

IRRADIATION FACILITIES AND COMPLEXES OF INRP RFNC-VNIIEF

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Abstract

There are presented in the review the facilities and complexes that were created and are applied in the Institute of Nuclear and Radiation Physics (INRP) RFNC-VNIIEF to simulate under laboratory conditions the effect of NM penetrating radiation on the special-purpose objects. There is given a brief description of the design and characteristics of different-type electron accelerators, pulsed nuclear reactors (PNR) as well as two irradiation complexes PUL'SAR and LIU-10M-GIR2 that are located in the adjacent halls.

INTRODUCTION

Within several decades there was being created in INRP RFNC-VNIIEF a specialized stock of irradiation facilities on the base of electron accelerators, PNR and complexes aimed at carrying out - under laboratory conditions - system researches of radiation resistance of armament and defense technology (A and DT) standard objects against the effect of NM penetrating radiation.

According to state standards there is performed certification of experimental facilities as test equipment - simulating facilities for B and BT testing as to radiation effect of NM, power generating systems and space.

IRRADIATION COMPLEX PUL'SAR

The multi-purpose irradiation complex PUL'SAR [1,2] that has been under operation since 1991, possess widest test potentialities in factor-by-factor and joint loadings for laboratory elaboration and resistance tests of B and BT against NM penetrating radiation.

The leading facility of the complex is a high-power pulsed linear induction accelerator of electrons LIU-30 [3-5]. Into the complex structure there is also included a booster reactor BR-1M [6] aimed at generation of gamma-neutron radiation - both independently and jointly with accelerator LIU-30 [7]. In order to provide more precise simulation of penetrating radiation effect, into the complex there are included: pulsed electron accelerators STRAUS-2 and ARSA and generator of X-radiation pulses ILTI-1. The typical chart of PUL'SAR facilities arrangement is given in Fig.1 while the basic characteristics of the facilities are available in Table 1.

Fig.2 gives the chart of LIU-30 accelerating system of which is evident that it is produced of 36 sequentially connected modules with self-contained supply and independent control of each module. Into accelerator structure there are also incorporated a transportation channel and output device with a target ensuring the required characteristics of electron beam and bremsstrahlung field.

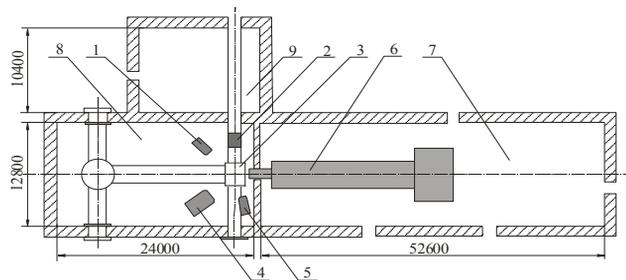


Fig. 1. Chart of PUL'SAR irradiation complex facilities arrangement. 1 - accelerator ILTI-1; 2 - booster-reactor BR-1M; 3 - object under irradiation; 4 - accelerator STRAUS-2; 5 - accelerator ARSA; 6 - accelerator LIU; 7 - accelerator hall; 8 - irradiation hall; 9 - reactor hall.

Table 1. Irradiation complex PUL'SAR

Facility	Radiation characteristics
LIU-30	$P_{bs}^{max} = 1,5 \cdot 10^{13}$ R/s in \varnothing 11 cm, $P_{bs}^{1M} = 5 \cdot 10^{11}$ R/s in \varnothing 60 cm, $E_{bound.} = 4, 15, 25, 40$ MeV, $\tau_{th} = (5-25)$ ns
BR-1M	$\Phi_n^{max} = 10^{15}$ n/cm ² in \varnothing 10 cm, $\Phi_n^{1M} = 5 \cdot 10^{12}$ n/cm ² , $D_\gamma^{max} = 160$ kR, $D_\gamma^{1M} = 1,1$ kR, $W_0 = 11$ MJ, $\tau \geq 55$ μ s
STRAUS-2	$P_{bs}^{max} = 10^{12}$ R/s in \varnothing 5 cm, $P_{bs}^{1M} = 10^9$ R/s in \varnothing 80 cm, $E_{bound.} = 3$ MeV, $\tau_{bs} = (18-25)$ ns
ILTI-1	$P_{uhr}^{max} = 3 \cdot 10^{10}$ R/s in \varnothing 5 cm, $P_{uhr}^{1M} = 5 \cdot 10^7$ R/s, $E_{bound.} \leq 700$ keV, $\tau_{bs} = 40$ ns
ARSA	$P_{bs} = 3 \cdot 10^{10R}$ P/s in \varnothing 10 mm, $E_{bound.} \leq 1$ MeV, $\tau = 10$ ns

where P_γ^{1M} (P_{bs}^{1M}), D_γ^{1M} (D_{bs}^{1M}), Φ_n^{1M} - dose rate, dose of gamma-radiation, bremsstrahlung and neutron fluence at a distance of 1m from facility at the area with diameter \varnothing .

