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RFNC–VNIIEF research facilities aimed at experimental acquisition of basic and applied knowledge in the fields of nuclear, radiation, and fast-process physics

(on the 75th anniversary of the Atomic industry)

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Contents

Abstract. Described are problems in the field of nuclear physics, for the solution of which a subdivision of experimental physics was created during the implementation of the atomic project as part of Design Bureau 11 (KB11). This subdivision is now the Institute of Nuclear and Radiation Physics (INRF) — the center of competence of the Russian Federal Nuclear Center–All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF) in the field of experimental nuclear and radiation physics. The paper outlines the transformation of these problems with time and the formation of new areas of activity based on them. Data on the current state of the development of the experimental base of VNIIEF (YARF) are presented, as are prospects and plans. The paper is an extended version of a report at the session of the Physical Sciences Division of the Russian Academy of Sciences dedicated to the 75th anniversary of the Atomic industry, December 7, 2020.

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1. Introduction

The formation and development of the experimental base of the Russian Federal Nuclear Center–the All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF) is inextricably linked with the development, testing, and improvement of nuclear weapons.

During the period of the development of the first samples and their development, there was a rather long list of questions in nuclear physics that had to be answered, either by conducting experimental studies or consciously by taking risks, choosing an answer from among possible ones (as was the case with the statement by S P Korolev: 'The moon is solid!').

To get answers to some of the questions, established at Design Bureau 11 (KB11) (now VNIIEF) in 1952 was an experimental physics division "for experimental substantiation of ideas, methods of calculation, and characteristics of products in laboratory and expeditionary conditions" (quote from the order for KB11 on the establishment of a subdivision of experimental physics). The most important of the questions were the determination of nuclear reaction cross sections for physical and mathematical models of the computational study of thermonuclear combustion processes and the problems of gamma-ray and neutron spectrometry.

Experimental research was carried out simultaneously along three lines: analysis and refinement of domestic and foreign nuclear data, development of methods for physical measurements during full-scale tests of products, and development of laboratory sources of ionizing radiation and instrument facilities for recording radiation [1–8].

The general picture, which clearly traces the logically determined path of development of the experimental base for scientific research in the field of nuclear physics, whose purveyor and organizer was Georgii Nikolaevich Flerov, is shown in Fig. 1, where three time intervals are distinguished:

— the initial stage was when charge calculations required knowledge of nuclear processes and reliable quantitative data on the main nuclear reactions were practically absent or contradictory (according to different publications). One of the most important tasks of this stage was the experimental determination of the quantitative value of the critical mass of weapons-grade materials;

— the second period — between the tests of the first nuclear charge samples and the termination of full-scale tests in accordance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT, 1996) — is characterized by a huge amount of work on measuring the actual parameters of the nuclear charges produced (the characteristics of the sources of ionizing radiation) and work on the development of tools that made it possible to perform such measurements and conduct research to obtain dependable data on the reliability of nuclear weapons;

— the third time period is when full-scale tests of nuclear charges are completely stopped. The tasks of maintaining the country's nuclear arsenal, along with the study of physical models of the operation of nuclear charges, still required and still require experimental confirmation of the reliability and safety of nuclear weapons and maintenance and development of the experimental base created for these purposes and modified considering new areas of use.

The current state of the experimental base is the result of many years of activity of the experimental physics department in areas that originate in solving the problems of developing and improving nuclear charges. The development of the experimental base was accompanied by the emergence of new opportunities for its use in related areas [9].

Radiography (with different sources of ionizing radiation and multi-angle and multi-frame recording) with a wide range of tasks — from gas-dynamic studies to controlling the uniformity of fuel in rockets or the detection of defects in massive metal structures — began with radiographs of fast processes, BIM-type betatrons ('small-size pulsed betatron'), and small accelerator tubes.

Research and testing on radiation resistance began with the recording of the induced potential on the blasting cables in full-scale tests. Today, radiation physics is an extremely wide area of activity: from research into the mechanisms of radiation damage to ensuring the radiation reliability of space technology.

Measurements of the radiation fields of our products led to the development of scientific and methodological foundations for monitoring special materials in closed packages, to the development of equipment for objective radiation monitoring in systems for the physical protection of objects, to the design of radiation devices for customs and border monitoring and equipment for monitoring compliance with international agreements [1, 10].

Completing the tasks of determining the critical mass of weapons-grade materials served as the basis for the development of a fleet of pulsed research reactors, which provide unique opportunities for research in the field of nuclear energy safety.

Shown in the third time interval (Fig. 1) are only the main areas of activity that have been further developed.

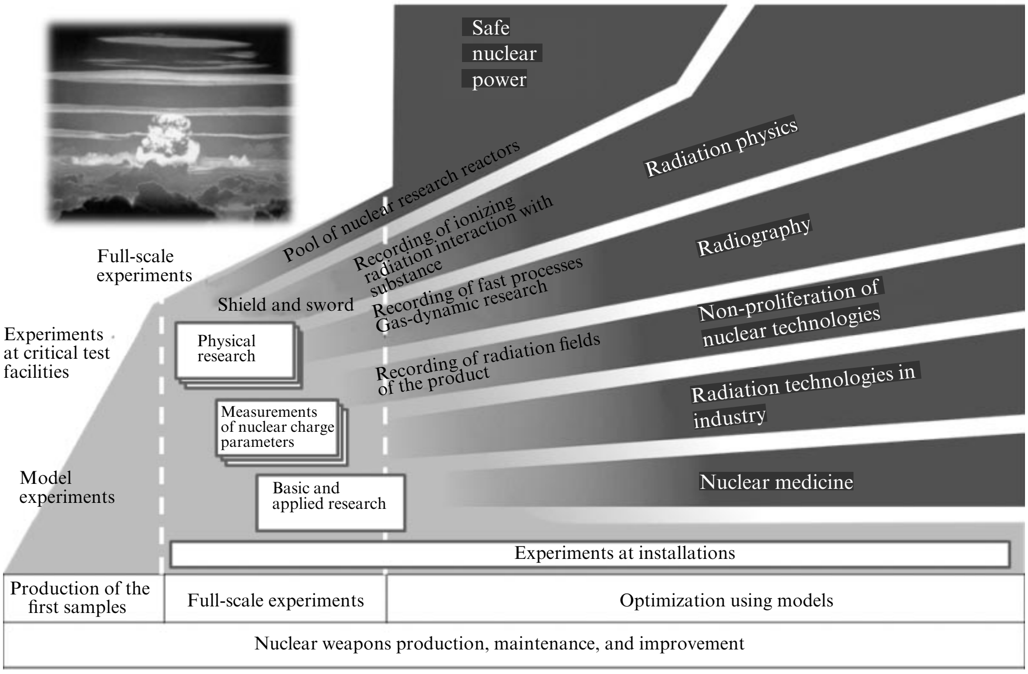

Figure 1. General picture of the development of the experimental base of VNIIEF.

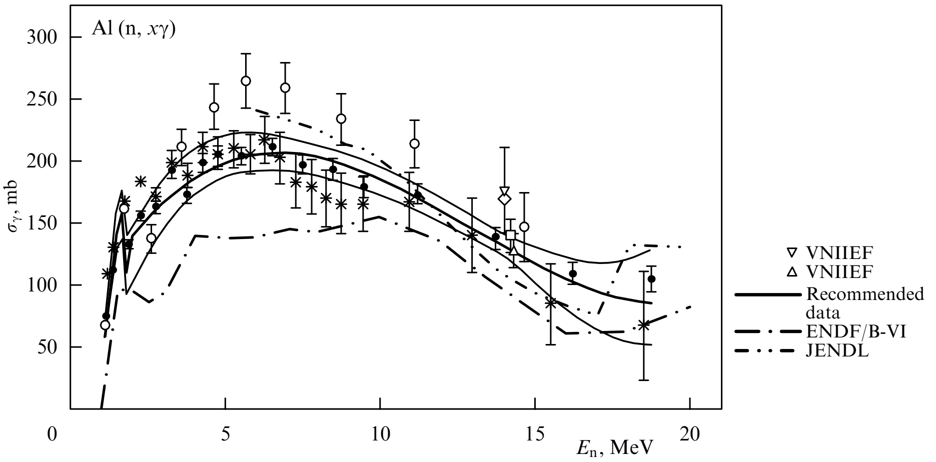

Figure 2. Example of evaluation and refinement of the recommended data (shown by a solid thick curve) based on the results of a comparison of the experimental and calculated values of the reaction cross section $(n, x\gamma)$ for aluminum depending on the neutron energy obtained by different authors (denoted by different symbols and curves). ENDF — Evaluated Nuclear Structure Data File, JENDL — Japanese Evaluated Nuclear Data Library.

2. Measurements of elementary constants and model experiments

The calculation methods used in the development of a nuclear charge (NC) were confirmed by comparing the calculated data with the experimental results obtained on model assemblies of nuclear materials (the 'model approximation' method). Figure 2 [11] shows an example of experimental results for determining the total integral cross section for the production of gamma-ray photons on aluminum for gamma-ray photons with an energy of 0.75–1.0 MeV.

