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Historical Survey of Solid-Propellant Rocket Development in Russia

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Nomenclature

æ = Pobedonostsev's loading parameter, which prevented a sharp increase of pressure at the initial stage of motor operation caused by erosive burning (the ratio of the burning surface to the area for gas flows)
B = thermochemical constant
I = specific impulse
K = ratio of heat capacities: C_P (isobar) to C_V (isochoric)
M = Mach number
P = pressure
P_{chamber} = pressure in motor
P_α = pressure at motor exit section
R = gas constant
T_P = temperature of solid-propellant combustion products at constant pressure
U_T = solid-propellant combustion rate depending on pressure
α = inert to solid-propellant weight ratio
ρ_T = fuel density

I. Introduction

IT is very difficult to present the whole history of the development of Russian solid-propellant rockets in the 20th century within a short paper.

There are no detailed documents on this kind of work for the era of the 1920s. For the period from 1960 to 1990, a great number of rockets were designed for different purposes, developed, and put into service. Rocket manufacturing took place in secret defense plants and access to information on rocket manufacturing and testing was strictly limited. There were no detailed analyses of the matter presented in the mass media. Therefore, any detailed description of the development of guided and unguided solid-propellant rockets is very difficult. Some of the rockets that had successfully passed static and flight tests were never put into service and some were not even tested. There is no need to try to give a full description of each particular rocket in the present paper. It will be more reasonable to consider rockets with particularly innovative designs and those in which new scientific and engineering solutions were embodied, or those that were developed and adopted. Let us consider the characteristics of the rockets that have been adopted by the Russian military up to the present time.

II. Period Before 1945

The first Russian rocket establishment for the manufacture of dry-fuel rockets was founded in Moscow in 1680. Under the rule of the Emperor Peter the Great, in 1717, the Russian army added to its arsenal a flare rocket with a length of 25 mm and a firing altitude of more than 1 km. It was in use for more than 150 years.[1]

In the 19th century, there were rocket units in the Russian army. The source of gas and energy formation was black powder. Therefore, the power and accuracy characteristics of those rockets were not very good. When rifled artillery with smokeless powder rockets came into use, the rocket units were abolished.

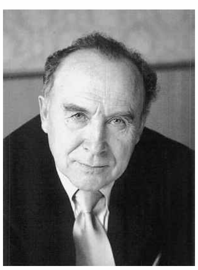
The idea of improving solid-propellant rocket design and function was, however, still alive. In 1881, N. I. Kibalchich (1853–1881) proposed a design of a guided solid-propellant rocket for atmospheric flights.

In 1912, I. V. Volovsky proposed a design of a system for salvo firing and obtained a patent. In the same year, Tikhomirov (1859–1930) (Fig. 1) proposed the design of a solid-propellant rocket-torpedo and obtained a patent. In 1915, Tikhomirov patented a jet aircraft. In the same year, I. P. Grave (1874–1960) developed and in 1916 tested pyroxylin unrestricted-burning grains with a diameter of 70 mm as a source of gas formation for a solid-propellant engine. However, the invention was not a success because after pressing and drying (to remove volatile alcohol–ether solvent–plasticizer) the grains became deformed and cracked.

In 1919, Tikhomirov addressed the head of the Russian government, V. I. Lenin (1870–1924), via the Executive Officer of the government of Russia, V. D. Bonch-Bruyevich (1873–1955), with a proposal to establish a state plant where his ideas could be realized. On 1 March 1921, in connection with that proposal, the first State Research and Experimental-Design Laboratory of the Military Department of Russia was established in Moscow. It was here that Tikhomirov's inventions[2] were developed.

In 1928, Tikhomirov's laboratory was given the name the Gasdynamics Laboratory (GDL). Tikhomirov was the head of the laboratory until the end of his life (1930). After Tikhomirov's death, B. S. Petropavlovsky (1898–1933) became the head of the GDL.

The laboratory remained in Moscow until 1925, when it was transferred to Leningrad. On 21 September 1933, in connection with the order of the Red Army Commander, Marshal M. N. Tukhachevsky (1893–1937), the laboratory was consolidated with a Moscow organization, the Jet Propulsion Study Group. Some time later, the State



Alexey M. Lipanov graduated from the Department of Physics, the University of Tomsk, in 1959; he received a candidate of technical sciences (1965) and a doctor of technical sciences (1970) degrees from Research Institute-125. In 1975 he became a professor in mechanics of liquid, gas and plasma from the U.S.S.R. Highest Examination Board. He worked at Research Institute-125 from 1959 to 1975. In 1975 he was appointed rector of the Mechanical Institute of Izhevsk and head of the Department of Aircraft Engines. In 1983 he was a deputy minister of the Ministry of Higher Education of Russia. He was elected a corresponding member of the U.S.S.R. Academy of Sciences in 1987 and in 2000 became an academician of the Russian Academy of Sciences. He is a recipient of the U.S.S.R. National Award (1985) and the RF Governmental Award (1999). He is currently the director of the Institute of Applied Mechanics and the chairman of the Presidium of the Udmurt Scientific Center and two dissertation boards. He is the author of 12 monographs and many articles.

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Table 1 Characteristics of warplanes of 1930s and the rocket shells they carried

Designation	Type	Service date	Chief designer	Maximum flight velocity, km/h	No. of shells	Rocket shell index
E-4	Fighter monoplane	1928	Sukhoi, Tupolev	268	6	RS-82
E-15	Fighter biplane	1934	Polikarpov	369	6	RS-82
E-16	Fighter monoplane	1934	Polikarpov	455	8	RS-82
E-153	Fighter biplane	1938	Polikarpov	446	8	RS-82
SB (ANT-40)	High performance bomber, monoplane	1934	Tupolev	420–520	10	RS-132
Il-2	Attack plane monoplane	1941	Ilyushin	453	8	RS-82 RS-132

Fig. 1 Photograph of N. I. Tikhomirov.

Jet Research Institute (JRI) was founded in Moscow. At present, it is the M. V. Keldysh Research Center. The first director of JRI was I. T. Kleimyonov (1898–1938). In October 1933, the JRI became a part of the Machine Building Ministry.[2]

Thus, the GDL had existed for 12 years as an independent research establishment. From the beginning, its activity was concentrated on the creation of rocket shells based on smokeless powder. By that time, there was significant scientific and technological experience in manufacturing pyropowders in Russia. The pyroxylin (highly flammable nitrocellulose) powders were manufactured at the Okhtinsky, Kazansky, Roshalsky, and Kotovsky plants. A Corresponding Member of the Russian Academy of Sciences, D. I. Mendeleev (1834–1907), and an engineer, P. M. Zakharov, introduced a new method for pyroxylin dehydration by use of spirits instead of through the use of heated air. This dehydration method, which appeared to be safer, was first introduced in Russia and was later used in other countries as well.[3]

A professor of the Mikhilovskaya Artillery Academy, S. A. Brouns (1863–1933), proposed the composition of pyroxylin powders based on nonvolatile (trinitrotoluol) solid solvent. This approach allowed the manufacture of powders with properties that remained stable during storage and burning and provided suitable duration and sizes of rocket shell charges. The optimized variant of this composition based on nonvolatile solvent [76% pyroxylin, 23.5% trinitrotoluol, 0.5% centralite (stabilizer)] was used at the Leningrad State Scientific and Technical Institute for manufacturing rocket grains ordered by the GDL. O. G. Fillipov (1877–1941), S. A. Serikov (1886–1937), M. Ye. Serebryakov (1891–1974), and D. A. Ventsel (1898–1965) were the developers of the composition used in production. This was the first widely used solid propellant for rocket motors in the world.

In March 1928, a successful firing of a pulse-rocket shell with a caliber of 82 mm and a charge of pyroxylin–trinitrotoluol powder (PTP) took place. The mortar-boosted rocket shells had an initial mass of 22 kg and an initial velocity of 62 m/s. Their range was 2500–2800 m at a firing angle of 45 deg. An analogous shell without a powder charge had an initial mass of 20.7 kg, and its range was 250 m, or a factor of 10 less. The effectiveness of the reactive force action was obvious.[2] A charge for the pulse-rocket shell was assembled from 28 similar grains with diameters of 24 mm. The pulse-rocket shell had four sections, and in each section, there were seven grains. The length of the pulse-rocket shell was about 230 mm, and the diameters of the grain channels were 6 mm. The charges were prepared by mold pressing, and their lengths could not be larger than their diameters by more than a factor of 2.5. Such was the semi-industrial technology used by I. I. Kulagin (1902–1996) in the GDL.

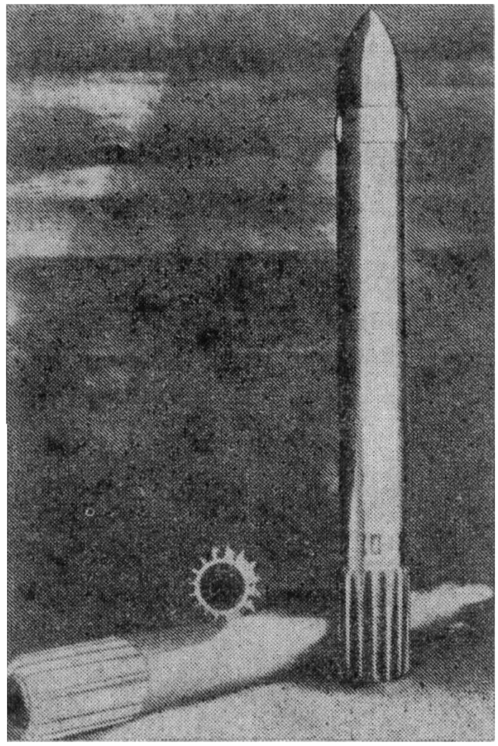

Fig. 2 Missile, 82 mm.

The pulse-rocket shells fired from the artillery gun were used under conditions different from those under which missiles were later launched, but the results were promising.

After 1930, rocket shells with PTP charges with calibers of 65, 82, 132, 185, 245, and 410 mm were under development at the GDL (rocket shells with calibers of 185, 245, and 410 mm presented by themselves turbojets without stabilizers). Strictly speaking, rocket shells of other calibers did not have salient stabilizers either, although they did have longitudinal grooves reminiscent of the lines on artillery shells created during passage through the barrel of the artillery gun mount (Fig. 2). The 410-mm missiles had a mass of 500 kg and a design range of 8 km.

In 1932, 82-mm rocket shells (RS-82) were air fired. For this purpose, an E-4 fighter was used. The layout of the E-4 fighter is shown in Fig. 3 (Ref. 4) [designed by P. O. Sukhoi (1895–1975) and A. N. Tupolev (1888–1972)]. The E-4 fighter had a flight speed of 268 km/h (Table 1). Rocket shells were packaged under the fighter wing on special launchers; there were three missiles on each side of the fighter body. A longitudinal section of the aviation RS-82 is shown in Fig. 4. Some characteristics of the 1932 RS-82 are given in Table 2.

