the atom and the harnessing of the energy within the nucleus, nuclear reactions in the stars and in the sun, and cosmic radiation are described in the first chapters of the book. The author then proceeds to an account of the properties of matter in terms of classical and modern concepts, using the theory of relativity and quantum mechanics. An appreciable portion of the book is devoted to the solar system, to the generation of energy in the sun's interior, to the chemical composition of the planets, the Milky Way, and to a discussion on the size and age of the universe. The book is highly readable and accessible to a wide audience.

Physics of Hot Plasmas and Controlled Fusion Reactions. In recent years, the problem of controlled thermonuclear reactions has spawned particularly intense research on the plasma state. This has in turn brought forth a number of books related to the theory, formation and harnessing of plasmas, of interest not only to the particular field but to other branches of science and engineering as well.

Ėlektromagnitnye svoistva plazmy i plazmopodobnykh sred [Electromagnetic properties of plasma and plasma-like media] by V. P. Silin and A. A. Rukhadze, 1961, 244 pages, is a work based on a presentation of the basic theoretical concepts on media with spatial dispersion of the dielectric constant (first chapter). The two succeeding chapters examine the properties of isotropic and anisotropic plasmas from the theoretical standpoint. The later chapters seek to generalize the effect of spatial dispersion on various phenomena in metals and investigate the dielectric constant in molecular crystals. The book systematically reviews a large fund of papers by Soviet and foreign plasma-research scientists (the bibliography groups together 285 titles) and is written for the benefit of physicists specializing in plasma work and for students in corresponding engineering and physics departments.

Theoretical problems are the subject of the book by J. L. Synge Relyativistskii gaz [Relativistic gas] translated from the English [International Press, 1957], 1960, 139 pages. This book might be termed an introduction to the kinetic theory of gases whose particles have velocities comparable to the speed of light. Such a gas is the limiting case of a "hot" plasma. The discussion of a relativistic gas is also interesting in its connection to the idea of a photon rocket for cosmic flights. The presentation is given from classical positions, circumventing the use of quantum mechanics, and based on the geometric approach in the special theory of relativity.

S. Braun's book Ėlementarnye protsessy v plazme gazovogo razryada [Elementary processes in a gas-discharge plasma] translated from the English [J. Wiley, 1959, as Basic Data of Plasma Physics], 1961, takes up questions of outstanding interest in plasma research. The book is based on a lecture course given at the Massachusetts Institute of Technology, and on technical papers of the electronics research laboratory. The list of contents is almost identical to that in other books on gas discharges, but this book surpasses its rivals in the large selection of drawings and tables presented predominantly in the sections on reaction cross sections, elastic collisions, charge transfer and diffusion.

Many important concepts presently employed in plasma research are borrowed from cosmic electrodynamics. The fundamentals of the physics of plasmas applied to cosmic phenomena are explained in the book Kosmicheskaya ėlektrodinamika by J. Dungey [Cosmic Electrodynamics], 1961, 205 pages, translated from the English [Cambridge University]. Its contents are based on the work of the British school of astrophysicists. The book is written at the level of the specialist, who may find in it an interesting and refreshing treatment of many familiar questions.

Proekt Shervud [Project Sherwood] (the USA controlled-fusion program) by A. S. Bishop, translated from the English,* 1960, 176 pages, has brought knowledge of the USA fusion program from 1951 to 1958 to an endless number of readers, including nonspecialists. The presentation as a rule keeps to a chronological order and is written for persons with limited technical training. It is accompanied by a brief description of the operating principles of some experimental fusion facilities. The book presents a vivid picture of the trends of the research program known under the code name Project Sherwood, and of the difficulties encountered in experimental attempts to translate theoretical concepts into reality.

A broad selection of readers who are not specialists in the field will undoubtedly be interested in reading D. A. Frank-Kamentskii's Plazma – chetvertoe sostoyanie veshchestva [Plasma – the fourth state of matter],

* Addison-Wesley, 1958.

1961, 132 pages, which presents the reader with an account, in popular style, of controlled-fusion problems. Although the book is written for the benefit of engineers and technicians, it is readily accessible to readers with a high school education. The fundamental methematical groundwork of the book is quite elementary, and the most difficult passages, intended for the scientifically-trained reader, are presented in small print.

Physics of Charged-Particle Acceleration. Under this heading, we call attention to four books published, two of which are in popular style.

L. M. Anan'ev, A. A. Vorob'ev and B. I. Gorbunov are the authors of Induktsionnyi uskoritel' élektronov — betatron [The betatron: inductive electron accelerator], 1961, 351 pages, a book which consists of monographs based on the results of research in the Soviet Union and abroad. The authors have behind them years of experience in betatron work. The book covers the topics: theory of electron motion, the electromagnet and its power supplies, the vacuum system, the injection arrangements, beam extraction from the doughnut, adjustment and tuning components, radiation shielding. The book will also be useful in the fact that it advertises the feasibility of using betatrons in the energy range up to 30 Mev for various applied functions (flaw detection, medicine, chemistry, etc.)

The symposium Uskoriteli [Accelerators], 1960, 124 pages, brings together a number of articles on charged-particle accelerators. Some of the articles offer a description of the ferrite buncher used to bring the cyclotron to the synchrocyclotron mode of operation; the cyclotron with periodically-varied magnetic field for accelerating multiply-charged ions; a new system for beam extraction from a synchrocyclotron, etc. The remaining articles discuss questions related to electron accelerators: a 6 Mev linear accelerator with constant phase velocity; dynamics and bunching of particles in linear accelerators; beam extraction from betatrons; and the problem of storage of electrons in synchro-clash accelerators.

Despite the appearance of new types of accelerators, electrostatic accelerators of charged particles and the cyclotron remain the most popular machines for nuclear research and various applied functions. Among the books which have appeared in popular-science style, we note Élektrostaticheskie uskoriteli zaryazhennykh chastits [Electrostatic accelerators for charged particles] by B. N. Gokhberg and G. B. Yan'kov, 1961, 51 pages, and N. D. Fedorov's Tsiklotron — tsiklicheskii rezonansnyi uskoritel' ionov [The Cyclotron - cyclic resonance accelerator], 88 pages, presents the operating principles, the history of the cyclotron's development, and the subsequent improvements on these accelerators, tracing the pedigree of the modern particle accelerators back to its beginnings.

NUCLEAR POWER ENGINEERING

Books under this heading may be arbitrarily divided up into three groups: 1) reference manuals of a general character; 2) books devoted to nuclear-reactor physics (including theory and design of reactors and physics of nuclear-radiation shielding); 3) books dealing with structural and power engineering problems in reactor design and operation.