Charge calculations required knowledge of nuclear processes in a wide range of interacting-particle energy. It was necessary to determine both the cross sections of the thermonuclear reactions themselves and the cross sections for the interaction of neutrons with the nuclei of many elements that make up the structure of the charge.

At the initial stage, the determination of 'effective' values of elementary constants was carried out on simplified ('plane') model assemblies. Later, when making thermonuclear charges with a fundamentally new, much more complex design (starting with the RDS-6 product), other parameters were experimentally determined on model assemblies: neutron 'utilization factors' and the generation and regeneration of tritium. Such model experiments required the creation of deuterium-tritium (DT) neutron generators, new detectors, and detection techniques.

A little later, at the stage of developing more advanced and powerful NCs, it was necessary to experimentally confirm the operability of new principles of charge design, in particular, estimates of neutron heating, etc.

Using a specially designed device simulating a thermonuclear charge and experimental setups, the cross sections and angular distributions of the D(n,2n)H reaction at a neutron energy of 14 MeV were measured, the cross sections for neutron capture by ^{238}U and ^{232}Th nuclei were determined, the average number of secondary neutrons of ^{235}U and ^{232}Th nuclei was determined during their fission by DT neutrons, a study was made of the passage through different shell layers for 14-MeV neutrons as well as for the neutrons of the fission spectrum, etc.

The structure of the model (see the ornament "Mephistopheles on a hydrogen bomb" created by the employees of the model group and shown in Fig. 3), reflecting the structure and design of the charge, provided for the placement of a neutron source and activation detectors for detecting neutron radiation in it. At the same time, elementary nuclear constants were measured

Figure 3. "Mephistopheles on a hydrogen bomb" ornament created by members of the 'model' group. According to the idea of the authors, the devil, sitting on a ball, in scale corresponding to the model actually used, thumbs his nose at the Americans with whom the competition was going on. A photo of the ornament was published in the journal *Uspekhi Fizicheskikh Nauk* (Vol. 161, No. 5, 1991) [*Sov. Phys. Usp.* **34** (5) 361–446 (1991)], posted on the front door of the I V Kurchatov museum in Moscow, published in the US book *Dark Sun*: *The Making of the Hydrogen Bomb* (1995), and reproduced in the journal *Atom* (2002).

using a high-intensity photoneutron source and a low-voltage neutron generator (accelerating tube). Work on the model made it possible to study the spatial and energy distribution of neutrons and various reactions occurring in the model.

Unique measurement methods were developed (as Andrei Sakharov said, "jewelry in terms of materials and design"), with the result that the need to correct the set of constants used in charge calculations was revealed.

Model experiments were considered a necessary component of the entire package of research and development work on the making of thermonuclear charges as the final stage of laboratory testing of charges before they were sent to the test site.

Model measurements and measurements of elementary constants complemented each other. An experimental study of the processes occurring in a thermonuclear charge and the use of theoretical data made it possible to determine the design of the first domestic thermonuclear charge.

3. Determination of the critical mass of weapons-grade materials. Experiments with breeding assemblies

Determining the critical mass of weapons materials in a nuclear charge is a key issue that arose during the development of the first samples of nuclear charges. To solve this problem, it was necessary to study the characteristics of the interaction of neutrons of different energies with the nuclei of heavy elements. It was also necessary to find out the number of neutrons per fission event, determine the energy spectrum of fission neutrons, and choose the optimal reflector material. The need to obtain answers to these questions served as a starting point and, for many years to come, predetermined the direction of the Experimental Physics Department's activity in the development of neutron sources [12] and in the development of appropriate measuring equipment, including neutron detectors.

In 1948, G N Flerov set up a neutron physics laboratory and conducted the first experiments to determine the critical mass of the first nuclear charges. The Laboratory for Critical Mass Measurements with Breeding Systems on Fast Neutrons was one of the first structures in the sector of experimental physics. Already in 1950, active work began on a stationary facility, which was an intense source of neutrons of the fission spectrum (Fig. 4).

At the facility, the upper and lower components of the breeding (critical) system were brought together. By changing the composition of the parts (and the distance between them), the criticality of the system was varied. The installation received the abbreviated name PBFN (Physical Boiler on Fast Neutrons). At PBFN-type facilities, studies of various models of nuclear charges were and are being carried out.

The special features of working at facilities with breeding assemblies include the need to conduct experiments with the closest possible approach to the critical state, which should ensure the accuracy of subsequent extrapolation. At the same time, reliable protection against accidents must be ensured due to the rapid separation of the assembly parts.

Developing and improving the means of ensuring safety at nuclear installations have been, remain, and will invariably be the most important issue during all the coming years of operation [13].

Over the past years, the PBFN design has been improved with the accumulation of expertise: modifications to the test benches (1st, 2nd, 3rd) and their modernized versions were made in 1950, 1955, 1959, 1963, 1976, 2001, and 2015 (Fig. 5). Common to the designs of all test benches was the division of the breeding system into two parts (upper and lower). In this case, the upper part was assembled on a fixed (or moving only in a horizontal plane) bench, and the lower part was assembled on a table, which was then remotely raised, ensuring the convergence of parts of the breeding systems. Emergency protection was provided by dropping the table and control plug under the action of gravity.

In addition to critical test benches designed to study small breeding systems, the Institute of Nuclear and Radiation Physics (INRP–VNIIEF) made the IKAR-S critical test bench for studying the nuclear-physical characteristics of large-sized systems simulating the core of a laser-reactor [14]. This work was part of a long-term research program at INRP–VNIIEF to study the possibility of making nuclear-pumped lasers. Currently, the IKAR-S critical facility is used as a tool for studying the radiation resistance of military equipment (ME) samples.

Since then, parameters of ≈ 1200 various breeding systems have been studied at the PBFN critical facility,

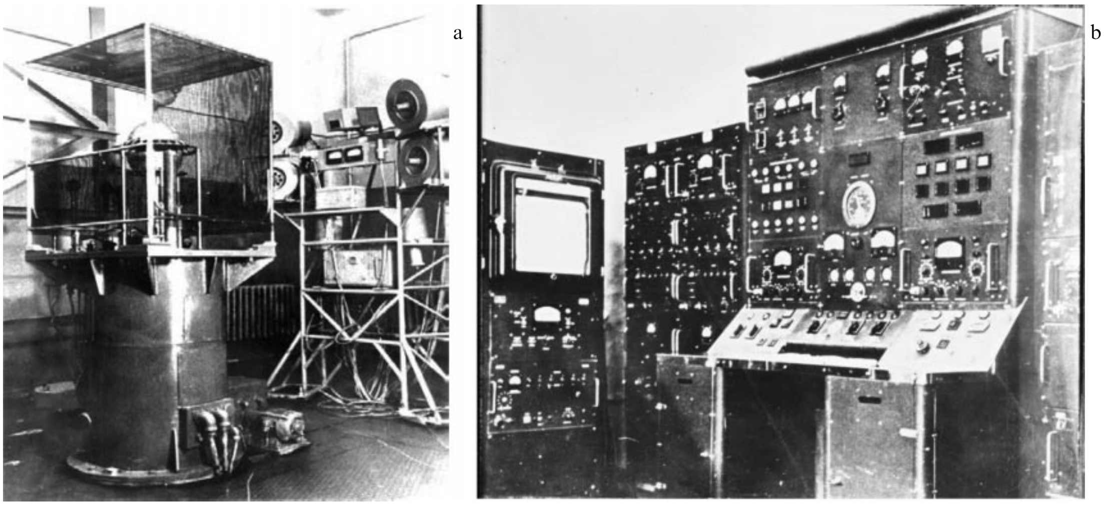

Figure 4. PBFN-1 facility (1955) for critical mass studies (a) and facility control panel (b). (Photographs by V A Razuvaev.)

Figure 5. Operating critical facility PBFN-3 (a) and its control panel (b). (Photos by A E Maleev.)

including those with an active zone of ^{235}U(96%), ^{235}U(90%), ^{235}U(75%), ^{235}U(36%); ^{235}U(90%) and Mo(9%) alloy; solid imitators of aqueous solutions of ^{235}U(90%), ^{239}Pu(88%) in α- and δ-phases and ^{239}Pu(98%) in the δ-phase. In experiments, the multiplication factor or reactivity was measured to determine the degree of subcriticality of the system. Most of the studied systems (structures) had a spherical geometry.

At the PBFN critical facility, investigations of spatial energy distributions of neutrons and total numbers of reactions, neutron spectra at the center of the breeding system, and leakage neutron spectra have been and are being carried out. The recording of decays in the density of prompt neutrons with time makes it possible to determine the decay constant and the Rossi-alpha constant, as well as the lifetime of prompt neutrons [15–22].

The possibilities of using various materials as reflectors (including water, polyethylene, copper, graphite, aluminum, iron, beryllium, beryllium oxide, uranium ^{238}U, natural uranium (U$_{\rm nat}$), concrete, lead, tungsten, nickel, molybdenum, titanium, boron carbide, and zirconium) were studied. For example, Fig. 6 shows the results of experiments on the choice of reflector material [20]. Over 30 test critical systems are listed in the International Handbook of Evaluated Criticality Safety Benchmark Experiments.