Each module of the accelerator channel contains one block of four inductors on radial lines (RL) with water insulation possessing common accelerating tube 2 (see Fig. 2). Each inductor has two radial lines formed by a central disc electrode and grounded toroidal screen disconnected on the internal diameter. The energy in the radial line is stored at their electric capacitance charging ~ 850 ns from five-cascade pulse voltage generators (PVG) produced using Arkadiev-Marx circuit. Into the accelerator structure there are included 72 PVGs, their total energy store being $\sim 1,5$ MJ. At closing the RL gap by controlled switches of trigatron type 3, located uniformly by azimuth, there are formed at the inductors output the pulses of accelerating voltage of alternate polarity. The acceleration of high-current electron beam takes place within the first voltage pulse $\sim 0,8$ MV/block amplitude and 30 ns duration at

half-height. To switch all radial lines there are used 2432 switches turned on with nanosecond accuracy according to the prescribed time program.

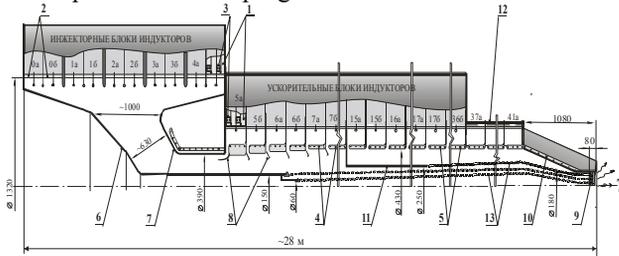


Fig. 2. Configuration of LIU-30 accelerating channel with additional cathode and focusing system, where 1 – radial lines; 2 – accelerating tube; 3 - switches; 4 – drift tubes; 5 – solenoid coils; 6 – basic two-emitter cathode; 7 – anode electrode of injector blocks; 8 - annular protective diaphragm; 9 – multilayered target; 10 – focusing system; 11 – additional (second) cathode; 12 – transportation channel; 13 – high-current electron coaxial beams; 0a, 0b, 1a ... 36b – numbers of injector and accelerating semi-blocks.

The voltage of each two inductors is concentrated in accelerating gaps formed by drift tubes 4. Inside the tubes there are placed solenoids 5 forming a magnetic field with induction ~ 0.5 T on the axis for the sake of stability and accelerating electron beam keeping from radial expansion. A 6-MJ capacitor bank serves as a source of magnetic field energy in the accelerator channel and output device.

The formation of hollow electron beam and its injection to the accelerating system is realized with the aid of a cylindrical foil-free magneto-insulated diode formed by cathode 6 and anode 7 summing up the voltage of four injector blocks of inductors. The beam increases energy when passing through 64 accelerating gaps and drifts to the distance of 4.2 m to target 9 of the output assembly or focusing section 10 (see Fig.2).

The LIU-30 facility uses the operation modes with the boundary energy of electrons equal to 4, 15, 25 and 40 MeV. The decrease of pulse duration is implemented through its front deceleration by intrinsic electromagnetic fields of the beam. At the accelerator output there are produced bremsstrahlung pulses of 4 ns duration at half-height while the bremsstrahlung dose is 1.5 kR at a 1 meter distance from the target and dose rate - $3 \cdot 10^{11}$ R/s.

With the aid of additional cathode 11 there is realized in accelerator LIU-30 the mode of two bremsstrahlung pulses formation per one startup of the facility. Fig.3 gives the configuration of accelerator tube with two cathodes. The diameters of emitting edges of the first cathode are 60 mm and 150 mm, while for the second cathode it is – 250 mm. In this case the dose of bremsstrahlung at a 1 meter distance from the target constitutes 300 R for the first pulse and 2.2 kR for the second one. The interval between the pulses can vary from 0.1 μ s to 1.5 μ s.