In the middle of 1933, a worker at the GDL, engineer–pyrotechnist, V. A. Artemyev (1885–1962), proposed new designs for the RS-82 and RS-132, with fin assemblies: These fin assemblies went considerably beyond the overall envelope of the rocket shell. All subsequent unguided rocket shells were fin stabilized.

By autumn 1933, when the JRI was established, many of the rocket shell designs were completed and passed the official tests for ground, aircraft, and ship firing.[5] N. I. Tikhomirov, V. A. Artemyev, B. S. Petropavlovsky, G. Ye. Langemak (1898–1938), I. I. Kulagin, Yu. A. Pobedonostsev (1907–1973), F. N. Poida (1906–1979), and others made large contributions to the development of these rocket shells.

During the same period, along with ordnance rocket shells, leaflet, signal, and flare rockets were being developed at GDL, as well as a launch booster for aircrafts and engines for jet planes.

After JRI was founded, the development of rocket shells continued. It had become clear by that time that the further use of rocket shells with PTP charges was not possible due to the limitations connected with various design and technological parameters (size, power characteristics, and the national manufacturing capacity required to provide the army with the armament in the required amount). These were the reasons that caused the transition from PTP charges to nitroglycerine powder (N-powder) charges, which were proposed by V. A. Brouns in 1911–1912 (Ref. 3).

Brouns also developed the basic technologies for nitroglycerine powder manufacturing. His successor, A. S. Bakayev (1895–1977), proceeded with the development of the technology, which ultimately in 1943 (Refs. 3 and 6) allowed the introduction of a continuous process for the manufacture of N-powder: This took place in one of the laboratories at the Moscow Central Research Institute of Chemistry and Mechanics (CRICM), at that time Research Institute-6. The head of the laboratory was B. P. Fomin (1903–1981).

Table 2 Characteristics of the 1932 aviation RS-82

Characteristic	Value
Rocket shell mass, kg	5
Charge mass, kg	1.3
Rocket shell length, mm	500–600
Charge length, mm	230
Thrust, kg	450
Duration, s	2.5
Flying range, km	5

In 1933, Bakayev proposed the use of N-powder for RS-82 and RS-132 rocket shells. N-powder had better power characteristics than PTP. As a result, it became possible to manufacture grains with the required diameters and lengths, and the manufacturing was performed on a larger scale. Some comparative characteristics of the PTPs and N-powders are given in Table 3.

N-powder had the following composition: colloxylin 57%, nitroglycerine 28%, dinitrotoluene 11%, centralite 3%, and vaseline 1%. Bakayev's proposal was accepted, and by 1935 at the plant in Petrovsky, Voroshilovgradskaya oblast, the Ukraine, special facilities for N-powder production had been built. Manufacturing of charges with the required calibers had started. At the same time, N-powders were produced at the Shlisselburg plant near Leningrad and at the pilot plant of the Moscow CRICM. After the replacement of PTP charges by N-powder charges, Pobedonostsev, under the direction of Langemak at the JRI, conducted large-scale experimental investigations on the regularities of N-powder burning in the rocket chamber. The parameter æ, Pobedonostsev's loading parameter, which prevented a sharp increase in pressure caused by erosive burning in the initial stage of motor operation, was established later. The design parameters of a motor that used N-powder and was made for RS-82 and RS-132 were also determined.

As a result, in 1937, RS-82 and its aircraft launchers were adopted by the air force of the Red Army; E-15, E-16, E-153 airplanes and others were used as carriers.

The next year the army was equipped with RS-132 and launchers for it; the SB and Il-2 aircraft were used as carriers. Some characteristics of air-launched rocket shells are given in Table 4. The RS-132 and its schematic are shown in Fig. 5. The rocket shell shown in Fig. 5 has a three-section charge; this type of rocket shell is a transition between the rocket shells with the PTP multisectional charges and the ones with a single-section ballistite charge.

Several rocket shells were packaged on special launchers under the wings of aircraft. Various werplanes are shown in Figs. 6–10. There were an equal number of them on each side of the aircraft body. The number of rocket shells for each aircraft is shown in Table 1, which also shows the values for the maximum flight velocities of the planes.

In 1939, air-launched rocket shells and launchers were successfully used in operations against Japanese troops near the Khalkhin-Gall river (Mongolia). The Commander of the Soviet troops was G. K. Zhukov (1896–1974).

Table 3 Power and ballistic characteristics of PTP and ballistite N-powder

Fuel	ρ_T, kg/m^3	R, m/deg	K	B, K	I, s $P_{\mathrm{chamber}}/P_\alpha = 40/1$	T_P, K	$U_T = U_l$; P^υ, mm/s for pressure range ($P_{\min} - P_{\max}$)
PTP	1.6	32	1.25		180	1940	$U_l = 0.37$, $\upsilon = 0.6$ (30–70)
N	1.6	30	1.25	325	202	2330	$U_l = 0.37$, $\upsilon = 0.6$ (30–70)

Table 4 Characteristics of air-launched rocket shells (1938–1939)

Rocket shell	Rocket shell mass, kg	Charge mass, kg	Number of grains in charge	Outer diameter of a grain, mm	Internal diameter of a grain, mm	Grain length, mm	Flying range, km	Rocket shell length, mm	Effect produced on a target
RS-82	7.98	1.040	7	24	6	230	6.2	714	Fragmentation
RS-132	23	3.500	7	40	8	287	7.1	845	Fragmentation

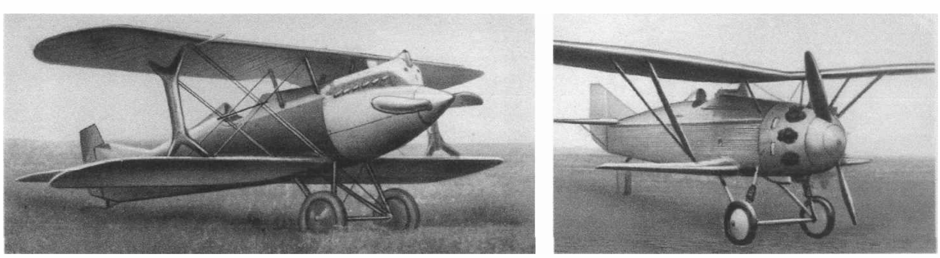

Fig. 3 Modification of the fighting machine E-4, designed by Sukhoi and created under the direction of Tupolev.

In 1938, the Chief Artillery Department of the Red Army ordered the JRI to design a missile for the army. However, it was not possible to attain an acceptable accuracy when firing separate unguided missiles. The way out of the situation was found when it was decided to design a multibarreled launcher, a missile system for salvo firing. This proposal was made by the Chief Engineer of the JRI A. G. Kostikov (1899–1950) (Fig. 11). The calculations were performed by engineer I. I. Gvai (1905–1960).

Simultaneously, a group of engineers including Pobedonostsev were developing engines for missiles for the army. The work was performed together with the laboratories of Bakayev and Fomin at CRICM, which was making powder and powder charges. Some characteristics of RS-132 are given in Table 5. As

Table 5 Characteristics of RS-132

Characteristic	Army RS-132(M-13)	Missile RS-132(M-13)	Prototype RS-132
Missile mass, kg	42.5	42	23
Charge mass, kg	7.05	7.2	3.8
No. of grains in charge	7		
Outer diameter of grain, mm	40		
Internal diameter of grain, mm	8		
Length of separate grain, mm	550		
Missile length, mm	1465	1400	840
Effect on target	Fragmentation		
Flying range, km	8.47	8.4	6.7
Explosive compound mass, kg		4.2	1.6

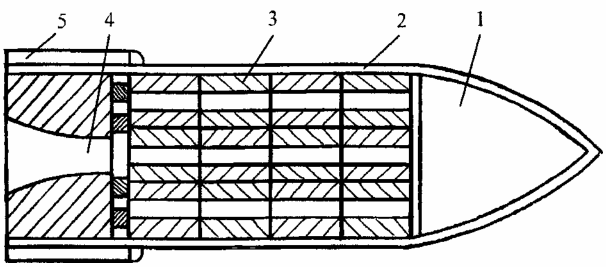

Fig. 4 Longitudinal section of RS-82: 1) destruct package, 2) wall of the engine body, 3) PTP charge (consisting of 28 unrestricted-burning grains, seven grains in a section, four sections, similar to that for the pulse-rocket shell with a caliber of 82 mm), 4) nozzle, and 5) buried fin.

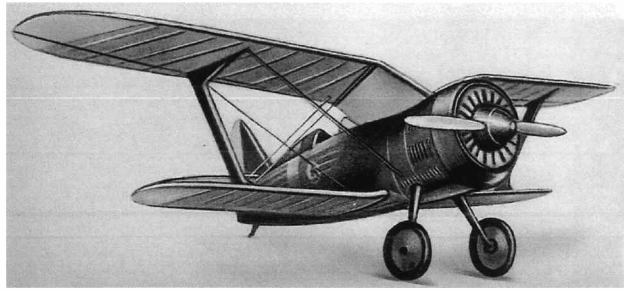

Fig. 6 Fighting machine E-15, designed by Polikarpov.

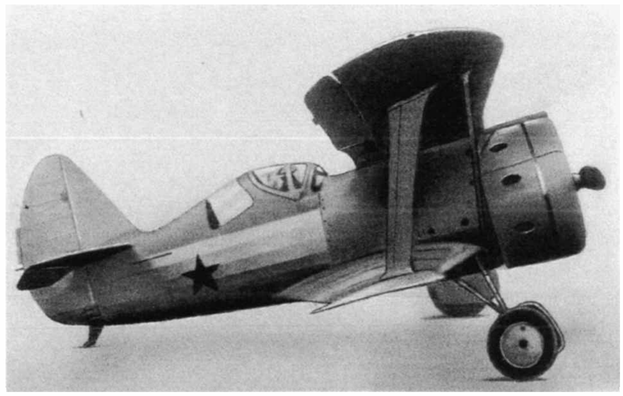

Fig. 7 Fighting machine E-16, designed by Polikarpov.

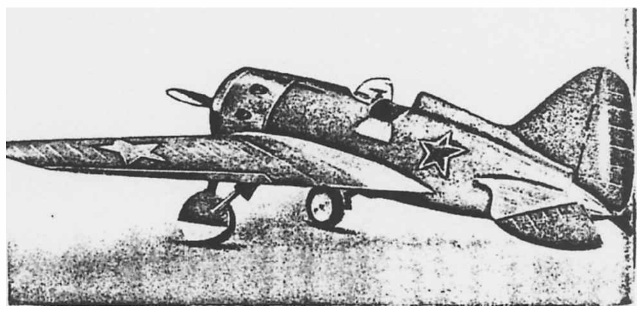

Fig. 8 Fighting machine E-153, designed by Polikarpov.