Reference Handbooks. These publications are intended for a broad readership embracing specialists involved in nuclear power work and in related branches of science and engineering, and contain information directly related to their daily work. Examples of such publications are: Spravochnik po yaderno-fizicheskim konstantam dlya raschetov reaktorov [Handbook of nuclear-physics constants in reactor calculations] (authors: I. V. Gordeev, R. A. Kardashev, A. V. Malyshev), 1960, 280 pages: Kratkii spravochnik inzhenera-fizika [Short handbook for the Engineer and Physicist] (compiled by N. D. Fedorov), 1961, 507 pages; R. Eger: Dozimetriya i zashchita ot izluchenii [Dosimetry and radiation shielding], translated from the German, 1961, 210 pages; Spravochnik po korrozii i iznosy yadernykh reaktorov s vodyanym okhlazhdeniem [Handbook of corrosion and wear for water-cooled nuclear reactors], translated from the English and edited by E. S. Sarkisov, 1960, 404 pages; Énergeticheskie reaktory SShA [Power reactors of the USA], translated from the English under the editorship of M. I. Minashin, 1960, 88 pages.

The first handbook mentioned contains experimental reference data processed and presented in a form convenient for practical consultation and use. The first and second chapters of the handbook include information on neutron cross sections in the region of thermal energies and on resonance-level parameters. The third chapter presents experimental data on inelastic-scattering cross sections and transport cross sections. The fourth and fifth chapters contain data on cross sections for intermediate and fast neutrons, fission yields and energies of fission products. The appendix outlines the best procedures for making practical use of the information presented.

The Short Handbook for the Engineer and Physicist compiled by N. D. Fedorov is of a more general character and dovetails with published texts on reactor design, on the basis of the concept that the bulk of the materials contained in the handbook involve reactor physics and engineering. Specialists in reactor design will find in this handbook the basic information which they need to have on hand most of the time in their practical work. The handbook also generously makes available information on accelerator techniques, thermonuclear reactions, nuclear physics, geology of atomic raw materials, isotopes, radiation medicine and radiation biology, and other problems.

The book by R. Eger contains reference material on radiation shielding. It presents fundamental physical constants, concepts and definitions related to dosimetry and shielding problems. Tables, formulas, and graphs needed for practical shielding calculations are given.

The handbook on corrosion and wear was written by a team of American specialists. The value of the handbook resides in the fact that it compiles a wealth of factual material relating to the very urgent problem of corrosion and wear of materials in the primary loop of water-cooled reactor systems. The first part of this handbook considers the flow scheme of a nuclear-power facility, presents general information on corrosive attack and wear, details information helpful in choosing materials, and also considers problems relating to water technology. The second part describes corrosion testing techniques and wear tests for some materials and combinations of materials, and tabulates necessary experimental data. The third part is devoted to special questions in corrosion and wear related to materials selection and the development of concrete design types in nuclear reactors.

The manual Power Reactors of the USA was released by the USAEC. It provides technical reference data on ten large nuclear-power facilities in operation, under construction, or being planned in the United States. The references include a brief standard description of a reactor, its flow charts, structural details, maintenance and ancillary systems, reactor control features, and detailed tabulations of data for reactors and reactor systems. The generously provided drawings and graphs illustrate the design and construction of the reactors described.

Nuclear Reactor Physics publications. Five books are discussed under this heading.

A symposium of articles by Soviet authors Issledovanie kriticheskikh parametrov reaktornykh sistem [Investigation of critical parameters in reactor systems], 1960, 118 pages, contains original articles pertaining primarily to theoretical calculations of neutron flux and critical parameters (critical mass and volume) in various reactor systems, viz.: uranium-graphite, uranium-beryllium, and slurried mixtures of uranium and plutonium. The symposium presents graphs and tables establishing relationships between critical parameters and relative concentration, and the nature of fissionable material and moderator, as well as fuel enrichment, for a broad range of neutron energy spectra.

Fizika promezhutochnykh reaktorov edited by J. Stehn, translated from the English [Physics of intermediate-spectrum reactors, USAEC] 1961, 626 pages, is devoted to problems which had hitherto not received systematic attention in Soviet literature. What is involved is a particular offshoot of reactor design: reactors with an intermediate-neutron spectrum. This book fills the gap in the literature to an appreciable extent. Although the scope of the questions treated in the work is restricted to an intermediate-spectrum reactor with beryllium moderator and sodium coolant, many of the experimental and theoretical research methods described in the book are of a more general character and may prove interesting and useful to specialists working on other reactor types.

A book by T. Kahan and M. Gauzie Fizika i raschet yadernykh reaktorov, translated from the French, * 1961, 392 pages, [Physique et Calculations des Réacteurs Nucléaires, Dunod (Paris), 1957] is the first volume of a projected three-volume treatise on nuclear engineering. The book starts off with the fundamentals of atomic and nuclear physics, goes into the phemonena of radioactivity and the properties of nuclear radiations, nuclear fission processes, and the chain reaction. Steady-state reactor theory and reactor dynamics, and methods of calculations for homogeneous and various types of heterogeneous reactors are discussed. The text is profusely illustrated with examples of numerical calculations, and characteristics of reactors now in operation.

J. Bowen and E. Meister are authors of Upravlenie yadernymi reaktorami [Control of nuclear reactors] translated from the English, 1961, 96 pages, a book devoted to control problems of gas-cooled uranium-graphite reactors, which have attained their maximum development in Britain. The performance of reactor control systems, system calculations, and the required accessory equipment are described. Radiation effects, reactivity, and rate of coolant flow are discussed in terms of how they affect an operating reactor. The problem of reactor stability in transients is probed. Requirements for system components and control loops are presented, and a brief description of instruments for measuring neutron flux is included.

H. Goldstein's Osnovy zashchity reaktorov [Fundamental aspects of reactor shielding], translated from the English (Addison-Wesley, 1959), 1961, 344 pages, directs the reader's attention to a discussion of fundamental research on radiation shielding. In this respect, it differs essentially from other works on this topic which have previously been translated into Russian, and which as a rule are limited to a presentation of the results of investigations, while the major attention is given to recommendations on the results of such investigations for use in engineering calculations.

Books on Nuclear Engineering and Reactor Heat Power Engineering. This group covers eight books, five on nuclear engineering and three on heat power, heat transfer, and related problems.

Books on nuclear-reactor technology. One important topic of power-reactor design is corrosive attack on reactor materials in water-cooled reactors. The correct solution to problems of water management in nuclear-power installations will be impossible without an intimate knowledge of the corrosive processes occurring at high temperatures and under high pressures. The symposium Korroziya reaktornykh materialov [Corrosion of reactor materials] edited by V. V. Gerasimov, 1960, 284 pages, describes procedures for corrosion and electrical tests, discusses the effect of water composition on corrosion of structural materials,and the various modes of corrosion: stress corrosion, intergranular corrosion, corrosion of reactor materials. The book contains a large amount of empirical data which makes it useful as a handbook.