As a result of experimental researches in bremsstrahlung dose rate increase through beam compression at the output from the accelerator there are obtained:

maximal dose rate of bremsstrahlung $\sim 1.5 \cdot 10^{13}$ rad/s and dose ~ 240 krad (TLD) in a spot of ~ 100 cm² area and radiation pulse duration - 16 ns [8].

A pulsed reactor with metal core BR-1M (booster-reactor) is included to complex PUL'SAR [6, 7]. In a hall designed for joint operation with other facilities of complex PUL'SAR the center of BR-1M core can be arranged within the limits of 3 meters from the central axis of the hall (see Fig. 1).

At independent operation reactor BR-1M is placed in a hall with the following dimensions (14x10x8) m³. The object under testing can be arranged in any point of the hall as well as in a container of the central channel with the dimensions: $\varnothing 9.4 \times 30$ cm. The original design of the BR-1M core made it possible to achieve record parameters of fission pulse for fast pulsed nuclear reactors with metal core and essentially increase the resource of fuel elements what will give the possibility to use the facility within at least 25 years and realize all promising programs of researches.

Movable accelerators of electrons STRAUS-2 and ILTI-1 are aimed at simulating sequential in time effects of two or three pulses of NM gamma-radiation at their joint operation with accelerator LIU-30. Accelerator STRAUS -2 is created basing on a five-cascade double stepped line with water insulation the external diameter being equal to 1.3 m [9,10].

A small accelerator ARSA is aimed at simulating the effect of pulsed gamma-radiation on semiconductor devices and electronics; it also can operate jointly with other facilities of the complex.

The modes of joint functioning of the complex electro-physical facilities make it possible to form the required fields of loading on separate devices of large objects to study the functioning of protective systems and serviceability recovery of articles B and BT. At microsecond intervals between the radiation pulses of the facilities there can be provided the accuracy of LIU-30 synchronization with STRAUS-2 not worse than 10 ns, while with ILTI-1 ~ 50 ns.

IRRADIATION COMPLEX LIU-10M-GIR2

The irradiation complex LIU-10M-GIR2 was put into operation in 1994. It was created on the base of linear induction accelerator LIU-10M, pulsed nuclear reactor GIR2 and high-current pulsed electron accelerator STRAUS-2 that is also widely used for independent tests both in the mode of bremsstrahlung pulses generation and those with the use of electron beam put to the atmosphere. Into the complex there is also included a small pulsed accelerator of electrons ARSA. The chart of the complex facilities arrangement is presented in Fig.3, while the basic characteristics of the facilities are given in Table 2.

Accelerator LIU-30-10M [12] is produced on the base of the developed in VNIIEF stepped forming lines, the wave processes in which increase several times the output accelerating voltage as compared to the charging voltage of the line. The accelerating system consists of injector,

16 standard accelerating modules incorporating one inductor, electron beam transportation channel 4 meters long and output device with a target assembly. The dimensions of the accelerating system without the transportation channel are as follows $(12 \times 3.5 \times 2.4) \text{ m}^3$. The diameter of inductors is 1.1 m, the length – 0.58 m. The number of switches in the forming lines is 341. The maximal energy store in 18 Arkadiev-Marx generators is 184kJ. The acceleration and transportation of the beam is in the longitudinal guiding magnetic field with the induction of 0.5T. The energy store of the magnetic field capacitor bank is 0.65 MJ.

At joint operation of LIU-30 and STRAUS-2 accelerators with different time intervals the accuracy of synchronization constitutes $\pm 10 \text{ ns}$, ± 2 , ± 10 и $\pm 100 \text{ }\mu\text{s}$.

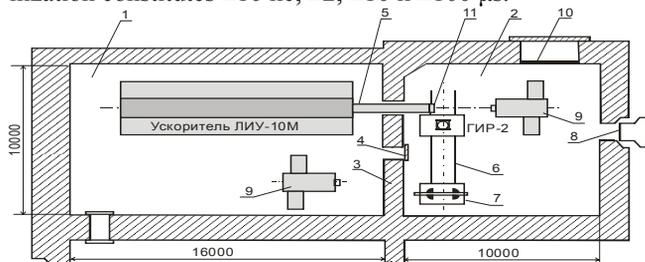


Fig. 3. Chart of LIU-10M-GIR2 complex facilities arrangement. 1,2 – accelerator and irradiation halls; 3 – protective wall; 4 – gate; 5 – beam transportation channel; 6 – reactor rail gage; 7 – core biological shielding; 8 – sliding hatch; 9 – two possible places of STRAUS-2 accelerator arrangement; 10 – gate opening; 11 – output device of LIU-10M.