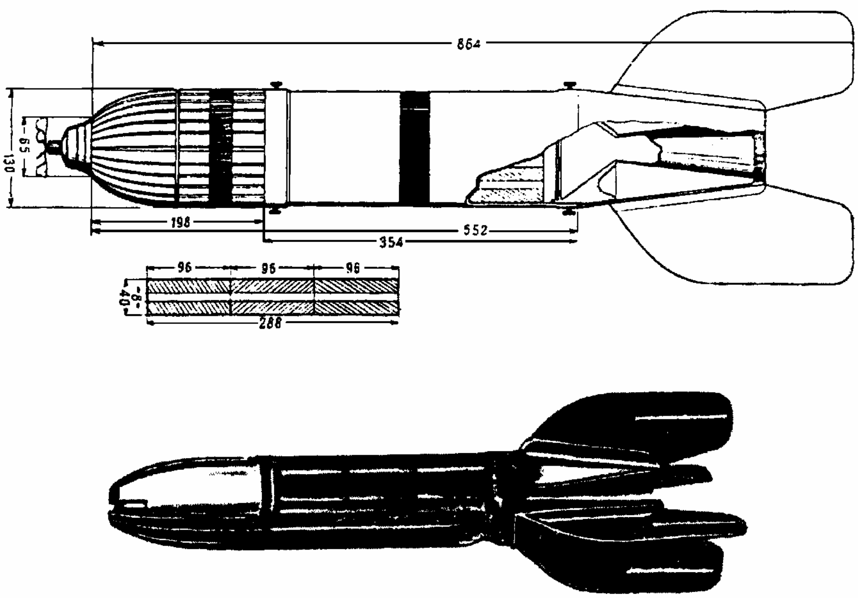

Fig. 5 Aviation missile RS-132, intended for hitting air and ground targets.

a result, early in 1939, after having considered the results of the firing tests, the State Commission signed a favorable report on the efficiency of the use of the missile system for salvo firing. A powerful high-explosive missile combined with salvo firing of about 16 missiles compensated, to a certain extent, for the low accuracy of individual missiles.

The operation of missile systems for salvo firing was demonstrated to representatives of the Ministry of Defense and the Industrial Ministry [S. K. Timoshenko (1895–1970), D. F. Ustinov (1908–1985), and K. Ye. Voroshilov (1881–1969)] on the polygon in the town of Krasnoarmeisk (Moskovskaya oblast) on 15–17 June 1941. On 21 June 1941, the decision was made to put these systems into service.

After 22 June 1941, field trials of the missile system for salvo firing were conducted at the front, on the order of I. V. Stalin (1879–1953). Firing was performed by the trial battery (the only one existing at that period) commanded by captain I. A. Flyorov (1905–1941). The intensive production of missile systems for salvo firing then began, and the Soviet Army adopted this new kind of weapon.

Noted that when World War II started, the plant in Petrovsky, Voroshilovgradskaya oblast, the Ukraine, where the N-powder charges were manufactured, was evacuated to the settlement of Dzerzhinsky, Luberetsky district, Moscovskaya oblast. The launcher manufacturing was transferred from the Voronezhsky plant Komintern to the Moscow plant Kompressor. As far as powder production was concerned, the situation was very complicated. The quantity of charges manufactured at the pilot plant, Research Institute-6, and at the Shlisselburg plant was far from sufficient to meet the needs of the front. Moreover, the Shlisselburg plant was blockaded on 8 September 1943.

Large-scale manufacturing of N-powders was planned to be in Perm, where construction of a powder plant was begun; it did not begin operation until 1943.

PTP charges had already been used experimentally, but, unfortunately, they were produced in Leningrad, which appeared to be in the zone of action of the front. It was at that time that the engineer N. P. Putimtsev (Special Technological Bureau-40, the city of Kazan) proposed to produce pyroxylin powders at the Kazansky powder plant; in the meantime, the facilities for manufacturing the N-powders would be put into operation in Perm. Putimtsev successfully fulfilled the task, and in December 1941, the production of pyroxylin-saltpeter powders (pyroxylin, potassium saltpeter, rosin, diphenylamine) started in Special Technological Bureau-40 and at the powder plant in Kazan. Scientists from Research Institute-6 and the JRI (Moscow) took part in fulfilling the task together with the engineers from Special Technological Bureau-40. Great assistance to Putimtsev was given by, B. P. Zhukov (1912–1999), G. N. Sudakova, N. A. Kuzmin (1912–1945) (Research Institute-6), V. V. Shnegas (1876–1943), I. M. Silayev, O. P. Mikhilusov (Special Technological Bureau-40); and Poida (JRI).

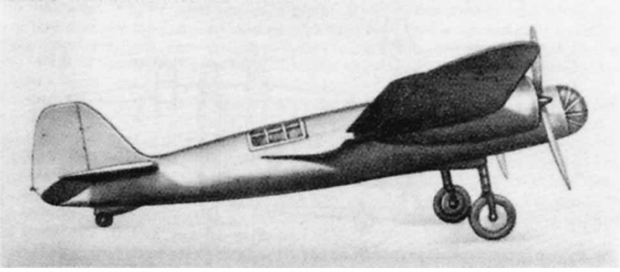

Fig. 9a High-speed bomber with the engine right Cyclone.

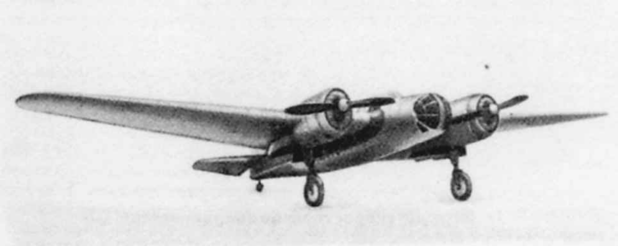

Fig. 9b Spain-Suiz 12 Y.

Fig. 11 Photograph of A. G. Kostikov.

Fig. 10 Attack plane Il-2, returning with the damage, received in an air battle World War II.

Table 6 Characteristics of missiles in service 1941–1945

Data	Missile						
	M-8	M-13	M-20	M-31	M-13DD	M-13IA	M-31IA
Caliber, mm	82	132	132	300	132	132	300
Length, mm	1090	1465	2090	1760	2210	1415	1760
Mass, kg	13.3	42.5	57.6	92.4	62.7	42.5	92.4
Destruct package mass, kg	5.4	21.3	21.3	52.4	21.3	21.3	52.4
Flight range, km	8.5	8.47	5.05	4.3	11.8	7.9	4.0

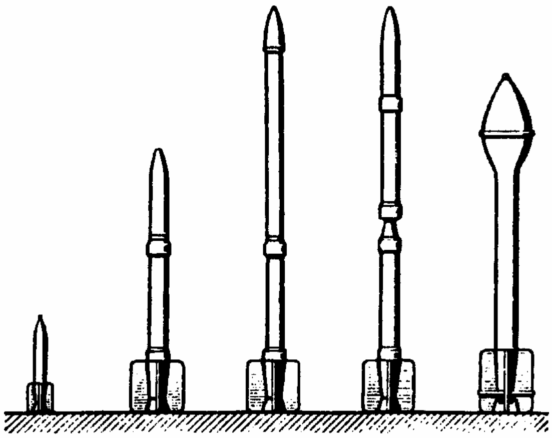

Fig. 12 Missiles in Soviet army service during the period of World War II.

After the beginning of World War II in connection with decisions by the Soviet Government, many scientists from the Academy of Sciences and institutions of higher education were recruited to work on the improvement and design of missiles. Academician Ya. B. Zeldovich (1914–1987) of the Institute of Chemical Physics under the direction of academician N. N. Semenov formulated the theory of the processes accompanying powder burning. He produced an analytical expression for the burning rate of powder at steady-state conditions. He also qualitatively explained the phenomenon of erosive powder burning. O. I. Leipunsky (1910–1989) discovered experimentally the phenomenon of erosive burning. Leipunsky developed an approximate formula for the erosion coefficient calculation in dependence on the value of the flow velocity of the combustion products of powder burning in the channel of a charge. To calculate pressure, the hypothesis of averaging the parameters was used in accordance with the laws of mass and energy conservation. The powder-burning rate was considered to be a function of the pressure of the products of combustion and the charge temperature. To express the burning rate, the erosion coefficient was used as a multiplier. The expression is called Bory's formula (1922, France).

During the war a large number of new missile systems for salvo firing were developed for the army, air force, and naval forces. Characteristics of some of the missiles are given in Table 6.

As can be seen from Table 6, the M-8 missiles and M-13 missiles developed by 1941 had a range of 8.5 km and charge masses of to 5.4 and 21.3 kg, respectively. The M-20 missile using pyroxylin–saltpeter powder (manufactured until 1943), and a warhead mass similar to that of the M-13 missile had much a smaller range. At the same time, the initial mass of the M-20 missile was larger than that of the M-13 missile. Improved accuracy (IA) missiles spun in flight with a small angular velocity; therefore, their range was about 7% less than that of nonspinning missiles. Their accuracy, on the other hand, was twice as good. The spinning of the missiles was produced by their rotation as they moved along the guides.

The long-range M-13DD missile had a range of 11.8 km, and its warhead had the same mass as the M-13 missile, that is, 21.3 kg. The already mentioned missiles were not too cumbersome, and during loading they could be lifted by two soldiers. Missiles for the years 1941–1945 are shown in Fig. 12.

Table 7 Institutions, types of missiles and propellants, military branches, and time needed for missile development

Institutions	Years of development	Missiles	Propellants	Military branches
GDL, SIAC	1928	Pulse-RS-82	PTP	Army
GDL, SIAC	1933	RS-82	PTP	Air Force
		RS-132		Air Force
JRI, CRICM	1937	RS-82	N	Air Force
	1938	RS-132	N	Air Force
JRI, CRICM, Special Technological Bureau (STB)	1941	RS -132	N[a]	Army
JRI, CRICM, Institute of Chemical Physics AS USSR (ICP ASUSSR), (STB)	1941–1945	RS-82	N	Army
		RS-300		Air Force
		RS-300 UK		Navy

[a]From 1941 until 1943 pyroxylin–saltpeter powder made by Putimtsev and Zhukov was used with N-propellant.

In summary, Table 7 gives information on the institutions and establishments participating in the creation of various missiles and propellants, the time of development of the missiles, and the military branches adopting the missiles.