At the PBFN critical test bench, studies of the nuclear-physical characteristics of models of various blankets were carried out: a molten-salt blanket, a cascade blanket for an electronuclear installation with a threshold fissile material of ^{237}Np, breeding systems containing vanadium, lead, etc. Carried out on the premises of the PBFN facilities was the preliminary assembly of GIR (reactor gamma-ray source), RIR (collapsing pulsed reactor), and BR-K1 ('Kaskad' booster reactor, option 1) reactors.

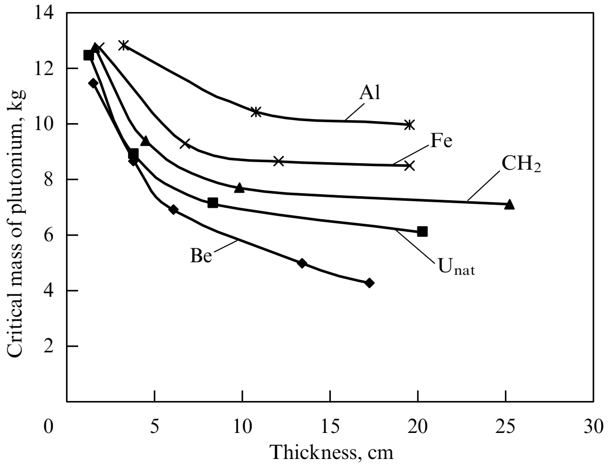

Figure 6. Dependence of the critical mass of plutonium in the δ-phase on the material and thickness of the reflector.

4. Full-scale tests. Development of instruments and installations for nuclear physics research and measurements in full-scale experiments

> *Any explosion is a process that, like human life, goes through all stages of development: it is born, grows, ages, and dies. Only in the atomic bomb, this process takes place in microseconds. And if we can record these instantaneous processes in the form of graphs on paper or on photographic film, consider that the atomic bomb is in our pocket.*
>
> (First Deputy Scientific Director of the Atomic Project K.I. Shchelkin)

The problem of determining the parameters of a nuclear charge (NC) in the first decades was the key task of the subdivision of experimental physics.

Measurements during a nuclear explosion make it possible to obtain information about the mode of operation of a nuclear charge and the correctness of the chosen calculation and design scheme, make it possible to clarify the mechanisms and levels of impact of the damaging factors of a nuclear explosion on various military and civilian objects, and permit selecting the necessary means of protection.

Determining the parameters of an NC involves proposing, developing, mastering, and implementing a variety of diagnostic methods. These may include: methods for recording the parameters of radiation from a nuclear explosion (optical, thermal, gamma-neutron, electromagnetic), determining the parameters of shock and seismic waves, methods for radiochemical analysis of explosion products, and methods for identifying the nature and magnitude of the response of structures and materials to the impact of damaging factors of a nuclear explosion (degradation of functional characteristics, structural changes in substances, etc.) [3]. It is quite obvious that the choice of measurement methods and measuring instruments mainly depend on the version of the test.

In full-scale tests, it was required to obtain data (by at least two methods reliant on different physical principles) on the main design parameters of products: neutron multiplication constant, charge energy release (its TNT equivalent), fusion mixture combustion temperature, spectra of all types of radiation, and shock wave parameters [3].

As is well known [23], before the signing of the CTBT, more than 700 nuclear tests were conducted in the country (in the USA, more than 1000). The tests took place under a wide variety of conditions: on the surface of the Earth, in the atmosphere, underground in wells and adits, and under water. Measurement technology developed and changed simultaneously with the making of new product samples and in accordance with changes in test editions.

In fact, all methods of on-test physical measurements were unique. Several hundred devices and instrument assemblies have been developed and tested, which ensured the recording of information about the operation of products in the most complex experiments.

The research on and recording of pulsed ionizing radiation in a wide range of fluxes and of spatial, temporal, spectral, and energy characteristics are a new engineering and technical area, a new scientific and technical branch. The testers at the Department of Experimental Physics (of course, acting together with specialists from other departments, enterprises, and institutes) actually came to be the founders of this new branch of science [24–29].

In the early years, the Department of Experimental Physics carried out intensive work on the development of a complex of gamma-neutron and radiochemical measurements in relation to atmospheric tests of nuclear and thermonuclear charges.

During the period when nuclear charges were being improved on the basis of new physical principles and technologies, their development gave a major impetus to progress with the experimental base.

A network of installations and equipment was made: new (for that time) electron accelerators MV-15 (1957) and LU-50 (1981) (Fig. 7), B-30 betatron (1960), EG-2 (1952–1954), EG-5 (1957), and EGP-10 (1962) electrostatic ion accelerators (Fig. 8), the DT-neutron NG-150M generator (Fig. 9), a network of pulsed aperiodic reactors, at the PBFN critical test bench. New means of registration, radiation detectors, and methods for processing results have been developed (for example, a 4π-neutron and gamma-ray detector (Fig. 10)).

It is pertinent to emphasize the importance of developing a method for absolute calibration of scintillation detectors in terms of responsivity to thermonuclear neutrons, as well as a calculation method for determining their responsivity for the rest of the energy range of recorded neutrons [30, 31]. This value had not been experimentally determined before due to the lack of appropriate neutron sources.

Figure 7. LU-50 electron accelerator. Boundary electron energy is 50 MeV, photoneutron energy ranges from 0.1 to 15 MeV (made jointly with the Moscow Radio Engineering Institute). (Photo by V A Razuvaev.)

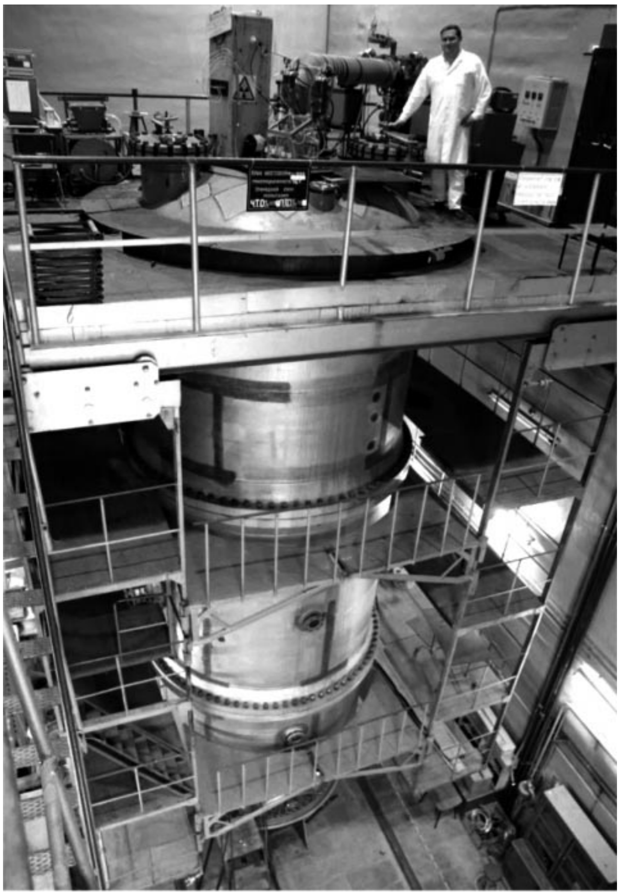

Figure 8. Electrostatic charge exchange generator (tandem) EGP-10, operating energy range of accelerated protons from 1.0 to 12 MeV; types of accelerated particles: ions of protium, deuterium, tritium, oxygen, carbon; source of negative ions is a duoplasmotron. (Photo by A E Maleev.)

Figure 9. Reference source of thermonuclear neutrons: pulse duration of 30 ns, repetition frequency of $(1-5)\times10^5$ Hz, uncertainty in determining the fluence of 14-MeV neutrons is ±2.5%. Static neutron generator developed at the D V Efremov Scientific Research Institute of Electrophysical Equipment (NIIEFA), pulse mode implemented in VNIIEF. (Photo by A E Maleev.)

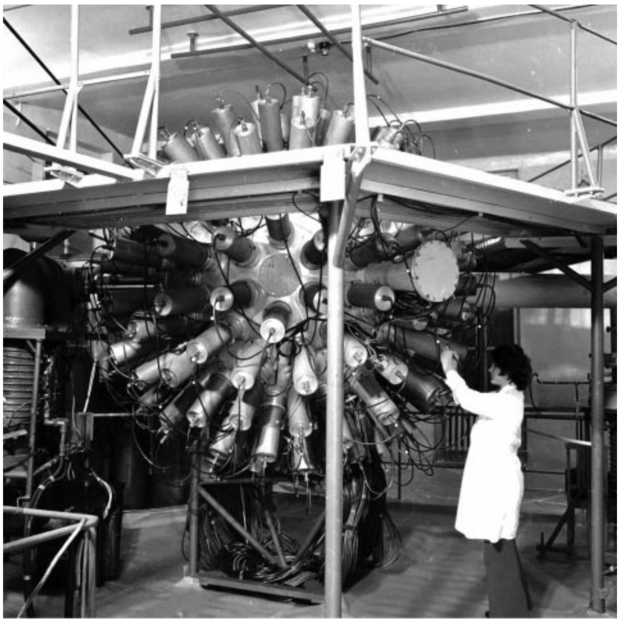

Figure 10. 4π-detector of neutrons and gamma-ray photons. (Photo by V A Razuvaev.)