Table 2. Irradiation complex LIU-10M-GIR2

Facility	Radiation characteristics
LIU-10M	$P_{bs}^{max} = 4 \cdot 10^{12} \text{ R/s}$ in $\varnothing 8 \text{ cm}$, $P_{bs}^{1m} = 4 \cdot 10^{10} \text{ R/s}$ in $\varnothing 55 \text{ cm}$, $E_{bound} \leq (20 \div 25) \text{ MeV}$, $\tau_{bs} = (10 \div 20) \text{ ns}$
GIR2	$\Phi_n^{max} = 10^{14} \text{ n/cm}^2$ in $\varnothing 30 \text{ cm}$, $\Phi_n^{1m} = 3 \cdot 10^{12} \text{ n/cm}^2$, $D_\gamma^{max} = 60 \text{ kR}$, $D_\gamma^{1m} = 3 \text{ kR}$, $W_0 = 7 \text{ MJ}$, $\tau \geq 300 \text{ }\mu\text{s}$
STRAUS-2	$P_{bs}^{max} = 10^{12} \text{ R/s}$ in $\varnothing 5 \text{ cm}$, $P_{bs}^{1m} = 10^9 \text{ R/s}$ in $\varnothing 80 \text{ cm}$, $E_{bound} = 3 \text{ MeV}$, $\tau_{bs} = (18-25) \text{ ns}$
ARSA	$P_{bs} = 3 \cdot 10^{10} \text{ R/s}$ in $\varnothing 10 \text{ mm}$, $E_{bound} \leq 1 \text{ MeV}$, $\tau = 10 \text{ ns}$

Reactor GIR2 (reactor gamma-source) is a pulsed reactor with metal core and neutron reflector (see Table 1). The irradiation process on GIR2 can be realized only inside the core in the hall with the following dimensions: $(10 \times 10 \times 8) \text{ m}^3$. The maximal fluence of neutrons with the energy of $> 0.1 \text{ MeV}$ beyond the “neutron window” is $1.1 \cdot 10^{14} \text{ n/cm}^2$, beyond the reflector – $1.5 \cdot 10^{13} \text{ n/cm}^2$. The dose of accompanying γ -radiation is 40 and 60 kR, correspondingly.

The use of booster mode of the complex operation makes it possible to generate 200-J fission pulses of GIR2, pulse width 1...2 μs and high – up to 10 pulses per session – pulse repetition rate.

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ELECTRON ACCELERATORS

The researches in radiation resistance are also performed in INRP on direct-action pulsed electron accelerators RIUS-5 and RIUS-3B [13].

To simulate the effects of gamma-radiation dose in armament and defense technology (A and DT) articles there are applied linear resonance accelerators of electrons LU-50, LU-10-20 and LU-7-2 [14, 15].

The characteristics of accelerator LU-50 are as follows: energy of accelerated electrons - 55 MeV; average current of electrons – 0.24 mA; pulse current – 10 A; average energy of bremsstrahlung quanta $\sim 6 \text{ MeV}$; pulse duration - 10 ns; bremsstrahlung exposure rate up to 3.3 kR/s at a distance of 1 meter from the target at the area $\varnothing 0.18 \text{ m}$ the heterogeneity being no worse than 30%. The average beam power is 10 kW.

The characteristics of accelerator LU-10-20 are as follows: regulated energy of accelerated electrons is $(5 \div 9) \text{ MeV}$; average current – 1.3 mA; pulse duration – 3.5 μs ; pulse repetition rate - $10 \div 1000 \text{ Hz}$; power of electron radiation absorbed dose near the output window – up to 5 Mrad/s; bremsstrahlung exposure rate at a 1 meter distance from the target at the area $\varnothing 0.2 \text{ m}$ the heterogeneity being no worse than 30% - up to 500 R/s. The average power of electron beam is 10 kW. The accelerator irradiates the objects with the dimensions up to $700 \times 750 \times 2000 \text{ mm}$.

The characteristics of accelerator LU-7-2 are as follows: energy of electrons is 6.5 MeV; pulse duration – 4.5 μs ; average power of electron beam – 2kW, average bremsstrahlung exposure rate – up to 250 R/s at the area of 800 cm^2 the heterogeneity being no worse than 30%; pulse repetition rate - 600 Hz.