III. Creation of Strategic Solid-Propellant Missiles in Russia After World War II

After World War II, the development of rocketry entered a new phase as a result of the serious competition between the liquid-fueled rockets in the former Soviet Union and the solid-fueled rockets in the United States. In fact, the GDL, under the direction of V. P. Glushko, has been developing liquid-propellant rocket engines since 1929. The work continued until the war and then after the war at JRI. In the postwar period, the investigative and experimental-design work on liquid-fuel engine improvement was conducted on a significantly larger scale. Several new design offices and research institutes were established for the development of liquid-fuel engines and missiles. The liquid-fueled missiles were given first priority because they were superior to solid-propellant missiles in thrust, controllability, and accuracy.

By 1957 a two-stage intercontinental ballistic missile (ICBM), the R-7 (SS-6 Sapwood by NATO classification) with a liquid-fuel engine was developed and launched [chief designer, S. P. Korolev (Fig. 13)]. Under the direction of academician Korolev, the space program was successfully initiated using his liquid-fueled rocket engines. The design offices, directed by academicians M. K. Yangel (1911–1971), V. N. Chelomey (1914–1984), V. P. Makeev (1924–1985), and others, simultaneously worked on the creation of liquid-fueled missiles for various purposes. All of the strategic missiles of the 1950s were liquid fueled.

Solid-propellant missiles had their own advantages, however: simplicity in design and operation, launch readiness, good operational characteristics, and better possibilities for the creation of mobile systems. Additionally, in 1951, a guided solid-propellant missile Polaris was adopted in the United States. Because of this, the Soviet scientists had to develop solid propellants with a higher power-producing capability than the N-propellants. They had to learn how to make motors of various sizes, to improve the design of

Fig. 13 Photograph of S. P. Korolev.

Fig. 14 Photograph of R. Ye. Sorkin.

solid-propellant missiles, to learn how to control the flight characteristics of solid-propellant missiles, to decrease the internal ballistic and power parameter spread for the motors, to provide them with 10–15 years of active life, and so on. These were the main problems the Russian scientists were trying to solve during that period; it was not possible to overcome the general distrust of solid-propellant missiles without resolving these issues.

A. First Strategic Guided Solid-Propellant Missiles

In the 1950s, there was no concrete information on the maximum possibilities of the ballistite propellants in Russia. In particular, almost nothing was known about the possible maximum charge caliber, the weaker pressure and temperature dependence of the ballistite propellant burning rate, and various other important parameters. There were also no generalized theoretical investigations underway that would allow setting the requirements for the values of the propellant specific impulse, the coefficient of an inert-to-propellant weight ratio of motors (the ratio of the mass of a motor without charge to the mass of the charge placed into the motor), and operational times. Such an analysis was done later, in the late 1950s and early 1960s. At the end of 1950s, the supporters of the ballistite propellants insisted on expediency in using these kinds of fuels. It was the ballistite propellant RST-4K that was used when the first guided ballistic solid-propellant missile, RT-1, was developed in the Special DO-1 (chief designer, Korolev and deputy chief responsible for the RT-1 missile development, I. N. Sadovsky).[7,8]

The work was being performed together with the Research Institute-125 (Director, B. P. Zhukov and development and experimental-design work by Pobedonostsev).

The developmental design work showed that in using grains with sizes of 0.6, 0.7, and 0.8 m for the third, second, and first stages, respectively, and a cluster of four engines on each stage, it was possible to make a missile using RST-4K propellant with a range of 200–2500 km and a payload weight of 800 kg.

At the end of 1958, the Soviet government approved this project, and in December 1959, the government passed a resolution obliging Special DO-1, together with the related institutions, to develop such a missile. In all stages of this missile, motors with cartridge-loaded charges with armored outer surfaces and a stagnation zone were used. Restricted extruded grains were made with four longitudinal slits milled in the forward end. As a result, the propellant burned on the side of the channel and on the lateral surfaces of the slits, providing the dependence of the burning surface on the magnitude of the burned dome, which was close to constant. The engine shells were made out of glass-reinforced plastic, and the bases were removable and made out of steel. The nozzles were made out of a titanium alloy with a sputter coating of Al_2O_3 on the inlet and exit cone. The flight-weight motors had ratios of inert-to-propellant weight fractions α equal to 0.19, 0.26, and 0.39 for the first, second, and third stages, respectively. Note that the missiles of the World War II period had $\alpha \simeq 2$, that is, each kilogram of propellant carried 2 kg of the inert mass of an engine. These design innovations led to the development of missiles that had an inert-to-propellant weight ratio five times better than that of missiles of the war period, despite the use of the same types of propellants.

On 28 April 1962, the first launch of an RT-1 missile was performed on the launch pad at Kapustin Yar, Astrakhanskaya oblast, and in June 1963, the flight tests were completed. The flight tests confirmed that the missile met the main requirements. The missile was built, but it was not added to the Army's arsenal.

At this time, the applied chemists had not been successful in designing a motor grain with a diameter of 1 m using ballistite propellant. The ballistite propellant of that period had low performance. It became clear that it would not be possible to make large rockets based on ballistite propellant. Later, ballistite propellants were used for small missiles, solid-propellant hot-gas generators, boosters for larger missiles, and other purposes, but never for strategic missiles.

In 1960, Professor Sorkin (1910–1983, Fig. 14) at Research Institute-125 solved the problem of optimizing the design of solid-propellant ballistic missiles.

Based on Sorkin's method, the author, together with A. M. Gorodetskaya, performed systematic theoretical studies on the dependence of the missile range on the following parameters: the payload, the inert-to-propellant weight ratio of engines, specific impulse, number of stages, and initial mass of a missile. By the end of 1960, this work had been accomplished, and the results were reported to the government via the Director of Research Institute-125, B. P. Zhukov.

Since 1958 (Ref. 7) the formulation chemists in the city of Bisk, directed by the Head of the Institute, Ya. F. Savchenko (1913–1984), and his Associate Administrator (later Academician of the Academy of Sciences of the Union of Soviet Socialist Republics), G. V. Sakovich, had conducted work on the creation of composite solid propellants (CSP) using butyl rubber as a binder. It had been shown that this was the way to create case-bonded charges, which could be obtained by pressure casting the propellant into a motor case with subsequent polymerization.

The specific impulse under standard conditions was raised to 233–235 kgf · s/kg, and the admissible deformation of the propellant in the channel reached 50%. It was clear that using this type of propellant would make it possible to develop an ICBM with a range of about 10,000 km and a much better inert-to-propellant weight ratio as compared to the RT-1 missile.

On 4 April 1961, before the RT-1 missile flight tests started in the summer of 1961, the government passed a resolution on the development of the RT-2 missile. Korolev was the initiator of this decision. This missile was a three-stage design. The first stage was 1.8 m in diameter and had a charge mass of 34.5 tons, thrust of

91 tons, and flight duration of 75 s. The second stage was 1.5 m in diameter, had a mass of 12 tons, thrust of about 44.0 tons, and duration of 80 s. The third stage was 1 m in diameter, had a mass of 3.5 tons, and duration of 65 s.

The Special DO-1 under the direction of academician Korolev, appointed as the chief designer, was the main executor of the governmental order. At that time, the Special DO-1 was a department of the General Machine Building Ministry. The Ministry of Defense also received an order, under a government resolution of 5 September 1962, to develop the operational–tactical missile 9M76 with a range of 1000 km as a part of the system TEMP-S (SS-12 according to NATO classification).[8] The Moscow Institute of Heat Engineering was in charge of developing this missile. The Chief Designer was A. D. Nadiradze (later an academician) (1914–1987, Fig. 15). This was a two-stage missile with cartridge-loaded charges with a stagnation zone. It used a composite propellant based on polyurethane and ammonium perchlorate oxidizer with a specific impulse of 242.8 s under standard conditions. The inventors of the formulation were G. V. Kalabukhov, H. N. Moskvinov, and V. M. Sidorov. It should be noted that Kalabukhov was one of the initiators of the creation of composite solid propellants in Russia. He began his work in the development of composite solid propellants in 1947. The propellant for the missile 9M76 and the technology for its manufacture were developed at Research Institute-125. This institute was also responsible for making the cases of both stages; the nozzle block (consisting of four nozzles) was made at the Moscow Institute of Thermal Engineering.

Fig. 15 Photograph of A. D. Nadiradze.

The engine shells were made of glass-reinforced plastic; bases were removable and made of steel. Flight control was performed by the injection of the combustion products of the CSP into the area behind the nozzle exit sections with the help of deflectors. This caused considerable loss in specific impulse, but made it possible to control pitch, yaw, and bank. The charges had inhibited outer surfaces and burned in the port and on the ends. On the ends (the front and the nozzle ones), there were conic grooves for regulating the changes of the burning surface area as a function of the magnitude of the burned dome. To solve the problem, small parts of the outer surface of the charge on the front ends were left uncoated. Flight tests of the 9M76 missile were performed on the launch pad at Kapustin Yar, and the RT-2 missile was tested on the northern pad, Arkhangelskaya oblast. The work on these missiles started almost simultaneously and was finished at the same time.

In 1967, as a part of the TEMP-S system the 9M76 missile (Fig. 16) was added to the arsenal of the Strategic Missile Forces and was later put into army service. In 1968, the Strategic Missile Forces adopted the RT-2 ICBM (Fig. 17). Note that the 9M76 missile was carried by a fighting vehicle, (mobile launcher), like the

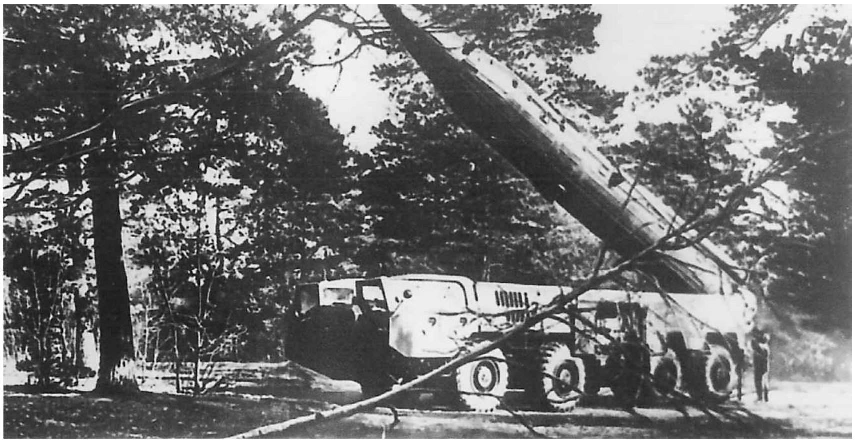

Fig. 16 TEMP-S rocket system with 9M76 rocket in transport-launcher container.