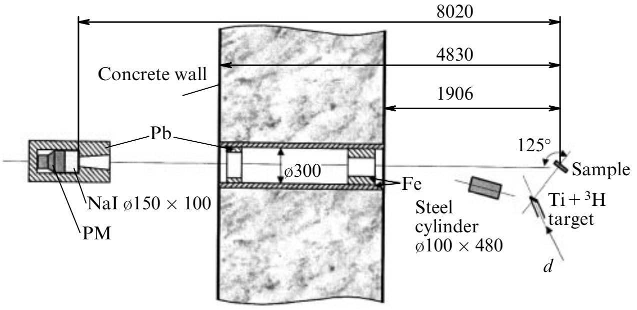

Figure 11. Geometry in which the cross sections for the production of gamma-ray photons and their spectral composition were measured. Dimensions are in millimeters.

The uncertainty in determining the spectral sensitivity of the detectors of neutron techniques was initially at least 40–50%. The use of the NG-150M neutron generator made it possible to reduce the error in determining the responsivity of the detectors by a factor of ~ 10.

The making of a gamma spectrometer and the large-scale implementation of Monte Carlo computational methods made it possible by the mid-1980s to develop a technique for measuring the cross sections for the production of gamma-ray photons and their spectral composition. This permitted carrying out measurements (Fig. 11) of the cross sections for the production of gamma-ray photon spectra during inelastic scattering of neutrons by several dozen different materials, including fissile ones. The measurement error at the time of completion of the work was at the level of the best foreign studies.

While on the subject of determining the parameters of a nuclear charge, one should at least briefly mention radiochemical methods for analyzing the products of a nuclear explosion, which make it possible to determine the energy release and the date of the explosion, determine the amounts of different elements in the explosion products, study the processes of radioactivity migration, and solve many other applied problems [3]. For about 10 years, VNIIEF developed the country's first radiochemical complex (RCC) (commissioned in 1964): special buildings and a set of equipment (an example is a separator (Fig. 12)) and methods that implement extensive functionality for processing radioactive samples taken during nuclear tests. For many years, the complex of radiochemical studies was one of the country's best equipped and strongest in functionality [33].

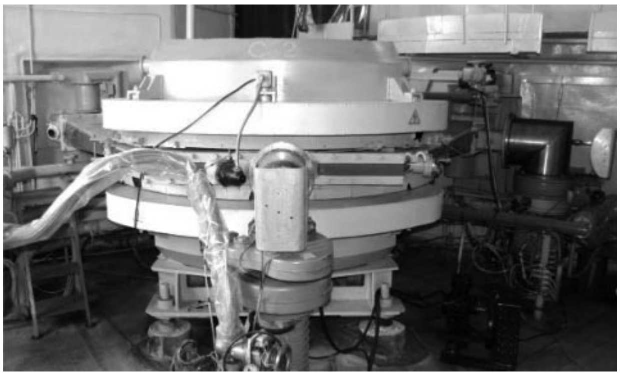

Figure 12. S-2 electromagnetic mass separator. (Photo by A E Maleev.)

The developed radiochemical methods were used in all atmospheric tests conducted by VNIIEF and in almost a hundred underground tests.

For many years, the complex has been carrying out work on the production of highly enriched isotopes of fissile materials.

Radiochemical methods and equipment were used in the study of the Norwegian Sea in the area of the sunken submarine *Komsomolets*.

Radiochemical methods are still the key ones in the development and certification of protective structures that ensure the radiation and environmental safety of explosion experiments.

5. New knowledge in nuclear physics

Over years of full-scale testing, INRP specialists have developed many dozens of physical measurement techniques and made hardware and methodological tools for virtually all underground tests in adits and wells with VNIIEF charges.

New knowledge in the field of charge engineering and fundamental and applied physics was obtained in the course of nuclear physics research, the development of physical measuring techniques, and measurements in full-scale experiments [34–44]. Here are some of them:

- information about the spatial and energy distribution of neutrons and the density of nuclear reactions in NCs (using physical models);
- results of research in the area of radiation damage physics;
- information about the feasibility of high-power nuclear-pumped gas lasers [45];
- data on the light yield of plastic scintillators under electron, proton, and alpha particle irradiation;
- measured data on the dependence of the brightness temperature of the shock wave front in the air on its propagation velocity;
- experimental data on the cross sections and spectra of gamma-ray production in inelastic neutron scattering by fissile and structural materials;

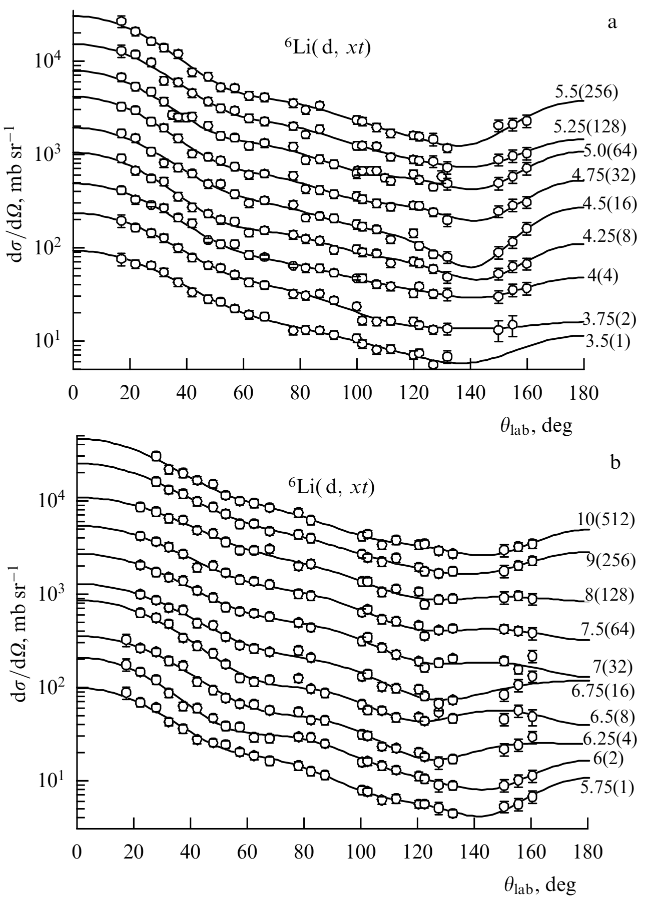

Figure 13. Differential cross sections for the ^{6}Li(d, xt) reaction (circles are experimental data, curves are descriptions) at deuteron energies (a) $E_{\mathrm{d}}^0 = 3.5-5.5$ MeV and (b) $E_{\mathrm{d}}^0 = 5.75-10$ MeV (on each curve, the first number indicates E_{d}^0, and the number in parentheses is the multiplier for the cross sections) [50].

- data on fission cross sections, spectra, and fission neutron multiplicity; refined neutron spectra for ^{235}U fission by neutrons with an energy of 14 MeV and for various angles of fragment expansion;
- data on the physics of fission by neutrons, protons, deuterons, tritons, and gamma-ray photons;
- results of studies of isobar-analogue and giant resonances in nuclei of medium and heavy weight;
- data on the first-detected Gamow–Teller resonance in the compound nucleus in the ^{117}Sn(p, n)^{117}Sb reaction [46];
- data on the first-discovered giant threshold anomaly in the ^{7}Li(t, p)^{9}Li reaction; for its analysis, a resonance theory of threshold phenomena was developed; analysis yielded the characteristics of the ^{10}Li nucleus for the first time [47, 48];
- values of the cross sections for the formation of tritium in the reactions ^{6}Li + d, ^{7}Li + d, ^{9}Be + d measured by the radiochemical method;
- preparation of the first reference book on nuclear data for thermonuclear fusion, which transformed into the SABA (Sarov Base) electronic library [49];
- nuclear-physical constants for a broad range of nuclei of transuranium elements, including those for short-lived isotopes;
- results of nuclear-physical measurements on the neutrons of a nuclear explosion using the time-of-flight technique: fission cross sections for isotopes of transuranium elements; data on obtaining distant transuranium elements;
- data on the development of experimental techniques for measuring isentropic compressibility.

Due to the continuation of nuclear physics research at existing facilities of the experimental base, interesting results have been obtained over the past decade [50–54], including the measured differential (in angle) cross sections for the production of charged particles in the main channels of reactions ^{6}Li + p, ^{6}Li + d, ^{6}Li + t, ^{7}Li + p, ^{7}Li + d, ^{7}Li + t, ^{9}Be + p, ^{9}Be + d, ^{9}Be + t, ^{11}B + t. Integral cross sections were determined from them, a significant part of which was obtained for the first time or significantly refined the existing global data. By way of example [50], Fig. 13 shows, in the laboratory coordinate system, the differential cross sections measured for the first time for the ^{6}Li(d, xt) reaction, one of the most important reactions in thermonuclear burning, with the inclusion of 'on-the-fly' reactions. Obtaining these data was the dream of several previous generations of nuclear physicists.