D. Hoisington's Osnovy yadernoi tekhniki [Nucleonics fundamentals, McGraw-Hill, 1959], 1961, 398 pages, is devoted to fundamental concepts on the structure of matter and the uses of atomic energy. Beginning with a highly-compressed presentation of the basic physical concepts involved, the author proceeds to acquaint the reader step by step with the structure of matter, the properties of atoms and nuclei, natural and artificial transmutations of nuclei, etc. Much attention is directed to future perspectives in the development of nuclear power, to radiation shielding, and to equipment for recording radiations. In its manner of presentation, the book is accessible to readers at any level, without requiring any specialized training.

H. Crouch's Yadernye korabel'nye silovye ustanovki, translated from the English [Nuclear ship propulsion, Cornell Maritime Press, 1960], 1961, discusses the basic questions encountered in the building of nuclear-propulsion units. Details of such installations, their economics, the selection of nuclear fuels available, and methods of nuclear physics and power physics calculations relating to the reactor core come under discussion. An attempt is made at evaluation of various nuclear reactors as candidates for maritime propulsion applications. Much attention is given to safety problems on board nuclear-fueled ships.

Techniques for optimizing the values of structural variables in nuclear-power installations, with an eye to minimizing costs of electric power generated at nuclear-fueled electric power stations form the subject matter of the book Vybor optimal'nykh variantov v reaktorostroenii [Optimization of reactor design variables] by P. Margen, translated from the English, 1961, 101 pages. The material is presented in application to gas-cooled uranium-graphite reactors. However, many concepts lend themselves to successful application to other reactor types as well. We feel free to say that the book is, all in all, the first attempt to find a comprehensive solution to the complex problems of optimizations in nuclear-power engineering.

One of the outstanding problems faced in the operation of nuclear reactors is control and monitoring of reactor-produced radiations. The book Upravlenie yadernymi reaktorami by M. Gauzie and T. Kahan, translated from the French [Control of Nuclear Reactors, Dunod (Paris) 1957], 1961, 174 pages, offers detailed descriptions of equipment for monitoring radioactive pile radiations and reactor control gear. Particular emphasis is laid on the biological hazards attendant upon reactor operation, and techniques of radiation shielding.

Books on nuclear reactor heat power engineering. B. V. Petunin's Teploénergetika yadernykh ustanovok [Heat power engineering for nuclear installations] 1960, 232 pages, makes available information on nuclear chain reactors, calculations and design of nuclear power installations with steam cycles and gas-turbine cycles. The characteristics of the coolants used are discussed, and technological flow charts of the most typical nuclear electric power stations now in operation or under construction are examined in full detail. Information needed for calculations and designing heat-exchange equipment, heat exchangers, and steam generator units for nuclear electric power stations is also provided.

The basic information from the fields of thermodynamics and heat transfer needed for analysis and calculations of heat removal processes in nuclear reactors and for the conversion of heat to other forms of energy are

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presented in the book Prikladnaya termodinamika i teploperedacha [Applied thermodynamics and heat transfer], 1961, 548 pages. As is the case with other books under this heading, the contribution by I. I. Novikov and K. D. Voskresenskii, authors of the above work, may be of use not only to specialists in the particular field, but also to undergraduate and graduate students majoring in related subjects.

Heat generation in nuclear reactors and methods for extracting heat for practical use are discussed in Otvod i preobrazovanie tepla v yadernykh reaktorakh,* [Heat removal and conversion in nuclear reactors].by R. Alami and P. Ageron, translated from the French,1961. The chief merit of the book is the large number of examples on calculating heat removal and the use of reactor heat, as well as the concise and excellently systematized exposition of the material.

NUCLEAR FUELS AND MATERIALS

Nuclear Geology. This section includes books covering nuclear geophysics as well as nuclear geology proper.

M. M. Konstantinov and E. Ya. Kulikova are authors of Uranovye provintsii [Uranium provinces], 1960, 306 pages, which is the most complete reference available to date, to our knowledge, of literature data on the geology of uranium provinces and uranium deposits in other countries. The appended bibliography embracing almost all the literature published on uranium geology up to 1958 inclusive and a map showing the locations of the most important ore provinces and uranium deposits in the capitalist countries, compiled on a tectonic basis, add to the value of the book.

The first chapter furnishes a general picture of uranium provinces and their status in the scheme of the metallogenetic zoning of the earth, of details of ore provinces in various geotectonic structures, and of the epochs of endogenetic and exogenetic accumulations of uranium in the earth's crust. The authors state some new and quite original concepts, among the most intriguing of which is the inference of preferential confinement of uranium mineralization in pre-Cambrian shields to zones of conjugate Proterozoic folded belts with more ancient land masses. Chapters II-VIII deal with uranium provinces and uranium deposits on the regional level, considering separate continents. These chapters give the geological and metallogenetic characteristics as well as the geotectonic sequences of the territory covered. The presence of such an over-all geological and metallogenetic "background" favorably distinguishes the work by M. M. Konstantinov and E. Ya. Kulikova from earlier published reference works on uranium geology (R. Nininger, M. Roubault, V. Domarev, W. Heinrich, etc.). Chapter VIII contains some brief information on the raw materials base of the uranium industry in capitalist countries, and on its dynamics of development.

Extremely scant attention has been accorded such topics as prospecting, exploration and assaying of uranium deposits in the book literature to date. This gap in the field has been closed in appreciable measure by the appearance of D. Ya. Surazhskii's Metody poiskov i razvedki mestorozhdenii urana [Uranium prospecting and exploration techniques], 1960, 240 pages. The book is a handbook of techniques on the prospecting and exploration of uranium deposits.

The first section furnishes the general characteristics of payable types of uranium deposits and reviews the fundamental criteria governing profitable prospecting. The second section describes methods used in prospecting for uranium deposits based on the radiation emanation gas and salt aureoles associated with the deposits. The grouping of "radiation" techniques distinguishes between air surveys, land surveys, and underground surveys. Of the group of emanation methods, the book singles out one high-speed version of radon survey. The third section deals with methods of preliminary exploration, detailed exploration, and inventory of reserves in uranium deposits. The concluding chapter in the third section outlines the basic yardsticks followed in an industrial evaluation of uranium deposits, plus some special approaches to inventorying payable reserves.

The geological and geophysical management of uranium mines differs from other mining tasks in a number of specific features. The book Metody geologo-geofizicheskogo obsluzhivaniya uranovykh rudnikov [Methods in the geological and geophysical management of uranium mines] by G. I. Petrov, M. V. Kutenkov, I. M. Tenenbaum, and L. S. Evseeva, 1960, 217 pages, endeavors to throw some light on the multiplicity of geological-geophysical and hydrogeological operations involved. The book presents a brief account of the morphological and radiological characteristics of uranium deposits; describes systems of mine exploration and development used in uranium mining;

discusses techniques in handling geological and geophysical paper work in mining practice; discusses assaying procedures and questions related to grading, beneficiation, and charge mixing in ore processing; gives hints on techniques in accounting for losses and depletion; compiles balances of reserves and discusses questions relating to the participation of mine geologists in the planning and scheduling of mining operations. The last chapter is addressed to hydrogeological management of mines; here are described various ways of mine flooding, methods for coping with mine waters, oil and gas presence in ore-bearing rock, and geological-engineering, hydrogeological, and radiohydrogeological observations in uranium mines.