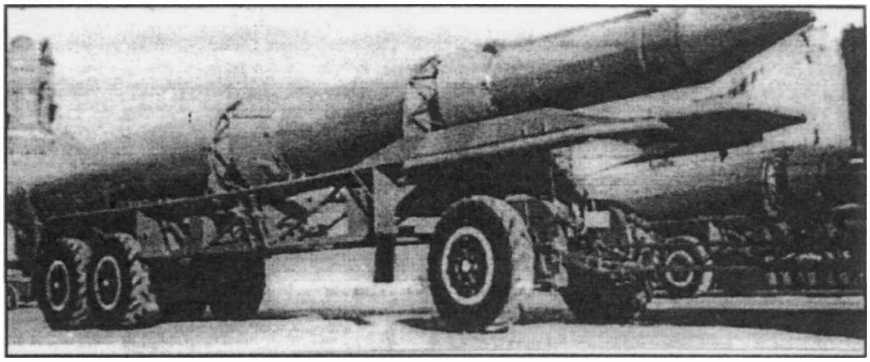

Fig. 17 RT-2 missile on parade in Moscow.

missiles used during World War II. It was launched from a special pallet, which was also carried by a fighting vehicle, together with a container, in which the missile was placed. The RT-2 missile was silo launched.

After the 9M76 missile was adopted, academician Nadiradze applied to the government of the Union of Soviet Socialist Republics with a proposal to develop an ICBM, which would have a mobile launcher similar to the 9M76 missile. At that time, the Soviet Army did not have in its arsenal a solid-propellant missile of this type with a mobile launcher. Nadiradze's proposal was accepted, and on 6 March 1966, the government passed the resolution on the development of an ICBM-15Zh42 as a part of the mobile land rocket TEMP 2S system.[8]

Previous experience allowed many technological innovations during the development of this new missile. First, for all three stages, single-nozzle propulsion systems with charges, tightly case bonded to the shells of the motor cases, were used. The nozzles were submerged into the engine. During the second and third stages of ICBM-15Zh42 flight, the control over pitch and yaw was performed by the injection of chamber gas into the nozzle exit cone. The gaseous products of combustion came from a special gas-generator placed in the described nozzle part of the internal volume of the motor. The charges for these gas generators were made of the propellant, which did not contain metal. The internal volume of the gas generator gas-dynamically communicated with the rest of the internal volume of the motor. The level of pressure in it exceeded the pressure in the main volume of the motor. This prevented the penetration of condensed particles of aluminum oxide into the effectors controlling missile flight.

The combustion products of the gas generator had lower temperatures than those of the main charges of the motor. Their influx into the main volume created a wall screen, which enhanced the efficiency of the submerged nozzle in the motor. The author participated in the analysis of the ablation of the material of the walls of the motor nozzles after static fire tests with the use of the gas generator and without it. In all of the cases, the material ablation from the nozzle walls was smaller when the gas generator was used.

On the first stage, jetavators were used for control over all channels. For stabilizing the missile in flight and creating additional controls, a cribrate stabilizer and a cribrate jetavator were used. The charges for all stages of the missile were axisymmetric and made from a composite propellant based on polybutadiene rubber as a binder and ammonium perchlorate as an oxidizer and were filled with aluminum.

Design and technological innovations allowed increasing the loading density of the engines to 0.92 and operating at an inert-to-propellant weight ratio equal to about 0.08. The value of the specific impulse at standard conditions was 256 kgf · s/kg. The initial mass of the missile was 41.5–44.2 tons. The propellant masses of the first, second, and third stages were 24.2, 7.6, and 3.5 tons, respectively. The Moscow Institute of Thermal Engineering was responsible for the general development of the missile and nozzle assemblies, as it was in the case of the 9M76 missile. Research Institute-125 was responsible for manufacturing the motor cases and case-bonded grains.

Other related establishments developed the thrust vector control system, ignition system, a container, a fighting vehicle, and other components for the 15Zh42 missile. The motor did not contain any metallic elements. Flight tests of the missile were conducted on the northern launch pad at Arkhangelskaya oblast. By the end of 1974, flight testing was finished, and the missile was added to the arsenal of the Strategic Missile Forces. In general, there were 35 launches. A schematic view of the missile is given in Fig. 18 (Ref. 8).

Note that the period of the development of the 9M76, RT-2, and 15Zh42 missiles was a period of intensive studies in a number of related areas. Without these studies, the experimental-design work described here would not have been possible. Studies were conducted on, among other things, 1) the physical–chemical processes in motors, under the conditions of ablation of heat-reflecting coats and solid-propellant burning; 2) the development of new, improved solid propellants; 3) providing the manufacturers of the solid propellants with raw materials and manufacturing facilities; 4) the development of new types of structural materials; and 5) solving the problems of controllability,Let us briefly consider the Russian work on the listed problems.

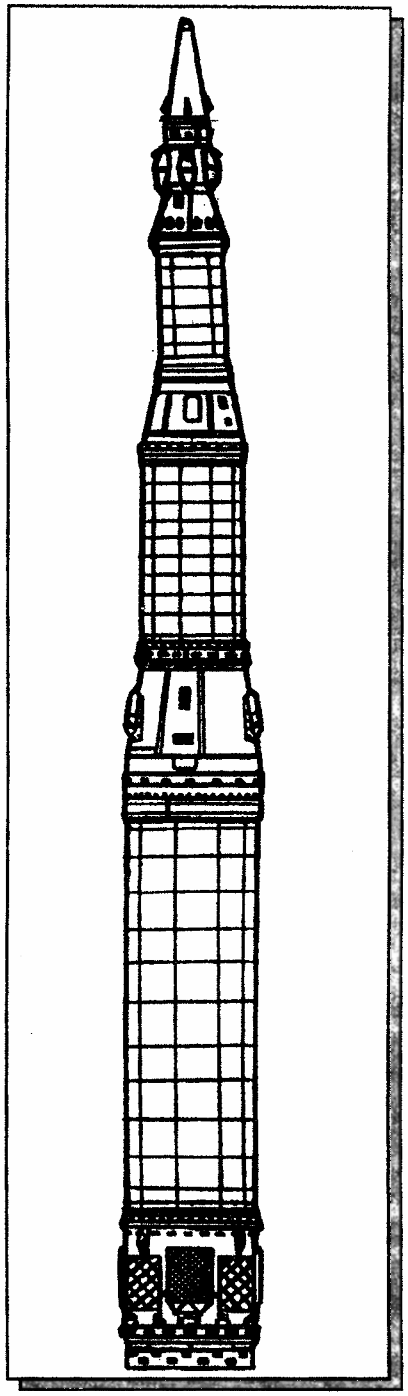

Fig. 18 TEMP-2S, 15Zh42 missile.

B. Development of Theoretical Understanding of Intrachamber Processes

Here, the term intrachamber processes will refer to the processes in the free volume of a motor and in a nozzle, the processes taking place in the presence of solid-propellant burning and ablation of heat-reflecting materials, and the processes of deformation of a motor body and charge. The list of the investigation trends is rather long, and the media are very different. Therefore, initially the methods of the description of the processes were simple. After a certain amount of experience had been accumulated and more powerful computational means had been developed, they became more sophisticated.

At Research Institute-125, work was conducted under the direction of R. Ye. Sorkin. The author was one of the developers of the mathematical models of the flow of the combustion products in the free volume of the combustion chamber and in the nozzle. Models of the processes were investigated thoroughly using the following assumptions.

The first assumption is averaging, which is acceptable for quasi-stationary periods of solid-propellant motors in the absence of erosive burning.

The second assumption is one-dimensional nonviscous movement. With nonerosive burning and given data on heat exchange, this is one of the simplest and most effective approaches for the investigation of wave processes, nonuniform heating of the burning surface of the charge, and gradual initiation of its combustion including stagnation zones; in the mode of quasi-stationary operation, this approach allows determination of pressure changes affecting the charge.

The third assumption is two-dimensional and three-dimensional nonviscous movement. In conjunction with one-dimensional movement they allow calculation of the precipitation of the condensed particles on the heated surface of the charge and permit more accurate calculation of the process of initiation of combustion and the beginning of the quasi-stationary operation mode.

The fourth assumption is three-dimensional nonuniform viscous movement (with the help of the hypotheses of Reynolds and Boussinesq), which permits development of detailed model of the heterogeneous flows, including the burning out of particles of aluminum (in the general case, the burning out of agglomerates), possible erosive burning, the size distribution of the condensed particles and their distribution over the free volume of the engine, and other processes and phenomena. Viscous heterogeneous flows give a detailed picture of the processes at the initial and quasi-stationary periods of the operation of the engine.

The last assumption is three-dimensional homogeneous flows. If such a flow takes place in addition to heterogeneous flows, then it is possible to obtain acoustic phenomena, oscillating processes, and self-oscillating burning in the presence of solid-propellant burning and to study the process of oscillation into the environment, etc.

Modeling and investigating the processes in the free volume of a motor were performed by scientists at other institutions as well (V. V. Vilunov, I. M. Vasenin, A. A. Shishkov, B. G. Yerokhin, A. N. Kriyko, L. Ye. Sternin, A. A. Shriber, U. G. Pirumov, A. P. Tishin, and others).

In other scientific research institutes, such as the Institute of Chemical Physics of the Academy of Sciences of USSR (Zeldovich, Leypunnsky, B. V. Novozhilov, Yu. V. Frolov, A. D. Margolin, and others) and the Leningrad Military-Mechanical Institute (G. G. Shelukhinn, O. Ya. Romanov), the processes of the active burning of solid propellants were studied. The modeling of the burning processes has been studied for many years, and it is still far from being complete. Initially, double-base homogenous propellants were studied. Academician Zeldovich obtained the expression for the stationary burning rate and studied the modes of nonstationary burn-out at constant temperature of the surface of burning. Novozhilov applied this approach to the nonstationary modes of burning at variable temperature of the surface of burning. Sorkin combined Zeldovich–Novozhilov models of burning of solid propellant with the processes in the free volume of the engine. Recently, V. A. Babuk experimentally studied the burning processes of composite propellants containing perchlorate, and V. I. Kodolov and the author have developed a quantitative theory of solid-propellant burning. A large contribution was made by V. A. Kharitonov, V. M. Senyansky, V. I. Nickolaychik, V. D. Protasov, and others on the development of composite materials. A. T. Nikitin, Yu. V. Polezhayev, O. M. Alifanov, and others have performed mathematical simulations of insulation-related processes. The study of chemophysical processes in insulating coatings took place along with their production and testing. Two types of insulating coatings were designed: those capable of withstanding both intensive heat flows and erosive actions and those capable of withstanding only heat flows. In both cases, it was required that the insulating coatings have a minimum thickness. The developed mathematical models took into consideration the following factors: 1) endothermic processes during the heating of an insulating coating, 2) ablation of the coating as the result of heterogeneous chemical reactions, 3) process of carbonization decelerating the process of insulating coating ablation, and 4) possible phase transitions and anisotropy of properties of insulating coatings.