6. Research pulsed nuclear reactors

The solution to the problem of determining the value of the critical mass of weapons-grade materials, the making of a physical boiler on fast neutrons, and the study of breeding systems were at the origin of work on the development of pulsed research reactors.

The second source was the development of computational and theoretical foundations for designing reactors (proposals for a system of closed equations for reactor dynamics) and experimentally evaluated proposals for key design elements [55–58]. The findings in this work had a significant impact on the domestic ideology of designing pulsed reactors. Subsequently, the materials were summarized in the book and monograph by V F Kolesov [59, 60].

The results of theoretical substantiations and design studies of VNIIEF were considered, as a rule, by the branch scientific and technical council (STC). For example, the decision of the STC to construct at VNIIEF the world's most powerful pulsed fast neutron reactor — BIGR (fast pulsed graphite reactor) with a unique ceramic core, made by powder metallurgy methods — was approved by authoritative scientists of that time (A P Aleksandrov, I K Kikoin, M D Millionshchikov, N A Dollezhal', Yu B Khariton, A A Bochvar, et al.). Based on these decisions, a special resolution of the Central Committee of the CPSU and the Council of Ministers of the USSR on the construction of the BIGR was adopted. For many years, this become an important area of activity of the experimental physics division [61–68].

Pulsed research reactors are devices that provide for a short time the conditions for the development of a fission chain reaction with prompt neutrons. At VNIIEF, self-extinguishing pulsed nuclear reactors (PNRs) were developed, in which a burst of fission was initiated by the rapid introduction of excess reactivity, and extinguished due to a negative temperature–reactivity feedback. In these reactors, the prompt chain reaction during a burst is controlled only by an internal self-extinguishing mechanism. The pulse duration and its energy are determined by the level of realized supercriticality, which is introduced by the pulsed block after its preliminary calibration.

An idea of the path traveled and the unique fleet of pulsed nuclear reactors developed at VNIIEF can be obtained from Fig. 14 and Table 1.

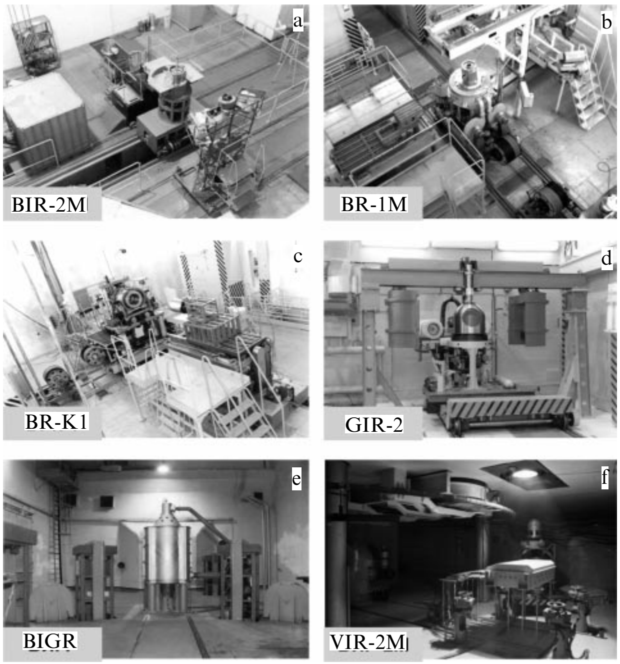

Figure 14. Pulsed nuclear reactors. (a) BIR-2M fast pulsed reactor. (b) BR-1M booster reactor. (c) Booster-reactor Kaskad BR-K1. (d) GIR — reactor gamma-ray source. (e) BIGR fast pulsed graphite reactor. (f) VIR-2M water pulsed reactor.

The PNRs developed at VNIIEF have specific features, which include:

— 'zero' energy release (fuel burnout during operation does not exceed a few grams or even fractions of a gram);

— absence of coolant (core cooling occurs, as a rule, due to natural convection or forced air cooling);

— small size of the core (see Table 1);

— a small number of reactivity control units (RCUs), which simultaneously perform the function of emergency protection units;

— a high enrichment of the fuel (as a rule, ≈ 90% for the ^{235}U isotope);

— the main mechanism of negative temperature–reactivity feedback for a PNR with a metal and ceramic core: thermal expansion; for a PNR with a solution core: thermal expansion and radiolytic boiling;

— accurate prediction of pulse parameters (uncertainty: ±10%);

— special preparation of the experiment for each PNR pulse, with the intervals between pulses being determined by the experiment preparation time.

In addition to generating pulses, all PNRs can operate in the static mode, as well as in the mode of generating pulses on delayed neutrons (quasi-pulses).

In many cases, nuclear reactors (in essence by design) operate under conditions that are classified in conventional power reactor technology as a reactive nuclear accident. In order to reliably operate such facilities, special full-fledged studies are needed to identify signs of an approaching accident and check on the possibility of emergency situations, where special experiments determine the limits of safe operation of nuclear facilities (the threshold for plastic deformation of fuel elements, their possible displacement, the appearance of defects, for example, according to the analysis of mechanical vibration spectra of fuel elements, etc.).

Pulsed nuclear reactors are unique facilities that make it possible to carry out various physical studies [69, 70].

Using PNRs, experiments are being carried out on the comparative behavior of fuel of reactors of various types and on the assessment of the enthalpy levels leading to the destruction of fuel elements (Fig. 15).

Using PNRs at INRP, unique experiments have been carried out aimed at substantiating the limits of safe PNR operation: the long-term behavior of reactors in the power self-regulation mode has been studied, and high-speed emergency protection has been worked out, which makes it possible to interrupt the development of a pulse with dangerous parameters.

Table 1. VNIIEF pulsed nuclear reactors.

Reactor	VIR-2M water pulsed reactor	BIR-2M fast pulsed reactor	TIBR transportable fast pulsed reactor	BIGR fast pulsed graphite reactor	BR-1 booster reactor	RIR collapsing pulsed reactor	GIR-2 reactor gamma-ray source	BR-K1 Kaskad booster-reactor
Start of operation of the 1st version, last version	1965 2013	1965 1991	1970	1977	1978 2009	1981 1984	1984 1993	1995 ~ 2023
Present state	In operation	Decommissioned	Transferred to NIIP*	In operation	In operation	2 experiments	In operation	Physical start-up
Fuel mass, kg	7.1 (104.8 l)	121	124	833	173	~ 25	178	1469
Core dimensions, cm	∅ 55 × 63	∅ 22 × 22	∅ 27.5	∅ 76 × 67	∅ 27 × 27	~ ∅ 24	∅ 30	∅ 62 × 82
Cavity, mm	∅ 142, ∅ 300	∅ 40	∅ 28	∅ 100	∅ 100	—	—	∅ 355 × 375
Energy release per pulse, MJ	65	3	7	280	10	450	7	100
Peak temperature, °C	250	300	700	900	590	Explosion	400	620
Maximal pulse half-width, μs	2650	55	480	2000	68	~ 2.5	300	600

* V V Tikhomirov Research Institute of Instrument Engineering.

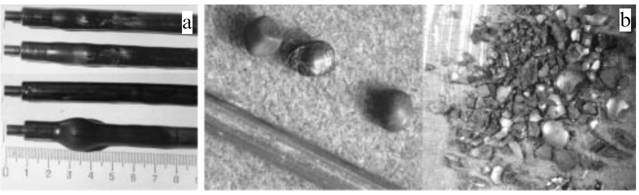

Figure 15. (a) Samples of fuel rods from a pressurized water power reactor (VVER) after irradiation at the BIGR. (b) Microfuel before and after irradiation. (Photographs by V A Razuvaev.)

7. Radiation resistance

The Division of Experimental Physics has come a long way to achieve the current state of providing research and assessment of the levels of radiation resistance (RR) of military equipment samples, a path from a sector to the Institute of Nuclear and Radiation Physics [71, 72]. This is the path from discovering the effects of radiation damage in full-scale tests of nuclear charges in the form of 'radiation interference' signals on charge detonation cables in field tests to experiments on specially designed installations that simulate effects that cause functional and power radiation damage.

The problem of ensuring radiation resistance and its assessment became acute with the termination of full-scale tests and the requirements for a comprehensive assessment (taking into account various damaging factors of a nuclear explosion) of the resistance of a wide range of objects — from microcircuits to large-sized equipment.

7.1 Development of electron accelerators

An important constituent of research into radiation resistance problems was the work on the making of electron accelerators — sources of ionizing radiation.

It is valid to say that INRP has made its contribution to world science in designing accelerators and to the formation of the principles of physical modeling of the impact of damaging factors of nuclear explosions. Results of the production and use of accelerators were marked by the awarding of two Lenin Prizes, two State Prizes, and a Prize of the Government of the Russian Federation to the staff of INRP.

In the course of work on the development of accelerators, new engineering and technical solutions were found and practically implemented, in some cases overcoming the world's doubts about the possibility of their implementation (efficient beam transmission over long distances, the design of ring spark gaps with a nanosecond turn-on jitter, etc.). The problems were especially aggravated in the development of ionizing radiation sources providing a combination of high doses, short pulses, and large irradiation areas.