Termicheskie issledovaniya uranovykh i uransoderzhashchikh mineralov [Thermal investigations of uranium and uraniferous minerals] by Ts. R. Ambartsumyan, G. I. Basalova, S. A. Gorzhevska, N. G. Nazarenko, and R. P. Khodzhaeva, 1961, 148 pages, has done the job of systematizing and generalizing the factual material made available in thermoanalytical investigations of uranium and uraniferous minerals. The book presents standard curves of heating and dehydration, and data obtained from studies of variations in the physico-chemical properties of minerals by means of crystallographic-optical, x-ray diffraction, microchemical, and luminescence techniques of analysis. A. G. Betekhtin's classification is used as the basis for the description of minerals.

Yu. M. Dymkov is author of Uranovaya mineralizatsiya Rudnykh gor [Uranium mineralization of the Erzgebirge (Krušné Hory)], 1960, 100 pages, which provides a brief description of the genetic features of the hydrothermal uranium deposits in the oldest ore region of Central Europe. The book describes vein formations and parageneses, epochs and stages of mineralization, mineralization cycles; voices some views on interaction between solution and minerals, on the formation of the cationic composition of solfatara and geothermal springs, etc. In the view of the author, the Erzgebirge uranium deposits formed in the Variscian metallogenetic epoch, but also show signs of transformations belonging to the Alpine epoch.

The geochemical interpretation of the processes of uranium mineralization is based on an analogy with the modern fumarole-solfatara process. The assumption entertained is that, as the temperature of the magmatic hearth declines, the latter releases magmatic gases in a sequence determining the regular succession of anions in solutions. Metals, alkali earths, and alkalis gained exit from the host rocks in places where active interaction between the host rock and acidic solutions occurred.

Radioaktivnye élementy zemli [Radioactive elements of the earth] by A. A. Saukov, 1961, 161 pages, is one of a series of popular-science editions. It presents an account of the history of the discoveries of radioactive elements and radioactive transmutations in the uranium, actinouranium, and thorium families; of the structure of the earth's crust and the abundance of various elements and radioactive isotopes in the crust; of the content of radium, uranium, and thorium in different rocks, soils, and natural waters, of the radioactivity of the atmosphere and of uranium minerals; of the thermal budget of the earth and the energy resulting from the decay of radioactive elements present in the earth's crust; of the migration of radioactive elements and of geochemical cycles; of genetic types of uranium occurrences and of different techniques in prospecting for deposits of radioactive elements. Written in a lively and engaging form, this book will be found useful by nonspecialists interested in familiarizing themselves with the status of radioactive raw materials.

During recent years, the scope of work involving determinations of uranium and thorium and their radioactive-decay products has become significantly expanded. Radiochemical and radiometric techniques used in determining decay products of uranium and thorium solely by the radioactivity of the latter elements are of unquestionable interest in this area. Metody analiza estestvennykh radioaktivnykh élementov [Methods in the analysis of the natural radioactive elements], 1961, 152 pages by V. L. Shashkin, systematically reviews material from 126 papers and reports on methods for determining radioactive elements in the uranium and thorium papers, culled from the literature of a selection of Soviet and foreign publications up to 1960, inclusive. The seven chapters of the book take up the questions of the radioactive properties of natural radioactive elements, methods for measuring radioactivity, physical methods of analysis, methods for determining uranium and thorium isotopes, determinations of protactinium, actinium, radium and polonium isotopes, and, finally, the principles of complex radiochemical analysis.

The brochure Radiometricheskii ékspress-analiz dobytykh rud [Radiometric express-analysis of mined ores], 1960, 78 pages, is the first roundup of mining experience on rapid analysis of radioactive ores. It contains a brief discussion of the physical fundamentals of the method and the elements of technological complexes at mines. The bulk of the attention is centered on methods and organization of rapid analysis using RKS-1, RKS-2, and RKS-3 devices, techniques for determining corrective factors, and the analysis of errors in measurement. The appendix lists technological conditions for planning of monitoring points using the RKS-1 facility.

One of the radiometric techniques used in determining radioactive ores is the β-γ method of analyzing radioactive ores. This technique was developed back in 1947 and much experience of import has been amassed to the present on its use. A brochure by Kh. B. Mezhiborskaya, V. L. Shashkin and I. I. Shumilin, entitled Analiz radioaktivnykh rud β-γ metodom [Analysis of radioactive ores by the beta-gamma technique], 1961, 64 pages, provides a description of modern techniques in the analysis of radioactive ores by measuring their beta and gamma emissions. The brochure will actually serve well as a manual on the analysis of radioactive ores via quantitative radiometry techniques.

One of the methods in nuclear physics which has won itself the widest popularity in beryllium determinations is the photoneutron method. The brochure Fotoneitronnyi metod opredeleniya berilliya [The photoneutron method in beryllium determinations] by Kh. B. Mezhiborskaya, 1961, 51 pages, describes the analytical technique based on exploitation of the photoneutron reaction affecting the beryllium nucleus. It takes up the general questions related to the use of nuclear-physics techniques in beryllium determinations, and describes a laboratory variant of the photoneutron method. Taking into account the special role played by health physics problems in the practical use of nucleonic techniques, the author includes in her brochure instructions on safety techniques for handling neutron radiations.

The list of reference literature includes all of the recent papers published, to 1960 inclusive, on the question.

Nuclear Metallurgy. Steadily increasing attention has been focused recently on the technology of uranium and thorium metals, directly related to the development of new alloys suitable for use as nuclear fuel. This has encouraged interest in the symposium of the proceedings of the A. A. Baikov Institute of Metallurgy of the USSR Academy of Sciences, Stroenie splavov nekotorykh sistem s uranom i toriem [Structure of alloys of some uranium-thorium systems], edited by O. S. Ivanov, 1961, 492 pages. The symposium contains the results of extensive investigations on the structure, phase transformations, and properties of a series of binary, ternary, and quaternary uranium-thorium base alloys, and high-melting compounds of those metals, particularly their oxides, beryllides, and carbides. The alloy given the fullest treatment is an alloy of uranium with zirconium, niobium, molybdenum, and chromium, readily soluble in γ-uranium and exhibiting a relatively small thermal-neutron capture cross section.