By the present time, a significant body of experience has been accumulated in modeling chemicophysical processes in insulating coatings and in the calculation of the deflected mode of the insulating coatings.

It is necessary to mention the scientists working in the field of accuracy, such as O. N. Ivanov, D. A. Bykov, and A. B. Kazachenko. Based on the assumption of the homogeneity of the properties of solid propellants, they have developed a set of models, including simple one-dimensional and complicated three-dimensional ones, which allows prediction with a good degree of probability of the stress-deformation processes in solid propellants during their use and storage, at the stage of their hardening and aging.

The mathematical models available at this time allow theoretical computation of turbulent flows of homogeneous media. By means of the Reynolds hypothesis, it is also possible to calculate, although with less accuracy, heterogenous flows, erosive burning, and the influence of the deflected mode on the interior ballistics processes. The mathematical simulation computes the deflected mode of a charge and the motor body, ablation of insulation in the chamber and nozzle, as well as solid propellant burning. This led to significant reductions in the scale of experimental verification at the stages of bench and flight testing, and the process of design and verification became scientifically justified and close to being optimal.

C. Creation of New Types of Solid Propellants and Manufacturing Facilities for Their Production

The creation of solid propellant was always a complicated and dangerous task. In the early days of the manufacture of ballistite propellants, containing such explosive substances as nitroglycerin and nitrocellulose, the greatest risk was explosion. Of course, it was the use of the explosive substances that allowed the production of increasingly powerful solid propellants. The same situation was observed later when composite propellants came into production.

In 1960s and 1970s considerable attention was paid to the investigation of the thermodynamic properties of these two types of solid propellants in the Soviet Union. If they had met requirements, samples of the propellants were used and investigated more thoroughly. Not only the theoretical determination of the expected performance characteristics of the developed propellant was important; no less important was the determination of the pressure dependence of its burning rate, its explosive risk when in use, its aging during storage, its physical–mechanical characteristics, etc. Unfortunately, most of these parameters can be determined only experimentally. This makes the process of verifying new compounds and correcting their properties rather complicated. However, accumulated experience allowed the creation of a large set of propellants that met the requirements of the rocket programs.

Such establishments as Research Institute-125, the State Institute of the Applied Chemistry (SIAC), the Altaisky Research Institute of Chemical Technologies, the Permsky Research Institute of Chemical Products, the CRICM, the Institute of Organic Chemistry of the Academy of Sciences of the Union of Soviet Socialist Republics, the Leningrad and Moscow Chemical–Technological Institutes and many other research establishments dealing with chemical studies contributed to the creation of new solid propellants.[9,10] Most of them carried out studies only on the properties of individual components of the propellants and were not involved in the creation of propellants in general.

Initially the composite propellants were manufactured based on butyl rubber with $J = 235$ kgf $\cdot$ s/kg when the motor chamber pressure is 4 MPa and the pressure in the nozzle exit section equals 0.1 MPa (the standard condition accepted in the Soviet Union). The properties of the propellants were improved with time. At the same time, other properties met the requirements. In particular, burning rate dispersion both over the bulk of the large-tonnage charge and

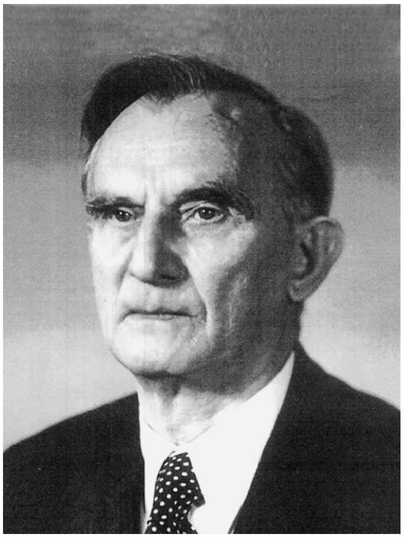

Fig. 19 Photograph of B. P. Zhukov.

at the transition from one charge to another was brought up to ±0.8. (This is the standard quadratic deviation.) The decrease in the value of the exponent in the expression for the burning rate of the propellant as a function of pressure made it possible to keep the pressure range in the motor close to the value mentioned earlier. The defects occurring in the processes of manufacturing charges and motors were almost excluded. Automated systems of control over the technological processes were widely used in the manufacturing of charges and engines.

A large contribution to the creation of new types of solid propellants was made by such enthusiasts, as B. P. Zhukov (Fig. 19) Kalabukhov, Savchenko (1913–1984), Sakovich, V. S. Shpak, V. A. Morozov (1933–1992), A. V. Marchenko (1932–1999), Z. P. Pak, E. L. Kazaryan (1929–1993), L. N. Kozlov, V. V. Moshev, and many others. New types of solid propellants were based on energetically more efficient components developed from those which were already known and those which were newly synthesized. Here we can name aluminum hydride (AlH_3) and (ammonium salt of dinitramide (ADND) $NH_4N(NO_2)_2$. The properties of each of these components were thoroughly studied; a safe means of obtaining and using them was found, including their use for solid-propellant production. Note that aluminum hydride is also used in nonsilver photography, in syntheses as a reducing agent, as the source of battery hydrogen, and for aluminizing the surfaces of materials. Any use of ADND other than for the production of rocket solid propellants is not yet known. However, in contrast to ammonium perchlorate, its use allows the production of ecologically clean solid propellants, due to the absence of hydrogen chloride in the combustion products. In comparison with the solid propellants based on ammonium perchlorate, the use of ADND propellants increases specific impulse of the solid-propellant rocket engine by 10 kgf · s/kg, and when it is used in combination with aluminum hydride, specific impulse can be increased by 5 kgf · s/kg more.

Work on the creation of new effective components for solid propellants is still going on. As an example, we can mention the American development of an effective new oxidizer for rocket solid propellants, known as CL-20 ($C_6H_6N_{12}O_{12}$). Its use will increase specific impulse by 10 kgf · s/kg more.

In Ref. 11 an analysis is provided of other components of solid propellants which can increase the specific impulse of solid-propellant rocket engines by 10–15 kgf · s/kg over those using propellants containing CL-20.

The creation of solid propellants, however, though very important, is not the final stage in the process. The technology for manufacture, necessary technological facilities, raw materials, control over the purity of the delivered components, and quality of the produced charges are also essential. It is also very important to provide safety during the processes of component blending, filling the motor case with the mass, and the pulling of the production tools after propellant polymerization. The conditions of warming up at the stage of polymerization should be optimal to provide the uniformity of the properties of the obtained charges.

The Ministry of Machine Building of the Soviet Union was responsible for the introduction of the production manufacture of new types of solid propellant; the Head of the U.S.S.R. Ministry of Machine Building, V. V. Bakhirev (1916–1991) contributed greatly to assure the high quality of the process of the production manufacturing of solid propellants. In this he was greatly assisted by his deputy chiefs V. N. Raevsky (1915–1986), L. V. Zabelin, and others.

Chief engineers of chemical–technological institutes, workers at the plants producing concrete solid-propellant compounding, and many other people related to manufacturing solid propellant contributed greatly to the creation of the new types of solid propellant.

D. Solution of Some Design Problems in Process of Creation of Solid-Propellant Missile Engines

The first solid-propellant guided missile was the 9M76 missile adopted in 1966. It had motors with cartridge-loaded charges, forming a stagnation zone together with the body of the motor. The idea of creating the stagnation zone belonged to Pobedonostsev. In combination with the use of glass-reinforced plastic motor case shells, the presence of the stagnation zone allowed the creation of motors with an inert-to-propellant weight ratio close to 0.2.

The transition to motors with case-bonded charges (the idea was borrowed from the Americans) allowed attainment of an inert-to-propellant weight ratio equal to 0.08. Giving up removable case end closures and transitioning to monolithic composite cases with case-bonded charges made it possible to attain an inert-to-propellant weight ratio equal to 0.06 (0.94 mass fraction). At the same time, the filled volume of the motors was increased. This parameter reached values of 0.95–0.97, despite the fact that the requirements on the change of gas influx as a function of the magnitude of the burnt dome remained practically the same; the curve of the gas influx should be close to its mean value during charge burning. If there were any deviations from this rule, it was as a consequence of the optimization of the design parameters of the engine and not a forced measure.

Note that at this stage of the solid-propellant rockets the motors were built with submerged nozzles, movable nozzles, and once or twice folding nozzle exit cones at minimal loss of specific impulse, and the transition to the use of carbon–carbon materials for nozzle manufacturing was realized.

It can be stated that scientists, engineers and other workers of the defense research and manufacturing community demonstrated their creativity and technical competence, providing wonderful results in their work on missile systems and their components.

E. Creation of Control Systems for Solid-Propellant Missiles

Flight control systems were undoubtedly developed based on results obtained during the design and development of liquid-propellant rocket engines. The possibility of regulating the injection of liquid-propellant components into a combustion chamber and using additional small engines for control enhanced the creation of guided missiles.

It was in 1934 when a group of workers directed by S. A. Pivovarov developed the first Russian gyroscopic device GSP-1 for missile flight control.

In 1939, the same group created a new automatic gyroscopic machine, which allowed three-plane stabilization, GSP-3 (Ref. 8). The control surface actuators of the control system had a feedback system, which significantly increased the quality of the flight control. An aerodynamic missile of the 212th project designed by Korolev was supplied with the GSP-3 autostabilization device. A liquid-propellant engine TRE-65 (a trial rocket engine) developed by Glushko, operating on nitric acid and kerosene, was used as a propulsion system for this missile. The missile had an initial mass of 165–230 kg and a payload weight of 35 kg. The guided missile of the 212th project was launched from a rocket rail, and its range was 50–80 km. The first launch of the missile took place in 1939.

World War II hindered work in this direction. After the war, the German experience in the creation of the V-2 liquid-propellant guided missile with a range of 300 km was thoroughly studied; the control system of the V-2 was also carefully investigated. Therefore, in Russia postwar work on control systems was based on the results obtained by the Russian scientists before the war and the results obtained by the Germans.

At the Research Institute of Devices, academician N. A. Pilugin (1908–1982) and the group under his direction made great contributions to the creation of flight control systems and the theory of design of precision-control systems for craft including airborne computers. At the same time, work on the development of rocket flight control devices was conducted in Special Technological Office-1 under the leadership of academician B. Ye. Chertok (see Ref. 12), who was one of the first deputy chiefs of academician Korolev.