Regularities revealed for the first time led to a new professional level of knowledge (an accelerating system of inductors in the form of transformers with single-turn primary and secondary toroidal circuits, the creation of an inductor on radial lines, the use of multistage stepped lines, etc.) [72, 73].

During the development of accelerators and irradiation systems, specialists from INRP obtained over a hundred copyright certificates and patents for inventions. These are just some of the results of the work of the school of A I Pavlovskii, head of the Division of Experimental Physics from 1971 to 1993 [74–77].

Specialists at this school developed the first domestic (1967) iron-free linear induction accelerator, which was later reproduced to equip the testing center for radiation resistance (Lytkarino), set up by a government decision. In 1977, a radial line accelerator was put into operation (energy of 14 MeV, beam current of 40 kA, current pulse duration of 20 ns) [73].

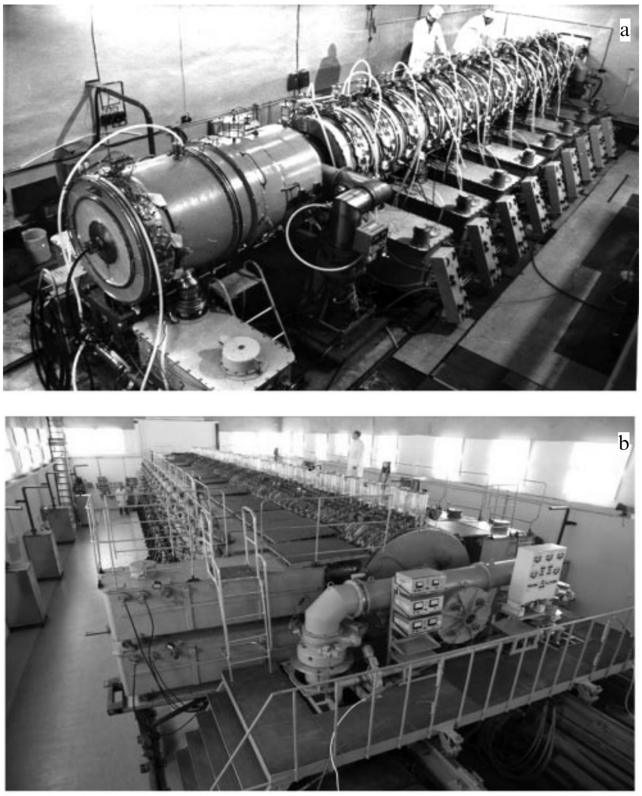

Figure 16. (a) General view of the LIU-10M linear induction accelerator as part of the industry's first irradiation complex. (b) LIU-30 accelerator is the basic unit of the irradiation complex. (Photographs by V A Razuvaev and A E Maleev.)

In the 1970s, a series of computational and experimental studies was carried out at VNIIEF, on the basis of which the government decided to construct the Pulsar irradiation complex.

In 1984, the first irradiation complex was put into operation (as a prototype of Pulsar) based on a radial line accelerator (Fig. 16a) and a pulsed nuclear reactor, and already in 1986 a new irradiation complex (Pulsar) was put into operation with one of the most powerful sources of bremsstrahlung in the world (Fig. 16b) [78, 79]. In 1994, the first irradiation complex was modified.

For the first time, developers of military equipment were able to simulate in laboratory conditions the impact of a nuclear explosion by generating pulses of bremsstrahlung and gamma-neutron radiation according to a given time program.

In order to provide a more complete simulation of the impact of penetrating radiation, both complexes were equipped with additional electrophysical installations: a STRAUS-2 (Stepped transforming accelerator 2) pulsed electron accelerator [80] (Fig. 17a) and a small-sized pulsed electron accelerator, ARSA (Arzamas–Sarov) [81] (Fig. 17b), placed in the irradiation halls of the complexes.

In addition, one of the complexes was additionally equipped with two X-ray pulse generators: an X-ray static setup and a linear resonant electron accelerator (Figs 17c and 17d).

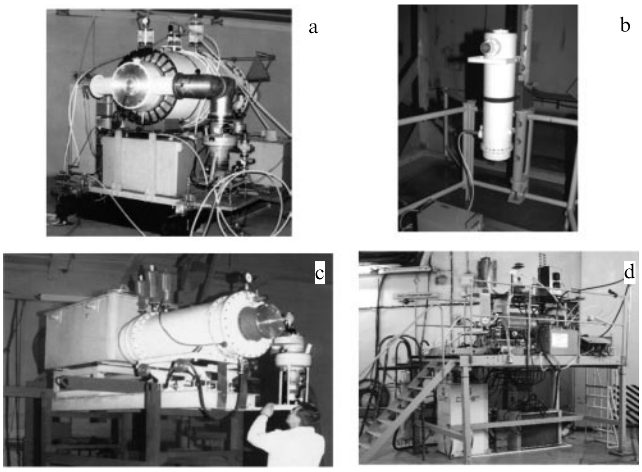

Figure 17. Equipment at the Pulsar complex. (a) General view of the STRAUS-2 accelerator, made on the basis of a five-stage double forming line with water insulation with an outer diameter of 1.3 m. Distinctive feature of the STRAUS-2 accelerator is that all its systems are mounted on a platform moved by a crane. (b) General view of the ARSA accelerator. Its design is based on the Arkad'ev–Marx generator with pulsed charging of storage capacitors. Radiation source is a sealed accelerating tube with a blade-type cathode. Source is synchronized with other electrophysical equipment at the complex. Productivity ranges up to 100 pulses per shift. Subnanosecond electron accelerator with a gas-filled shaper has been developed on the basis of a small-sized ARSA to determine the time resolution of detectors of various types to certify and monitor the performance of measuring channels. (c) General view of the ILTI-1 accelerator (laboratory transportable pulsed source). Movable generator of high-power X-ray pulses is designed to simulate the sequential action of two or three bremsstrahlung pulses in concerted work with other accelerators. In autonomous mode, the accelerator provides feeding of individual devices with radiation with a softened spectrum due to a specially designed close-focus accelerating tube with radiation output from the rear half-space of the target. In comparison with the generally accepted approach, this made it possible to increase the fraction of radiation energy in the prescribed range from 15% to 50%. (d) LU-7-2 transportable linear resonance electron accelerator, introduced into the irradiation complex in 2007. The accelerator, arranged on a carrier platform, can be used in industrial radiation technologies and for flaw detection in objects with large mass thicknesses. (Photos by A E Maleev.)

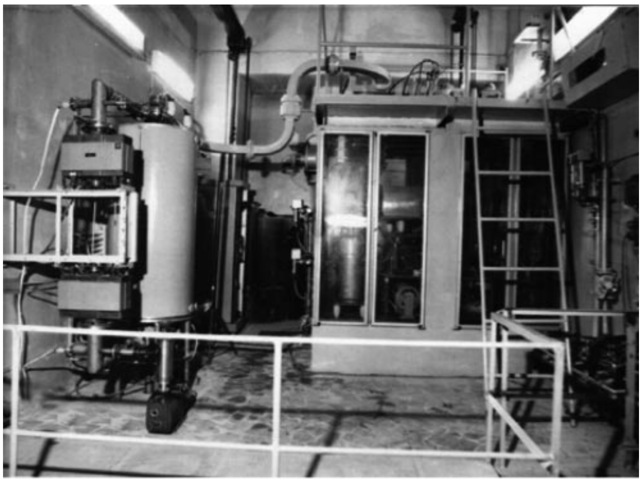

Figure 18. LU-10-20 linear resonance accelerator designed to simulate the dose effect of gamma-ray radiation. (Photo by V A Razuvaev.)

To simulate the effect of a gamma irradiation dose, the LU-10-20 accelerator was developed (Fig. 18).

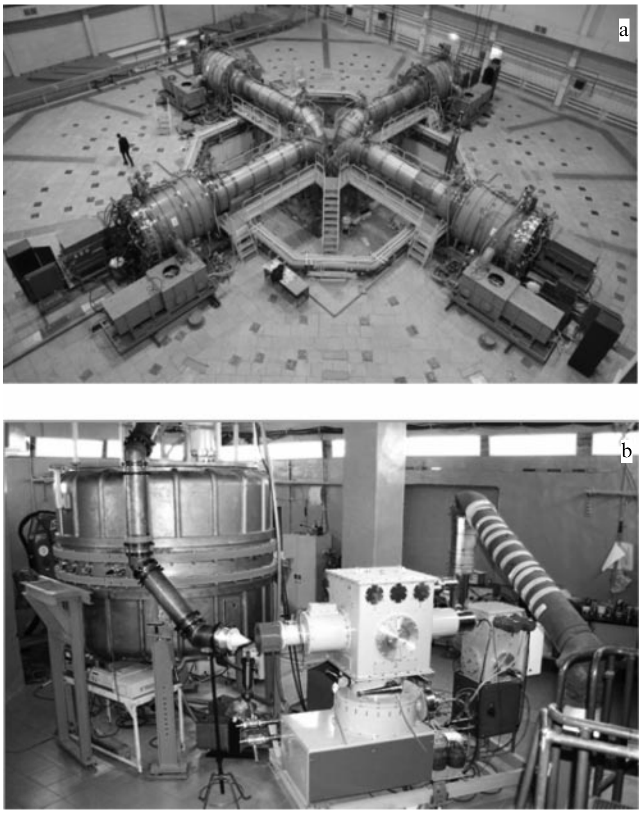

Figure 19. New-generation simulation facilities. (a) General view of the four-module Gamma facility. (b) Operating full-scale model of the Beta resonance electron accelerator. (Photos by A E Maleev.)