The outstanding problems in the metals technology of uranium and several structural metals are discussed in the monograph by G. Ya. Sergeev, V. V. Titova and K. A. Borisov entitled Metallovedenie urana i nekotorykh reaktornykh materialov [Metals technology of uranium and some reactor materials], 1960, 224 pages. Data on the structural, physical and mechanical properties of uranium and uranium alloys are supplemented by the close attention given to radiation effects and thermal-cycling effects on the dimensional and structural stability of nuclear fuels and fuel-element cladding materials, as well as heat treatment and machining of uranium. A special section is devoted to the manufacturing technology of fuel elements with all-metal hearts.

A broad range of topics is dealt with in the second edition of symposiums of the proceedings of the metallurgy and metal-studies department of the Moscow Engineering and Physics Institute. The symposium bears the title Metallurgiya i metallovedenie chistykh metallov [Metallurgy and technology of the pure metals], edited by V. S. Emel'yanov and A. I. Evstyukhin, 1960, 336 pages. The symposium is made up of 27 papers, covering such questions as techniques for refining chromium, niobium, and thorium, and research on the physical, corrosion, and diffusion properties and characteristics of zirconium and its alloys. Equipment and techniques for measuring internal friction in zirconium, niobium, uranium, and their alloys are described, and the results of a study of diffusion of sulfur, phosphorus, carbon, and alloying constituents in stainless steels are reported.

Berillii, khimicheskaya tekhnologiya i metallurgiya [Beryllium, its industrial chemistry and metallurgy], by G. F. Silina, Yu. I. Zarembo, and L. E. Bertina, 1960, 120 pages, constitutes a critical evaluation of published material and contains a description of the nuclear, mechanical, corrosion, and chemical properties of beryllium. It explains industrial methods used in fabricating pure beryllium and beryllium compounds.

Natrii, ego proizvodstvo, svoistva i primenenie [Sodium, its manufacture, properties, and uses, Reinhold, 1956], by M. Sittig, translated from the English, 1961, deals with one of the most promising coolants for reactor use.

One book meriting particular attention is this section is Osnovy avtomatizatsii tekhnologicheskikh protsessov gidrometallurgii redkikh i radioaktivnykh metallov [Fundamentals of process control in the hydrometallurgy of rare and radioactive metals], 1960, 296 pages. In a relatively compressed volume, the book manages to concentrate the basic information on process-control instrumentation, discusses the characteristics of controlled systems, and the planning of automatic control and monitoring loops.

In the translated literature, we take note of the extended monograph by C. Harrington and A. Ruehle Tekhnologiya proizvodstva urana* [Uranium Production Technology, Van Nostrand, 1959], translated from the English, 1961, 586 pages. The monograph embraces a wide selection of problems in the metallurgy, technology, and machining processes pertinent to uranium. Separate chapters deal with the production of uranium metal by reduction and casting and by direct reduction of uranium tetrafluoride. Press forging in the alpha-phase, rolling and machining are discussed in detailed fashion. Recommendations on health-hazard control are added.

The first edition of reviews of the Battelle Institute under the title Yaderno-goryuchie materialy [Nuclear Fuel Materials], translated from the English, 1961, 273 pages, will be of unquestionable interest to scientific workers and engineers at research institutes and industrial enterprises. The symposium Izvlechenie i ochistka redkikh metallov [Extraction and purification of rare-earth metals], translated from the English, 1960, 512 pages, may be placed under the same heading. The 22 papers forming this symposium, delivered at the London Institute of Mining and Metallurgy symposium, report the results of laboratory and pilot-plant investigations on the technology of uranium, thorium, beryllium, titanium, zirconium, hafnium, niobium, vanadium, selenium, and other rare metals. The symposium contains extensive experimental material and offers some theoretical inferences drawn from the discussions at the symposium.

Chemistry of Nuclear Materials. The books under this heading are conveniently grouped under the following subheadings: general chemistry; analytical chemistry; chemical technology.

In the area of general chemistry, we draw attention to the book Khimiya aktinidnykh ělementov [Chemistry of the Actinide Elements, McGraw-Hill] by G. Seaborg and J. Katz, 1960, 542 pages, supplemented by material published up to mid-1959. This monograph contains fairly complete information on the chemistry of the actinides and is useful either as textbook or manual.

V. V. Fomin is the author of Khimiya ėkstraktsionnykh protsessov [Chemistry of extraction processes], 1960, 166 pages, which generalizes upon and analyzes theoretical concepts now prevalent on the extraction mechanism, the most important process in modern chemical engineering. Alongside other topics, the author considers the dependence of distribution coefficients on the concentration of the extracted composition in the aqueous phase and electrolytic dissociation in the organic phase.

Two books on analytical chemistry are: V. K. Markov, A. V. Vinogradov, S. V. Elinson, A. E. Klygin, and I. V. Moiseev Uran, metody ego opredeleniya [Uranium and methods for determining uranium], 1960, 264 pages, and S. V. Elinson and K. I. Petrov, Tsirkonii, khimicheskie i fizicheskie metody analiza [Zirconium, chemical and physical methods in zirconium analysis], 1960, 212 pages.

The first of these books attempts to systematize the information accumulated in recent years in the field of the analytical chemistry of uranium. After a description of the physical and chemical properties of uranium and some uranium compounds, the panel of authors undertakes a detailed treatment of methods for qualitative detection and isolation of uranium, including gravimetric, volumetric, photometric, electrometric, luminescent, and radiometric techniques in uranium determination.

The book by S. V. Elinson and K. I. Petrov takes up the chemical and physical properties of zirconium and zirconium compounds, outlines the basic analytical reactions, and describes the most reliable and best tested photometric, radiometric, spectral, x-ray spectral, chemical, and physical methods for determining zirconium and impurities in zirconium.

The subheading "Chemical technology" is somewhat better represented in the current selection. Here the reader will find books devoted both to general aspects of the chemical technology of nuclear materials and to the technology of particular elements and compounds.

Ya. I. Zil'berman's Osnovy khimicheskoi tekhnologii iskusstvennykh radioaktivnykh ělementov [Fundamentals of the chemical technology of artificial radioactive elements], 1961, 332 pages, furnishes a systematized review of

* See also under the heading CHEMISTRY OF NUCLEAR MATERIALS.

information on the chemical technology of radioactive elements, dealing mainly with reprocessing of spent nuclear fuel. The book also touches on questions related to chemical and biochemical effects of ionizing radiations. The simplicity and compactness of the presentation enhances the value of this book as a textbook for undergraduate and graduate students majoring in nuclear chemical engineering.

M. Benedict and T. Pigford are the authors of Khimicheskaya tekhnologiya yadernykh materialov [Nuclear chemical engineering, McGraw-Hill, 1957], translated from the English, 1960, 528 pages. The book provides a wealth of information on methods for obtaining materials used in nuclear engineering and methods for reprocessing irradiated materials. Certain pertinent problems in nuclear physics are treated as accessory text material, and the equipment used in nuclear chemical engineering operations is described. Considerable attention is given to solvent extraction and isotope-separation processes, which have taken on industrial significance in step with the development and growth of nuclear power.