At the Research Institute of Devices, a special group was formed to develop a sea-launched rocket under the direction of academician N. A. Semikhatov; in 1952 the group moved from Moscow to Sverdlovsk (now the city of Yekaterinburg) to fulfill the task.

In Sverdlovsk, Semikhatov founded a scientific-production (SPA) association, Avtomatika, where the control systems for various types of rockets were made. The control system for the 9M76 two-stage rocket was made by Avtomatika, and the Research Institute of Devices made the control system for the 15Zh42 rocket.

By the early 1960s, the experience in the development of solid propellants was broad enough to make it possible to use many types of devices normally used for liquid-propellant rockets for flight control on solid-propellant rockets.

At the same time engineers, designers, and technologists engaged in making solid-propellant engines learned to manufacture motors with movable nozzles, with the nozzles partially recessed in the engine, a jet vane actuator for the control system, and other devices meeting the special requirements of solid-propellant rocket motors.

Gradually it was becoming possible to manufacture not only large guided missiles, but also small ones, including in-fighting and tactical missiles.

IV. Unguided Missiles of the Postwar Period

The scale of investigations and experimental-design work on the development of various types of missiles significantly increased in the postwar period. Missile systems, from short-range missile systems to ICBMs and space rockets, were designed and developed. The ICBMs were necessarily guided; the salvo-firing missile systems and some other missile systems were unguided during this period.

A. Salvo-Firing Unguided Missile Systems for the Soviet Army and Navy

First, let us consider the unguided salvo-firing missile systems (SFUMS), which had their roots in the SFUMS of the war period. The work on the creation of SFUMS first started at the Moscow Institute of Technology, founded in 1946 as a branch of the JRI. Later, in the 1950s, this work was transferred to the State scientific-production enterprise (SPE) Splav in the city of Tula.[13]

At the Moscow Institute of Technology, N. P. Gorbachyov directed the work on the creation of the SFUMS for the army (from 1946 to 1958). The systems for the navy were manufactured under the direction of N. P. Mazurov, S. S. Berezhkov, and V. A. Mastalygin (see Ref. 13).

A number of systems with spin-stabilized missiles having calibers from 40 to 240 mm, a distance deflection of about 0.005, and a range of 10–18 km were developed for the army. In all cases, unrestricted-burning charges made of the ballistite propellant were used. The launchers were mounted on the chassis of ZIL-151 and GAZ-63A trucks.

For the Soviet Navy, a number of antisubmarine systems with multibarreled jet-bomb firing installations, such as Uragan, Buran, Smerch-I, Smerch-II, and Smerch-III, were made. The systems enabled firing jet-bombs singly and in salvo over a distance of about 6 km. The systems are still in the arsenal of the naval forces not only in Russia, but also in a number of the countries of the world.

At the State SPE Splav, the Grad system with a range of 20.5 km was developed, and at the beginning of 1963, it was added to the army arsenal.[14] The missiles of the SFUMS Grad had a caliber of 122 mm. Aerodynamic stabilizers opened after the missile exited the launch tube due to the spin incurred while moving along the tube, and subsequent spinning was due to the aerodynamic stabilizers. The fighting machine BM-21 mounted on the chassis of the ZIL-131 truck had 40 guide rails. A blast-fragmentation missile, M21OF, of the SFUMS Grad had a length of 2880 mm, an initial mass of 66.3 kg, and carried a warhead with a mass of 18.4 kg. Its distance deflection was approximately 0.005, and its direction deflection was about 0.009. The Chief Designer of the SFUMS Grad was A. N. Ganichev (1918–1983). Based on the SFUMS Grad, several modifications were developed for airborne troops (Grad-V), for antipersonnel and antitank territory mining (Grad-I), and others. The SFUMS Grad was bought by many other countries, and at the present time 50 countries have this system in service.

In 1975, Splav manufactured the 220-mm SFUMS Uragan, with a cluster fragment bomb destruct package, for the Soviet Army.

The 9M27K missiles of the Uragan system had a range of 35 km and the same parameters for distance and direction spread as the M21OF missile. The Uragan missiles had a length of 5178 mm, an initial mass of 267 kg, and carried a warhead mass of 86.5 kg. Thus, the Uragan system carries a warhead 4. 7 times heavier and its range is 1.37 times greater than the SFUMS Grad.

B. Tactical Unguided Missiles for Soviet Army and Naval Forces[13]

The first missile of this category was the Neptune, with a range of 40 km (1951). Neptune was never put into service. However, the experience accumulated during its creation was successfully used for designing and finalizing two other missiles, Mars and Filin, which were added to the arsenal in 1958.

Some characteristics of Mars and Filin are given in Table 8. These missiles were larger in comparison to the earlier unguided missiles, and they were also quite different from each other.

These missiles had rather long ranges for missiles of the 1950s. Mars and Filin were designed and developed in the DO of the Moscow Institute of Technology under the direction of Mazurov. The Luna 3R9, 3R10, and 9M21 were also developed in the DO of Mazurov. The first two were added to the arsenal in 1961 and the third in 1964. Some parameters of these missiles are presented in Table 9.

Based on measurements conducted at the launch of these missiles (determination of the wind field at launch bulk temperature of the charge, energy on exit from the launcher, axial turn, etc.), their distance deflection did not exceed 0.008, though the range reached 45 km.

The DO of Mazurov developed an antisubmarine system Vikhr with an unguided missile, having a solid-propellant engine for the Soviet Navy; it was added to the arsenal in 1964. The missile had an initial mass of 1823 kg, a length of 6 m, a caliber of 540 mm, and a range of 24 km. Its warhead was submerged to a depth of 500 m. It was possible to launch one or two missiles from the launcher. The

Table 8 Characteristics of the Mars and Filin missiles

Missile	Initial mass, kg	Engine diameter, mm	Missile length, mm	Warhead mass, kg	Firing range, km
Mars	1750	324	9000	420	18
Filin	4950	612	10000	1200	26

Table 9 Some parameters of Luna series missiles

	Missile		
Parameter	3R9	3R10	9M21
Firing range, km	45	32	15–65
Initial mass, kg	9000	10500	2500
Warhead mass, kg	2150	2250	420–457
Missile length, mm	360	495	9000
Caliber, mm	415	540	544

developmental work on the Luna series for the Soviet Army was applied to the creation of the Vikhr system.

C. Unguided Missiles for the Soviet Air Force

As already mentioned, the first missiles developed at the JRI were for the Soviet Air Force and were used to fire at air, sea, and ground targets.

After World War II, in 1956, a turbojet missile, TRS-85, with a caliber of 85 mm, was designed in the DO directed by Ye. A. Pechersky. The missile weighed 5.5 kg and had a blast-fragmentation warhead.[15] There were 30 such missiles packaged in specially made launching racks mounted in MiG-17 fighters. Firing was performed in salvo, two missiles at a time, with an interval between the salvos of 0.1 s.

Now consider an unguided antitank aviation shaped-charge warhead missile, S-3K (KARS-160) (early 1960s). This missile could break through an armor of about 300 mm, and when fired from a distance of 2000 m target, these missiles could hit targets of about 7 m in diameter. (The lateral dispersion was less than 0.002, and distance deflection was 0.0035.) The initial mass of the missile was 23.5 kg, the diameter of the warhead was 134 mm, and its length was 1500 mm. The warhead mass was 7.3 kg. Aircraft such as the Su-7B carried the S-3K missile.

In Special DO-16 (chief designer, A. E. Nudelman), the unguided missile S-5 was developed. In 1955, it was added to the Soviet Air Force arsenal. The missile had a folding fin, which opened with the help of a spring and the incoming flow; during flight, the folding fin provided overspeeding to 1500 rpm and additional stabilization for the missile. The S-5 missile was fired from a distance of 2 km to a target; it had a distance deflection of 0.0035. It was meant to hit both ground and air targets. The warhead of the missile was supplied with an impact fuze. This missile served as the basis for the creation of several modifications. For instance, the S-5M missile had a blast-fragmentation warhead for hitting various types of ground targets (1959).

The S-5K missile (1960) had a shaped-charge warhead. The S-5K missile was capable of breaking through armor with a thickness of 130 mm, and it had rather good accuracy. When eight missiles were fired in salvo from a distance of 1 km to a target, the circular dispersion was about 4.5 m. This missile flew 1000 m in 2.3 s. The first type of launcher for the S-5 missiles contained nine missiles in a package. Then the number of missiles was increased to 16, and finally, the launcher YB-32 was able to launch 32 missiles. A MiG-27 fighter carried two YB-32 launchers. During flight testing, 64 missiles were launched by two YB-32 launchers carried by the MiG-27 fighter and 59 missiles (92%) hit targets.[15]

For radar jamming, the S-5P missile was designed (1964). The warhead of this missile contained chaff dipoles made of metallized glass fiber and had a radio fuze. These missiles were usually part of the equipment carried by fighter bombers to break through the enemy air defense; they were also carried by bombers for backfiring to defend against the attacks of enemy fighters and antiaircraft missiles.

Based on the same S-5 missile, the S-50 flare rocket (1959) was developed, with an illumination power 10^6 candles. The operational (illumination) part of the missile had a proximity fuze. The missile could be fired over a distance of about 3 km. The fuse actuated at an altitude of 640 m, and the burning of the illuminating mixture lasted for 18.3 s and terminated at an altitude of 970 m. While this was taking place, the missile descended by parachute. Depending on the intended use, the missiles of S-5-series had different initial masses in the range from 4 to 5 kg. Their lengths were approximately 880 mm and their duration slightly over 1 s. The S-5 missiles were exported in large numbers and were used in almost all of the local wars of the 1970s–1990s including in Ethiopia, Angola, Afghanistan, the Middle East (Arab–Israeli conflict) and in the Iran–Iraq war.

In 1965, the Soviet government gave an order to Special DO-16 to develop a new series of unguided missiles, S-8, with better tactical–technical characteristics than the S-5 missiles. Improvements were made through the use of folding fins under the action of a piston rod, which unfolded faster; the piston rod was pushed by the products of burning of the main charge of the solid-propellant missile engine. The unfolded fins were fixed; the motor had six nozzles, a larger thrust, and its duration decreased to 0.69 s. The basic missile of the S-8 series had an effective launch distance of 2 km and dispersion not worse than 0.003.

On its base, an S-8KOM missile was made with a 3.6-kg shaped-charge-fragment warhead. The initial mass of the missile was 11.3 kg. The missile was launched from a distance of about 4 km from the target, and in a normal hit, it was able to pierce armor with a thickness of 400 mm.