A I Pavlovskii's students continued the development of accelerators based on multistage stepped lines (SLs). Several dozen different schemes of generators with capacitive, inductive, and inductive-capacitive energy storage have been proposed. On the basis of SLs, a number of accelerators have been successively developed, in which the calculated characteristics of electron beams and the advantages of SL accelerators (compared to radial line accelerators) have been experimentally confirmed [82, 83]. In the mid-1990s, one of the most powerful stepped-line accelerators was put into operation.

As a result, step-line accelerators have formed a family of accelerators operating in autonomous modes and as injectors for high-power installations. The development of SL accelerators for their application, not only for radiation resistance problems but also for gas-dynamic research and structure evaluation by X-ray methods, continues to the present.

In addition, other developments involving accelerators are underway to develop the experimental base of VNIIEF.

A multiterawatt electrophysical Gamma installation is under construction (Fig. 19a). To date, a four-module facility has been made, which consists of four pulsed high-current electron accelerators that generate bremsstrahlung pulses with the highest photon energy of 2 MeV.

Together with RAS institutes, a resonance electron accelerator with a high average beam power is being developed. Its main element is an accelerating coaxial half-wave resonator with an operating frequency of 100 MHz. The accelerator is intended to operate in repetitively pulsed and continuous beam generation modes. The making of such an accelerator will make it possible to obtain accelerated electrons beams with energies of 1.5, 4.5, and 7.5 MeV in one common output device at an average beam power of up to 300 kW. The operating full-scale layout of the accelerator is shown in Fig. 19b [84].

7.2 Modeling installations and irradiation complexes: an experimental base at the federal level

Therefore, in order to study and evaluate radiation resistance, VNIIEF developed a base of experimental facilities consisting of high-current electron accelerators of various types and pulsed nuclear reactors, providing exposure to ionizing radiation with different amplitude-time and spectral-energy-angular characteristics: an exposure dose rate to bremsstrahlung up to 10^{13} R s^{-1} with a pulse duration $\sim 10^{-8}$ s, the highest flux density of fission-spectrum neutrons of 10^{18} n $(cm^2\ s)^{-1}$, with a fluence of neutrons with energies > 0.1 MeV up to 10^{16} n cm^{-2} [79].

The possibility of conducting research using the experimental base was provided by the development and improvement of existing detectors and the development of new ones, as well as methods and techniques for measuring the characteristics of high-intensity and high-dose ionizing radiation fields.

Proceeding from the foregoing, it can be stated that today at INRP:

- there is a unique test base for research and confirmation of the RR of a wide range of objects: samples of equipment (from microcircuits to complex multicomponent control systems);
- an infrastructure has been set up and put into operation to ensure the implementation of work on the RR;
- the methodological foundations for pursuing research for different objects and for various modes of operation of simulation installations have been worked out;
- unique knowledge has been acquired in the field of methodology of calculations and fundamental and theoretical substantiations of physical modeling of damaging radiation factors of nuclear explosions and outer space.

8. Radiography

In setting up the subdivision of experimental physics, a laboratory of X-ray studies was designated as part of it to develop methods for recording fast processes and conducting research on explosion dynamics. For many years, the laboratory has been developing various sources of ionizing radiation (direct-acting electron accelerators, pulsed X-ray machines, including portable ones, for express analysis, powerful 'plasma focus' sources based on high-current discharges in gases, etc.).

Under the conditions of the CTBT, the urgency of the problem of creating powerful pulsed X-ray systems for studying fast gas-dynamic processes in objects with large mass thicknesses is growing.

As a result of work on the development of new-generation facilities and complexes, VNIIEF subdivisions created a network of pulsed X-ray units with the latest means of recording and processing X-ray images.

The complex uses a new type of linear induction accelerator. The accelerator (Fig. 20a) surpasses domestic analogues by an order of magnitude in dose parameters and approaches the best foreign facilities of this class. The accelerating system (LIU-R-T) is designed on the basis of the technology developed at RFNC–VNIIEF of 'iron-free' linear induction accelerators with water-insulated inductors based on stepped forming lines with distributed parameters. This made it possible to double the acceleration rate and increase the electron beam current by 5–10 times over the current in the most powerful foreign radiographic devices (AIRIX (from the French: Accélérateur à Induction pour Radiographie pour l'Imagerie X), Dragon, France), made according to the scheme of classical linear induction accelerators with inductors on ferromagnetic cores.

Figure 20b shows a possible setup of a four-beam multichannel X-ray complex based on three synchronously operating BIM betatrons with a maximum electron energy of 70 MeV and an LIU linear accelerator (electron energy: 12 MeV). The complex is equipped with modern multi-frame electron-optical recording systems with almost real-time image output, as well as with computer radiography systems based on photochromic screens. The complex permits studying dynamically developing processes from four angles (up to 10 frames in one experiment) in objects of large mass thickness.

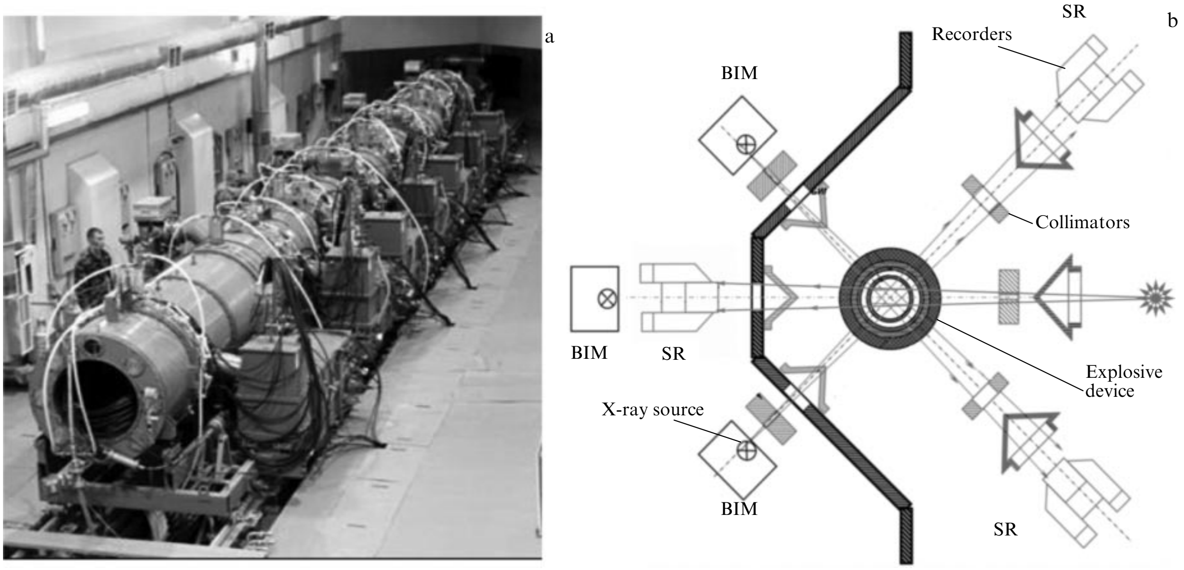

Figure 20. (a) General view of the LIU accelerator (photograph by A E Maleev). (b) Option to include equipment from the radiographic complex. BIM — small-sized pulse betatron, SR — recording system.

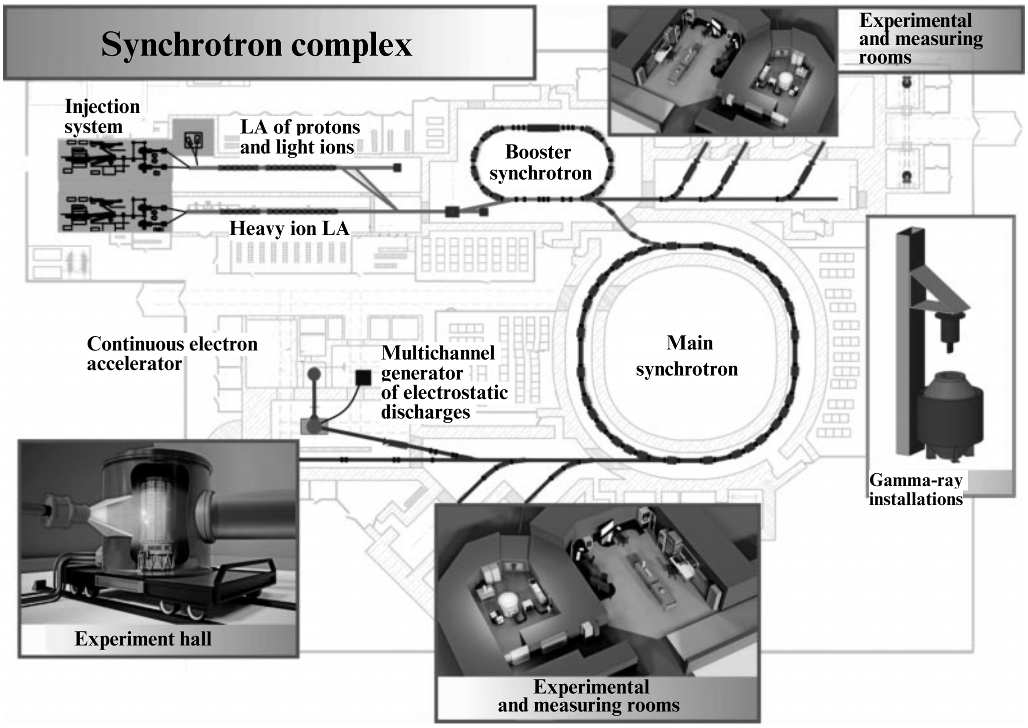

Figure 21. Composition of the equipment and premises of ICCRRT.