In order to develop the stock of testing equipment in RFNC-VNIIEF there are carried out the works on the creation of a multi-terra-watt facility GAMMA aimed at producing high-power 2-MeV bremsstrahlung pulses at the area of up to 1 m^2 . It is assumed that the facility will consist of several 2-MeV modules [16].

As a result of computation and experimental works performed there was created and is now successfully functioning the first module of the facility – high-current pulsed accelerator of electrons – GAMMA-1 [1].

The STRAUS-R pulsed accelerator (overall dimensions $4.7 \times 2.2 \times 2.4 \text{ m}^3$) aimed at roentgenographic researches and operating in the mode of electron beam focusing on the target, refers to a series of accelerators on stepped lines [17]. It is also used to study radiation resistance in the mode of bremsstrahlung pulses generation: boundary energy of electrons – 3.5 MeV, pulse amplitude of beam current - 55 kA, current pulse duration at half-height - $60 \div 65 \text{ ns}$, bremsstrahlung dose on the output flange - 11 kR, while at a distance of 1 meter from the target - 36 R the diameter of irradiated spot being 9 and 100 cm, correspondingly, at bremsstrahlung pulse duration at half-height – $(45 \div 50) \text{ ns}$ [18].

PULSED NUCLEAR REACTORS

Today there are 6 pulsed nuclear reactors in INRP: BIR-2M, BR-1M, BR-K1, BIR-2M, GIR2, BGR [6,7]. Being different in design, fuel composition and basic parameters these facilities can be divided to three groups.

Into the first group there are included the reactors with metal core BIR-2M, BR-1M, BR-K1 and GIR2 that are characterized by short pulse and comparatively low energy release. The fuel of these reactors represents an alloy of highly enriched uranium with molybdenum; it has high strength properties and provides operability of the core

elements under pulsed heating followed by occurrence of considerable mechanical stresses.

To the second group there can be referred reactor VIR-2M which core represents solution of uranium salt in usual water.

The third group includes reactor BGR with the core of unique high-temperature ceramic fuel in the form of compressed homogeneous mixture of dioxide of highly enriched uranium and graphite

Basic pulse characteristics of the enlisted PNR are presented in Table 3.

Table 3. Characteristics of RFNC-VNIIEF pulsed nuclear reactors

Reactor	BIR-2M	BR-1M	BR-K1	GIR2	VIR-2M	BGR
Core material	U+6%Mo alloy	U+9%Mo alloy	U+9%Mo alloy	U+9%Mo alloy	UO ₂ SO ₄ +H ₂ O	UO ₂ +C ceramic
Fuel mass, kg	121	176	1511	178	7.1(104 l)	833
Core dimensions, cm	Ø22x21.7	Ø27x27	Ø62x75	Ø30	Ø55x63	Ø76x67
Irradiation cavity, mm	Ø40	Ø100	Ø308x360	-	Ø142, Ø300	Ø100
Energy release, MJ	3	11	30	7	60	280
Half-width, µs	55	53	1200	300	2600	2000
Φ, 10 ¹⁴ n/cm ² >0.1MeV in the cavity on the surface of the core	5 0.6	10 3.5	5.1	1	7 1	70 8
Dγ, 10 ³ Gy in the cavity on the core surface	1 0.06	2 0.5	0.65	0.6	5 0.5	30 2.4

The reactors are equipped with different experimental devices making it possible to change the relation of neutron and gamma components of ionizing radiation in order to extend the potentialities of methodology of armament and defense technology (A and DT) testing. Below is given a brief description of the specified reactors excluding those considered before – BR-1M and GIR2.

Reactor BIR-2M (fast pulsed reactor, modified) is a typical representative of PNRs with metal core. The core components are produced of alloy of highly enriched (85% by ²³⁵U) uranium with molybdenum (6 mass %). Initially the reactor (BIR-1) was put into operation in 1965. In 1970 the reactor was displaced to a special-purpose building, updated and called BIR-2. After its equipping with automated systems SUZ (System of Monitoring and Safety Provision) and IIS (Integrated Information System) on the base of mini-computer, the BIR-2M reactor was put into operation in 1991.