Among the publications devoted to chemical engineering, we must take note of the book Tekhnologiya urana [Uranium technology], 1960, 330 pages, by V. B. Shevchenko and B. N. Sudarikov, which served as the basis for a course of lectures given by the authors at the D. I. Mendeleev Moscow Order of Lenin Chemical Engineering Institute. Following a brief introduction and description of the chemical and physico-chemical properties of uranium and uranium compounds, the authors consider uranium ores and minerals, their mechanical and high-temperature processing and leaching processes. They then proceed to a discussion of sedimentation, sorption, and extraction techniques in processing uranium ore leach liquors, and a discussion of topics related to refinement of uranium, production of oxides, uranium tetrafluoride and uranium hexafluoride, ending with the production of uranium metal.

N. P. Galkin and B. V. Tikhomirov, in their book Osnovnye protsessy i apparaty tekhnologii urana [Fundamental processes and process equipment in uranium technology], 1961, 220 pages, review and generalize upon material on this field appearing in the literature up to recently. The review includes papers on mechanical processes in the processing of solids and mixing in liquid media, and classification and dehydration steps. The general laws of mass transfer are presented, facilitating the study of diffusion processes encountered, including interdiffusion, ion exchange, extraction, crystallization, and drying.

Problems in chemical technology of uranium are also taken up in the first part of the book by C. Harrington and R. Ruehle, Uranium Production Technology, Russian translation published 1961, 586 pages (see earlier under Nuclear Metallurgy). This book limits its treatment in this area to the chemistry of the process of stripping-ore concentration, solvent-extraction steps, breakdown of uranyl nitrate, and production of uranium tetrafluoride. Purification by ether extraction and solvent extraction with TBP are also treated. The second part of the book discusses flow sheets in the production of important uranium compounds.

Khimiya i tekhnologiya ftoristykh soedinenii urana [Chemistry and technology of uranium and fluorine compounds], 1961, 349 pages, by N. P. Galkin, A. A. Maiorov, U. D. Veryatin, B. N. Sudarikov, N. S. Nikolaev, Yu. D. Shishkov and A. B. Krutikov, comprises a thorough and exhaustive review of material published to June 1960 inclusive on the physico-chemical properties of the most important fluorine compounds of uranium and methods for isolating and producing them. The fluoride-distillation reprocessing of spent nuclear fuel and the chemistry and technology of fluorine, hydrogen fluoride, and fluorine halides come under discussion.

A brief description of the properties of uranium and its ions, information on uranium ores, health measures to be observed in the purification of uranium concentrates, and, what is most important, the description and theoretical groundwork, based on published literature data, of technological processes in processing uranium concentrates to pure salts and uranium metal, may be found in the book Tekhnologiya pererabotki kontsentratov urana [Technology of reprocessing of uranium concentrates], 1960, 162 pages, by N. P. Galkin, A. A. Maiorov, and U. D. Veryatin.

Of the books devoted to the chemical technology of individual elements of nuclear interest, we must mention a book of a review character by G. E. Kaplan, G. A. Uspenskaya, Yu. M. Zarembo and I. V. Chirkov, Torii, ego syr'evye resursy, khimiya i tekhnologiya [Thorium, its raw materials resources, chemistry, and technology], 1960, 224 pages, which describes the physico-chemical, corrosion, and radioactive properties of thorium; considers topics in the analytic chemistry and production technology of thorium compounds. The review also includes a series of topics relating to the metallurgy, machining, and metallurgical technology of compacted and powdered thorium metal.

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This series of books also includes the review Litii, ego khimiya i tekhnologiya [Lithium chemistry and technology], 1960, 200 pages, by Yu. I. Ostroushko, P. I. Buchikhin, and V. V. Alekseev along with a large panel of co-authors. Treatment of the most prominent minerals, geochemical and physico-chemical properties of lithium and lithium compounds, the technology of lithium ore processing, and the analytic chemistry of lithium share space with the topics of lithium-ore processing and lithium metallurgy. The feasibility of using lithium as a reactor coolant has greatly enhanced interest in the metal and its technology. The review is compiled on the basis of data published in Soviet and foreign literature covering the period from 1918 to 1958.

We may also mention here the book Ionoobmennye membrany i ikh primenenie [Ion-exchange membranes and their applications], 1961, 163 pages by B. I. Laskorin and B. M. Smirnova, devoted to one of the most recent trends in chemical engineering: the use of electrodialysis with ion-exchange membranes in radiochemical production, the hydrometallurgy of uranium, and for debrining natural waters.

Teoriya razdeleniya izotopov v kolonnakh [Theory of isotope separation in columns], 1961, 284 pages, by A. M. Rozen, occupies a special place among books on this topic, constituting a generalization of the work of the author going back to 1945. All of the important counterflow separation processes are viewed from the standpoint of the general laws governing mass transfer in the first part of the book, and the relationship between engineering and physical concepts on the motive force behind the process established. Topics developed include general separation theory, and the use of the theory of similitude of transient processes to optimize the basic process variables. The monograph Vydelenie deiteriya iz vodoroda metodom glubokogo okhlazhdeniya [Separation of deuterium from hydrogen by the refrigeration method], 1961, 151 pages, by M. P. Malkov, A. G. Zel'dovich, A. B. Fradkov, and I. B. Danilov, will serve to a certain extent as a useful supplement to the book by Rozen. The physics and engineering fundamentals of the method are considered, results of investigations on the fractional distillation of liquid mixtures are reported, and flow sheets of industrial scaled-up plants are included. A selection is made of methods for purifying hydrogen and analysis of gas mixtures.