Table 2. Booster accelerator.

Parameter	Value	
Accelerated particle type	p	^{209}Bi
Injection energy, MeV per nucleon	7.5	3.5
Energy at output, MeV per nucleon	from 7.5 to 700	from 3.5 to 36
Intensity, number of particles per pulse	from 10^4 to 10^{11}	from 10^3 to 10^8
Highest repetition rate, Hz	1	
Ring perimeter, m	88	

In terms of the number of X-ray beams and the number of X-ray image frames of the object in one experiment, the complex surpasses the modern DARHT (Dual Axis Radiographic Hydrodynamic Test facility) complex in Los Alamos.

9. Promising work and activity areas

9.1 Establishment of the Interdepartmental Center for Comprehensive Radiation Research and Testing

The Interdepartmental Center for Comprehensive Radiation Research and Testing (ICCRRT) is being set up to conduct research and test the electronic component base (ECB) for resistance to the effects of ionizing radiation from outer space (IR OS) and their attendant effects.

The establishment of ICCRRT implies a transition to a new level of experimental simulation of impacts. The objects under study should be affected by charged particle beams (with a wide range of ions, from protons to Bi), produced by a synchrotron-type ion accelerator. Fluxes of particles of varying intensity should affect the test objects, together with electron and bremsstrahlung radiation, as well as with possible additional simultaneous exposure to electrostatic discharges.

The diversity of modes of experimental investigation is provided by the composition of the installations of the complex (Fig. 21) and the flexible possibilities of their autonomous engagement and concerted use according to specified programs. The requirements for the main parameters of the booster accelerator (BA) and the main synchrotron (MS) are given in Tables 2 and 3.

The formation of ICCRRT is carried out within the framework of broad cooperation between domestic institutions and industrial enterprises. The following institutions are involved in setting up the center: G I Budker Institute of Nuclear Physics (INF) SB RAS (Novosibirsk), National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) (NRNU–MEPhI) (Moscow), A I Alikhanov Institute of Theoretical and Experimental Physics (ITEP) of the National Research Center Kurchatov Institute (Moscow), Russian Federal Nuclear Center–All-Russian Research Institute of Technical Physics named after Academician E I Zababakhin (RFNC–VNIITF) (Snezhinsk), joint-stock company (JSC) D V Efremov Scientific Research Institute of Electrophysical Equipment (NIIEFA) (St. Petersburg), NIIEFA-ENERGO (St. Petersburg), Joint Institute for Nuclear Research (JINR) (Dubna), JSC Research Institute of Technical Physics and Automation (NIITFA) (Moscow).

Table 3. Main synchrotron.

Parameter	Value	
Accelerated particle type	p	^{209}Bi
Injection energy, MeV per nucleon	700	36
Energy at output, MeV per nucleon	from 700 to 4000	from 36 to 400
Intensity, number of particles per pulse	from 10^4 to 10^{11}	from 10^3 to 10^8
Highest repetition rate, Hz	1	
Ring perimeter, m	168.5	

It should be noted that the nature of the work on the establishment of ICCRRT goes beyond the unification and coordination of the efforts of organizations. The work requires the development of new technologies (for example, the technology of obtaining high-quality resonant structures with a reliable and durable coating), the deployment of new production facilities (for example, the production of powerful high-frequency (HF) oscillators and amplifiers), and the development of complex software products comparable in capabilities to modern foreign software packages.

9.2 Factory of superheavy elements

In Russia, the leader of work on the synthesis of superheavy elements is the International Intergovernmental Organization, the Joint Institute for Nuclear Research. Here, in the fusion reactions of calcium-48 ions ($Z = 20$) with targets from isotopes of heavy transuranium elements (plutonium-244, americium-243, curium-248, berkelium-249, californium-249), new elements with serial numbers 113, 114, 115, 116, 117, and 118 were synthesized [85]. A schematic diagram of the superheavy element synthesis is shown in Fig. 22.

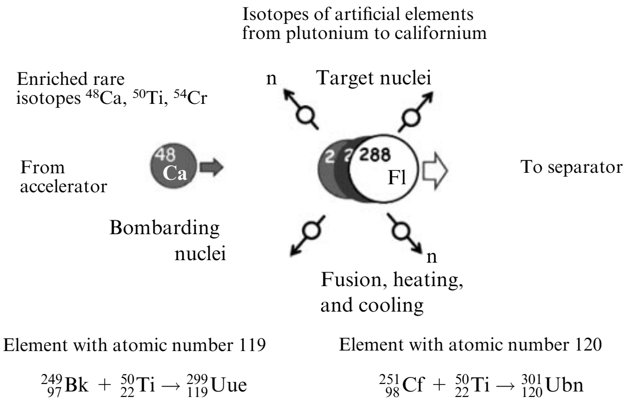

Figure 22. Scheme for the synthesis of superheavy elements.

Some of the target materials were obtained through partnership with the Oak Ridge National Laboratory (USA), and some were obtained as a result of joint work with organizations of the Rosatom state corporation: JSC State Research Center–Research Institute of Atomic Reactors (SRC RIAR), RFNC–VNIIEF, Elektrokhimpribor (EKhP) federal state enterprise.

Currently, within the framework of the comprehensive program "Development of engineering, technology, and scientific research in the field of atomic energy usage in the Russian Federation for the period up to 2024," developed by a decree of the president, work is underway to prepare for the synthesis of new elements with $Z = 119$ and $Z = 120$ (in the most promising reactions berkelium-249 + titanium-50 for element $Z = 119$ and californium-251 + titanium-50 for element $Z = 120$).

The participants in the project implementation and the tasks assigned to them are shown in Fig. 23.

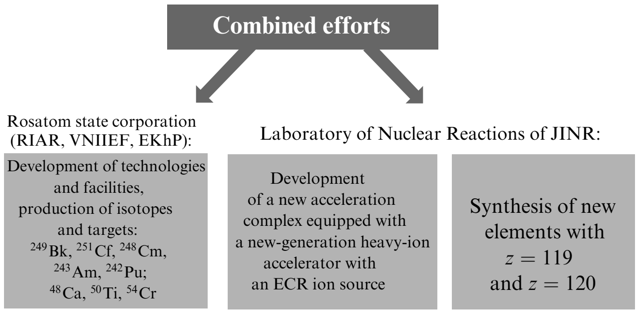

Figure 23. Project implementation participants and tasks assigned to them.

A significant modernization of the experimental base is to be carried out at JINR and at enterprises of the Rosatom state corporation.

In particular, at the G N Flerov Laboratory of Nuclear Reactions of JINR, the factory of superheavy elements accelerator complex will be modernized. The complex currently includes a DTs-280 purpose-oriented accelerator [86] capable of generating accelerated heavy ion beams, which are 10–15 times more intense than in existing accelerators, and a new-generation GNS-2 gas-filled separator for separating nuclear reaction products. In the future, the complex will be equipped with a new accelerator with a high-current injector of multiply charged ions involving a superconducting ion source based on electron cyclotron resonance (ECR) with the pump frequency increased to 28 GHz to obtain high-intensity beams of accelerated heavy ions, which will increase the sensitivity of experiments by 50–100 times.

The key problem in the synthesis of new elements is the availability of a sufficient amount of target materials (the minimum amount of material for preparing a target is about 20 mg). To solve this problem, organizations of the Rosatom state corporation will make an isotope separation complex based on a new-generation mass separator (RFNC–VNIIEF), develop technologies, and produce isotopes for the synthesis of superheavy elements (SRC RIAR, Electrokhimpribor federal state enterprise).

10. Conclusion

To research and test the radiation resistance of military facilities, VNIIEF has made a multi-link research and production complex at the federal level, which provides a complete cycle of research, design, manufacture, maintenance, and support for the long-term operation of simulators and irradiation complexes. The infrastructure that ensures the performance of work and the methodological foundations for setting up research for various objects and for various modes of operation of simulation facilities have been worked out.

This was the basis for the decision to establish an Interdepartmental Center for Comprehensive Radiation Research and Testing at VNIIEF.

The results of the scientific and practical activities of INRP on research into the interaction of radiation with matter, methods for detecting radiation, and studying the response of materials represent a significant contribution to the development of methodological foundations for the use of radiation technologies for military equipment, industry, medicine, and monitoring compliance with international agreements.

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