Reactor BIR-2M is a basic facility of the created in VNIIEF branch center of neutron measurements (OBNI). On the reactor there were obtained and certified the reference neutron field OP-2, neutron source OI-R-17 and source of thermal neutrons OI-T-22.

Reactor BR-K1 (booster reactor “Kaskad”, version 1) is a pulsed reactor with metal core. The core material is an alloy of enriched (36% by ²³⁵U) uranium with molybdenum (9 mass %). The reactor was put into operation in 1995 and represents a multi-purpose nuclear-physical facility aimed both at testing the elements of the conceptual project of two-section booster reactor “Kaskad” and at realizing different irradiation experiments.

The shape of reactor core represents a hollow cylinder with the following overall dimensions: length - 75 cm, external diameter – 62 cm. The size of the internal cavity is as follows: length - 36 cm, internal diameter– 30.8 cm. By analogy with reactor BR-1M, the core of reactor BR-K1 is of a circular structure: it is divided to discs (blocks) while the discs – to coaxial rings. The core blocks are put to a hermetic casing of stainless steel filled with helium. The distinguishing feature of reactor BR-K1 is a horizontal alignment of the core what ensures convenient loading of samples to the central cavity and considerable size of the cavity for irradiation.

Reactor VIR-2M (water pulsed reactor) is a pulsed reactor with a solution core using salt solution (uranyl sulphate) of highly enriched (90% by ²³⁵U) uranium in water as fuel. The volume of fuel solution is 104 l, uranium mass - ~ 7.1 kg. The fuel solution is filled up to a hard cylinder tight case of stainless steel (height - 2 m, Ø0.68 m, the wall thickness 65 mm). In the case bottom there is a hemispherical channel (PSK) its internal radius being 300 mm. The central channel (CC) with the internal diameter 142 mm and six channels for control rods (absorbing rods of lithium hydride) placed uniformly along the circumference 360mm in diameter are welded on the case head (cap).

As a rule, irradiation is realized in two experimental channels – central and PSK - as well as in any point of the bottom hall (10×10×2.5) m³ in the field of PSK radiation. The irradiated objects can also be placed into auxiliary experimental channels. The levels of reactor radiation in these channels are approximately 10 times lower than in

CC. The operation on static power up to tens of kilowatts is also possible. Reactor VIR-2M is fitted up with a shock table what makes it possible to simulate if necessary the effect of air-shock wave (ASW) with maximal overload 15 arbitrary units ~1s after n- γ -radiation pulse.

Reactor BGR (fast pulsed graphite reactor) put into operation in 1977 is a pulsed reactor with hard neutron spectrum most powerful in the world. It has got a shape of a hollow cylinder with the following dimensions by fuel: height - 67 cm, external diameter - 76 cm, internal diameter - 18 cm. The reactor core consists of elements which shape is similar to fuel rings of reactor BR-1M. The core is divided into 3 blocks: immobile block, block of coarse adjustment. A steel tube is used as a pulsed block. The core is put into a hermetic casing filled with helium.

Irradiation is possible in the central channel of the container (diameter - 10 cm, height - 550 cm) and outside the core in a hall with the following dimensions: $(11.5 \times 10 \times 8) \text{ m}^3$. Due to a high level of residual gamma-radiation the admittance to the hall is forbidden, thus, the irradiated objects are delivered to the core (from the opposite sides) remotely on the special trucks.

SUZ (System of Monitoring and Safety Provision) of the facility provides a means for generation in the automated mode of pulses on delayed neutrons of different shape including rectangular ones. This mode serves to simulate effects of NM radioactive products. The power in this case can vary from 0.5 до 500 MW, while duration - from 0.5 to 100 s.

The reactor is equipped with a pneumatic test-shock table UIS-5 what makes it possible to simulate the air shock wave as well as complex effect of ionizing radiation and air shock wave. The accelerated mass is up to 300 kg, overloads - up to 1500g, time of load ≥ 5 ms.

CONCLUSION

Today INRP RFNC-VNIIEF possesses a unique stock of electron accelerators and pulsed nuclear reactors as well as two special irradiation complexes to simulate under laboratory conditions the effects of NM penetrating radiation, power generating systems and space on the special-purpose objects. This ensures carrying out under laboratory conditions of system researches of В и BT standard objects radiation resistance against the effect of NM penetrating radiation. The works on keeping test and mastering new levels of effect are being constantly performed on the facilities. There are also carried out the works on creation of multi-terra-watt irradiation facility GAMMA.

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