Soviet Journals Available in Cover-to-Cover Translation

ABBREVIATION	RUSSIAN TITLE	TITLE OF TRANSLATION	PUBLISHER	TRANSLATION BEGAN Vol.	Issue	Year
AĒ	Atomnaya énergiya	Soviet Journal of Atomic Energy	Consultants Bureau	1	1	1956
Akust. zh.	Akusticheskii zhurnal	Soviet Physics – Acoustics.	American Institute of Physics	1	1	1955
	Antibiotiki	Antibiotics	Consultants Bureau	4	1	1959
Astr(on). zh(urn).	Astronomicheskii zhurnal	Soviet Astronomy—AJ	American Institute of Physics	34	1	1957
Avto(mat). svarka	Avtomaticheskaya svarka	Automatic Welding	British Welding Research Association (London)		1	1959
	Avtomatika i Telemekhanika	Automation and Remote Control	Instrument Society of America	27	1	1956
	Biofizika	Biophysics	National Institutes of Health*		1	1957
	Biokhimiya	Biochemistry	Consultants Bureau	21	1	1956
Byull. éksp(erim). biol. i med.	Byulleten' éksperimental'noi biologii i meditsiny	Bulletin of Experimental Biology and Medicine	Consultants Bureau	41	1	1959
DAN (SSSR) / Dokl(ady) AN SSSR	Doklady Akademii Nauk SSSR	The translation of this journal is published in sections, as follows:				
	Life Sciences	Doklady Biochemistry Section	American Institute of Biological Sciences	106	1	1956
	Life Sciences	Doklady Biological Sciences Sections (Includes: Anatomy, biophysics, cytology, ecology, embryology, endocrinology, evolutionary morphology, genetics, histology, hydrobiology microbiology, morphology, parasitology, physiology, zoology sections)	American Institute of Biological Sciences	112	1	1957
	Life Sciences	Doklady Botanical Sciences Sections (Includes: Botany, phytopathology, plant anatomy, plant ecology, plant embryology, plant physiology, plant morphology sections)	American Institute of Biological Sciences	112	1	1957
	Chemical Sciences	Proceedings of the Academy of Sciences of the USSR, Section: Chemical Technology	Consultants Bureau	106	1	1956
	Chemical Sciences	Proceedings of the Academy of Sciences of the USSR, Section: Chemistry	Consultants Bureau	106	1	1956
	Chemical Sciences	Proceedings of the Academy of Sciences of the USSR, Section: Physical Chemistry	Consultants Bureau	112	1	1957
	Earth Sciences	Doklady Earth Sciences Sections (Includes: Geochemistry, geology, geophysics, hydrogeology, mineralogy, paleontology, petrography, permafrost sections)	American Geological Institute	124	1	1959
	Earth Sciences	Proceedings of the Academy of Sciences of the USSR, Section: Geochemistry	Consultants Bureau	106- 123	1 6	1957- 1958
	Earth Sciences	Proceedings of the Academy of Sciences of the USSR, Sections: Geology	Consultants Bureau	106- 123	1 6	1957- 1958
	Mathematics	Doklady Soviet Mathematics	The American Mathematics Society	131	1	1961
	Physics	Soviet Physics—Doklady (Includes: Aerodynamics, astronomy, crystallography, cybernetics and control theory, electrical engineering, energetics, fluid mechanics, heat engineering, hydraulics, mathematical physics, mechanics, physics, technical physics, theory of elasticity sections)	American Institute of Physics	106	1	1956
	Physics	Proceedings of the Academy of Sciences of the USSR, Applied Physics Sections (does not include mathematical physics or physics sections)	Consultants Bureau	106- 117	1	1956- 1957
Derevoobrabat. prom-st'.	Derevoobrabatyvayushchaya promyshlennost'	Wood Processing Industry	Timber Development Association (London)		9	1959
	Élecktrosvyaz	Telecommunications	Massachusetts Institute of Technology*		1	1957
Éntom(ol). oboz(renie)	Éntomologicheskoe obozrenie	Entomological Review	American Institute of Biological Sciences	38	1	1959
Farmakol. (i) toksikol(ogiya)	Farmakologiya i toksikologiya	Pharmacology and Toxicology	Consultants Bureau	20	1	1957
FMM	Fizika metallov i metallovedenie	Physics of Metals and Metallography	Acta Metallurgica*	5	1	1957
Fiziol. zhurn. SSSR (im. Sechenova)	Fiziologicheskii zhurnal im. I. M. Sechenova	Sechenov Physiological Journal USSR	National Institutes of Health*		1	1957
Fiziol(ogiya) rast.	Fiziologiya rastenii	Plant Physiology	American Institute of Biological Sciences	4	1	1957
	Geokhimiya	Geochemistry	The Geochemical Society		1	1958
FTT	Fizika tverdogo tela	Soviet Physics—Solid State	American Institute of Physics	1	1	1959
Izmerit. tekh(nika)	Izmeritel'naya tekhnika	Measurement Techniques	Instrument Society of America		1	1959
Izv. AN SSSR, O(td). Kh(im). N(auk)	Izvestiya Akademii Nauk SSSR: Otdelenie khimicheskikh nauk	Bulletin of the Academy of Sciences of the USSR: Division of Chemical Sciences	Consultants Bureau		1	1952

continued

Izv. AN SSSR, O(td). T(ekhn). N(auk): Met(all). i top.	(see Met. i top.)					
Izv. AN SSSR Ser. fiz(ich).	Izvestiya Akademii Nauk SSSR: Seriya fizicheskaya	Bulletin of the Academy of Sciences of the USSR: Physical Series	Columbia Technical Translations		1	1954
Izv. AN SSSR Ser. geofiz.	Izvestiya Akademii Nauk SSSR: Seriya geofizicheskaya	Bulletin (Izvestiya) of the Academy of Sciences USSR: Geophysics Series	American Geophysical Union		1	1954
Izv. AN SSSR Ser. geol.	Izvestiya Akademii Nauk SSSR: Seriya geologicheskaya	Izvestiya of the Academy of Sciences of the USSR: Geologic Series	American Geological Institute		1	1958
Kauch. i rez.	Kauchuk i rezina	Soviet Rubber Technology	Research Association of British Rubber Manufacturers	18	1	1959
	Kinetika i kataliz	Kinetics and Catalysis	Consultants Bureau	1	3	1960
	Koks i khimiya	Coke and Chemistry USSR	Coal Tar Research Association (Leeds, England)		1	1958
Kolloidn. zh(urn).	Kolloidnyi zhurnal	Colloid Journal	Consultants Bureau	14	1	1952
	Kristallografiya	Soviet Physics — Crystallography	American Institute of Physics	2	1	1957
Metalov. i term. obrabot. metal.	Metallovedenie i termicheskaya obrabotka metallov	Metal Science and Heat Treatment of Metals	Acta Metallurgica	6	1	1958
	Metallurg	Metallurgist	Acta Metallurgica		1	1957
Met. i top.	Metallurgiya i topliva	Russian Metallurgy and Fuels	Eagle Technical Publications		1	1960
Mikrobiol.	Mikrobiologiya	Microbiology	American Institute of Biological Sciences	26	1	1957
OS	Optika i spektroskopiya	Optics and Spectroscopy	American Institute of Physics		6	1959
	Pochvovedenie	Soviet Soil Science	American Institute of Biological Sciences		1	1958
	Priborostroenie	Instrument Construction	British Scientific Instrument Research Association		1	1959
Pribory i tekhn. éks(perimenta)	Pribory i tekhnika éksperimenta	Instruments and Experimental Techniques	Instrument Society of America		1	1957
Prikl. matem. i mekh.	Prikladnaya matematika i mekhanika	Applied Mathematics and Mechanics	American Society of Mechanical Engineers		1	1958
PTÉ	(see Pribory i tekhn. éks.)					
	Problemy Severa	Problems of the North	National Research Council of Canada			
Radiotekh.	Radiotekhnika	Radio Engineering	Massachusetts Institute of Technology*	12	1	1957
Radiotekh. i élektronika	Radiotekhnika i élektronika	Radio Engineering and Electronics	Massachusetts Institute of Technology*	2	1	1957
	Stanki i instrument	Machines and Tooling	Production Engineering Research Assoc.		1	1959
	Stal'	Stal (In English)	Iron and Steel Institute		1	1959
Stek. i keram.	Steklo i keramika	Glass and Ceramics	Consultants Bureau	13	1	1956
Svaroch. proiz-vo	Svarochnoe proizvodstvo	Welding Production	British Welding Research Association		4	1959
Teor. veroyat. i prim.	Teoriya veroyatnostei i ee primenenie	Theory of Probability and Its Applications	Society for Industrial and Applied Mathematics		1	1956
Tsvet. Metally	Tsvetnye metally	Nonferrous Metals	Primary Sources		1	1960
UFN	Uspekhi fizicheskikh Nauk	Soviet Physics — Uspekhi (partial translation)	American Institute of Physics	66	1	1958
UKh	Uspekhi khimii	Russian Chemical Reviews	The Chemical Society (London)		1	1960
UMN	Uspekhi matematicheskikh nauk	Russian Mathematical Surveys	London Mathematical Society	15	1	1960
Usp. fiz. nauk	(see UFN)					
Usp. khim(ii)	(see UKh)					
Usp. matem. nauk	(see UMN)					
Usp. sovr. biol.	Uspekhi sovremennoi biologii	Russian Review of Biology	Oliver and Boyd		48	1959
Vest. mashinostroeniya	Vestnik mashinostroeniya	Russian Engineering Journal	Production Engineering Research Assoc.		4	1959
Vop. gem. i per. krovi	Voprosy gematologii i perelivaniya krovi	Problems of Hematology and Blood Transfusion	National Institutes of Health*		1	1957
Vop. onk.	Voprosy onkologii	Problems of Oncology	National Institutes of Health*		1	1957
Vop. virusol.	Voprosy virusologii	Problems of Virology	National Institutes of Health*		1	1957
Zav(odsk). lab(oratoriya)	Zavodskaya laboratoriya	Industrial Laboratory	Instrument Society of America	25	1	1959
ZhAKh Zh. anal(it). khimii	Zhurnal analiticheskoi khimii	Journal of Analytical Chemistry USSR	Consultants Bureau	7	1	1952
ZhETF / Zh. éksperim. i teor. fiz.	Zhurnal éksperimental'noi i theoreticheskoi fiziki	Soviet Physics—JETP	American Institute of Physics	28	1	1955
ZhFKh Zh. fiz. khimii	Zhurnal fizicheskoi khimii	Russian Journal of Physical Chemistry	The Chemical Society (London)		7	1959
ZhMÉI Zh(urn). mikrobiol. épidemiol. i immunobiol.	Zhurnal mikrobiologii, épidemiologii i immunobiologii	Journal of Microbiology, Epidemiology and Immunobiology	National Institutes of Health*		1	1957
ZhNKh / Zh(urn). neorgan(ich). khim(ii)	Zhurnal neorganicheskoi khimii	The Russian Journal of Inorganic Chemistry	The Chemical Society (London)		1	1959
ZhOKh / Zh(urn). obshch(ei) khimii	Zhurnal obshchei khimii	Journal of General Chemistry USSR	Consultants Bureau	19	1	1949
ZhPKh / Zh(urn). prikl. khimii	Zhurnal prikladnoi khimli	Journal of Applied Chemistry USSR	Consultants Bureau	23	1	1950
ZhSKh / Zh(urn). strukt. khimii	Zhurnal strukturnoi khimii	Journal of Structural Chemistry	Consultants Bureau	1	1	1960
ZhTF / Zh(urn). tekhn. fiz.	Zhurnal teknicheskoi fiziki	Soviet Physics—Technical Physics	American Institute of Physics	26	1	1956
Zh(urn). vyssh. nervn. deyat. (im. Pavlova)	Zhurnal vysshei nervnoi deyatel'nosti (im. I. P. Pavlova)	Pavlov Journal of Higher Nervous Activity	National Institutes of Health*		1	1958

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SIGNIFICANCE OF ABBREVIATIONS MOST FREQUENTLY ENCOUNTERED IN SOVIET PERIODICALS

FIAN	Phys. Inst. Acad. Sci. USSR
GDI	Water Power Inst.
GITI	State Sci.-Tech. Press
GITTL	State Tech. and Theor. Lit. Press
GONTI	State United Sci.-Tech. Press
Gosenergoizdat	State Power Press
Goskhimizdat	State Chem. Press
GOST	All-Union State Standard
GTTI	State Tech. and Theor. Lit. Press
IL	Foreign Lit. Press
ISN (Izd. Sov. Nauk)	Soviet Science Press
Izd. AN SSSR	Acad. Sci. USSR Press
Izd. MGU	Moscow State Univ. Press
LEIIZhT	Leningrad Power Inst. of Railroad Engineering
LET	Leningrad Elec. Engr. School
LETI	Leningrad Electrotechnical Inst.
LETIIZhT	Leningrad Electrical Engineering Research Inst. of Railroad Engr.
Mashgiz	State Sci.-Tech. Press for Machine Construction Lit.
MEP	Ministry of Electrical Industry
MES	Ministry of Electrical Power Plants
MESEP	Ministry of Electrical Power Plants and the Electrical Industry
MGU	Moscow State Univ.
MKhTI	Moscow Inst. Chem. Tech.
MOPI	Moscow Regional Pedagogical Inst.
MSP	Ministry of Industrial Construction
NII ZVUKSZAPIOI	Scientific Research Inst. of Sound Recording
NIKFI	Sci. Inst. of Modern Motion Picture Photography
ONTI	United Sci.- Tech. Press
OTI	Division of Technical Information
OTN	Div. Tech. Sci.
Stroiizdat	Construction Press
TOE	Association of Power Engineers
TsKTI	Central Research Inst. for Boilers and Turbines
TsNIEL	Central Scientific Research Elec. Engr. Lab.
TsNIEL-MES	Central Scientific Research Elec. Engr. Lab.-Ministry of Electric Power Plants
TsVTI	Central Office of Economic Information
UF	Ural Branch
VIESKh	All-Union Inst. of Rural Elec. Power Stations
VNIIM	All-Union Scientific Research Inst. of Metrology
VNIIZhDT	All-Union Scientific Research Inst. of Railroad Engineering
VTI	All-Union Thermotech. Inst.
VZEI	All-Union Power Correspondence Inst.

NOTE: Abbreviations not on this list and not explained in the translation have been transliterated, no further information about their significance being available to us. —Publisher.

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