Another variant of the S-8 missile was the S-8BM missile with a bunker-bursting warhead. It could pierce a layer of reinforced concrete having a thickness of 0.8 m. Its warhead had a mass of 7.41 kg. The initial mass was equal to 15.2 kg; it was launched from a distance of about 2.2 km from a target.

The next was the S-8DM missile. Its warhead was filled by a bulk-detonating mixture. Liquid-explosive components having a mass of 2.15 kg formed an aerosol cloud of the bulk-detonating mixture with blast action equivalent to the action of 5.5–6 kg of trinitrotoluol. The mass of the warhead of the S-8DM missile was 11.6 kg.

Based on the S-8 missile, a flare rocket, S-8OM, was developed. The S-8OM had an inflammable blend mass of 1 kg, and it provided the illumination power of 2×10^6 candles. The mass of the warhead of this missile was equal to 4.3 kg, and the initial mass was 12.1 kg.

Finally, based on the S-8, the S-8P missile was developed for passive radar jamming. On the actuation of the proximity fuze, the metallized glass fiber dipoles in the warhead were thrown out by a burster, creating a cloud with a volume of 500 m^3, which interfered with the operation of radar stations on wavelengths from 0.8 to 14 cm.

The missiles of the S-8 series were first launched by launchers containing 20 tubes each; the lengths of these tubes were 1700 mm and diameters, were 520 mm. Later, launchers with seven tubes 1780 mm in length and 332 mm in diameter were used. The Su17, Su24, Su25, Su27, MiG-23, and MiG-27 fighters and Me-8, Me-28, Ka-252, and Ka-50 helicopters could carry these missiles.

The next series of missiles developed at Special DO-16 was the S-13 series. They were intended to destroy runways and structures of various types made of reinforced concrete. Preserving all of the technical merits of the S-8 missiles, the S-13 missiles were able to pierce earthen coverings with a thickness of 3 m or coverings made of reinforced concrete with a thickness of 1 m. In a direct hit on a runway, about 20 m^2 of the surface were destroyed.

In addition to the S-13, the S-13T and S-13-OF missiles were developed and added to the arsenal. The first had a two-module warhead, the second module operated inside the object being attacked (after piercing the protective layer of earth or reinforced concrete). The second missile had a powerful blast-fragmentation warhead, bursting into 450 fragments, each with a mass of 35 g. These fragments were designed to pierce the armor of an armored personnel carrier or an infantry combat vehicle. Some characteristics of the missiles of the S-13-series are given in Table 10.

The S-13 missiles were launched out of five-tube launchers. The Su17, Su24, Su25, Su27, MiG-23, and MiG-27 airplanes, and Me-8, Me-24, Me-28, and Ka-252 helicopters were equipped with the S-13 missiles.

In the DO of Mazurov, Moscow Institute of Heat Engineering, the S-24 missile,[13,15] was developed. It had a four-fin stabilizer (Fig. 20), with a span of 600 mm; the missile caliber was 240 mm. The missile length was 2330 mm, and the initial mass was 235 kg. The mass

Table 10 Some characteristics of the aviation missiles of the S-13-series

Characteristic	Missile		
	S-13	S-13T	S-13-OF
Caliber, mm	90/122	90/122	122
Missile length, mm	2900	3100	2998
Initial mass, kg	To 60	To 75	69
Warhead mass, kg	23	21 ± 16.3	33
Explosive mass, kg	1.92	$1.8 \div 2.7$	7.0
Flying range	1100–4000	1100–3000	1600–3000

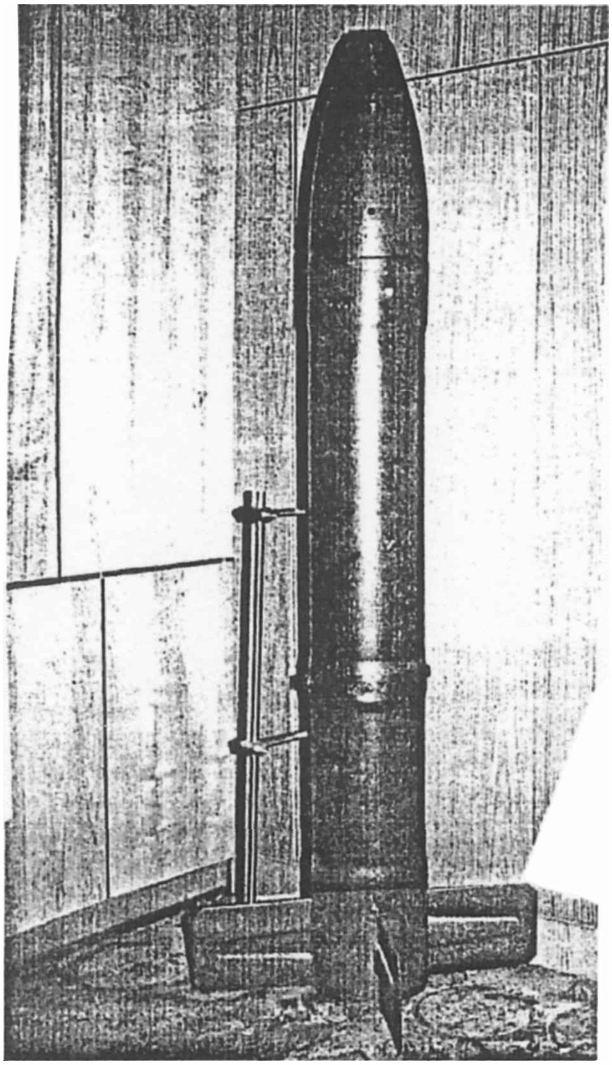

Fig. 20 Unguided S-24 missile.

of a blast-fragmentation warhead was 123 kg including 23.5 kg of explosive. The S-24 missile was launched from a distance of 2 km to a target; its probable circular deflection was about 0.3–0.4% of the range. The missile was equipped with a proximity fuze, actuated at a distance of 30 m from the target. In the configuration using a contact fuse, the warhead of the missile was designed to pierce armor of 25 mm in thickness, a brick wall of 2.5 bricks in thickness, or wooden-earthen covering consisting of 5 logs, each 30 cm in diameter, and then explode. The motor had seven nozzles providing the spin of the missile with an angular velocity 450 rpm. On the flightpath, the spinning was supported by stabilizers. The charge mass of the engine was 72 kg, and the duration was 1.1 s. The charge based on ballistite solid propellant contained five starlike grains. The Su-17 fighter–bomber was capable of carrying six S-24 missiles; the Su-25 attack plane carried about eight such missiles.

Let us conclude this section of the paper with the consideration of the transitional S-25 missile developed in Special DO-16.[15] The development of this missile was accomplished in 1971. The were two variants of this missile: 1) the S-25-O with a fragmentation warhead and 2) the S-25-F with a blast warhead. The S-25-O missile had a caliber of 340 mm, a length of 3307 mm, and an initial mass of 381 kg. The warhead weighed 150 kg and had an electronic fuse, providing the explosion at altitudes from 5 to 20 m depending on the preset of the fuse. The S-25-F missile had the same caliber, a slightly longer length (3310 mm) and an initial mass of 480 kg. Its blast warhead had a mass of 190 kg and contained 27 kg of explosive. The S-25 missile had four stabilizers, placed between four nozzles, and during flight, they provided the missile spin. The solid-propellant motor of the missile had a charge with a mass of 97 kg based on the composite propellant. The S-25 missile was launched from a distance of 4 km from the target. In 1973, it was decided to make this missile controllable. For this purpose, the warhead of the missile was equipped with a laser target-seeking device designated 2HI, a special power assembly with an actuator, and jet vanes. As a result, both variants of the missile were designated S-25L and were considered to belong to the category of guided missiles.

V. Guided Missiles

A. Salvo-Firing Guided Missile Systems

Strategic missiles were developed with guidance from the very start. In contrast, the salvo-firing guided missile systems (SFGMS) came into existence as the tactical and technical characteristics of unguided missiles were gradually improved. When all of the possibilities for further improvement in these areas were exhausted, it became necessary to move to the development of the SFGMS. The first system in this series was Smerch. Its missiles had a range of 70 km and a caliber of 300 mm. The range was three times less than that characteristic of the unguided missiles; however, the firing accuracy was twice as good. It had a cluster warhead, which contained 72 hitting elements, each with a mass of 2 kg (Ref. 14).

Work on the creation of new types of SFGMS is still going on.

B. Air-to-Surface Guided Missiles

After World War II, a great number of air-launched guided missiles were developed. The first ones (1940s–1950s) had control systems that were far from perfect. During the whole flight of a missile, an operator was needed. However, with the accumulation of experience, the possibilities for computational and remote control were improving. Finally, starting in the 1960s, control systems were created based on the principle: launch it and forget it. The first missile of this type with a solid-propellant motor was an X-15 missile, adopted in 1980 (Ref. 14). The missile was developed at the Machine Building DO Raduga in the town of Dubna, Moscovskaya oblast. The chief designer was I. S. Seleznyov. The control system was inertial without correction. The missile had an aeroballistic flight trajectory and flew beyond the atmosphere for 40 km. The range was from 150 to 300 km. The maximum velocity was up to Mach 5.

The TU-95MS, TU-22MZ, and TU-160 aircraft carried the X-15 missile. Each aircraft carried six missiles and was able to launch them at altitudes from 0.3 to 22 km with flight velocities of 300–600 m/s. The missile had an initial mass of 1.2 tons, a length of 4.8 m, a body diameter of 0.455 m, and a fin span of 0.92 m. It had a nuclear warhead with a power of 350 ktonne.

By the mid-1980s, the Machine Building DO Raduga developed an antiship missile, X-15S, based on the X-15 missile. It was equipped with a radar homing device. Before launching the missile, the approximate coordinates of a target location were entered into the memory of the homing device. For most of the flight trajectory, the missile was controlled by an inertial guidance system, and the radar active-homing device was actuated only in the terminal flightpath. The missile had a shaped-charge blast warhead with a mass of 150 kg. The range was the same as that of the X-15 missile. The X-15 missile is shown in Fig. 21.

Besides the mentioned aircraft of the TU series, this missile could be carried by the SU27K and SU27IB aircraft.

The Machine Building DO Raduga created an antiradar system, X-15P, based on the X-15 missile, to break through an enemy

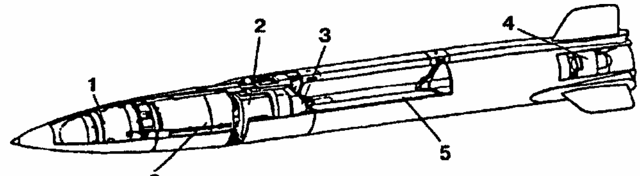

Fig. 21 Antiship X-15C missile: 1) radar homing device, 2) navigation system, 3) electrical equipment, 4) control drive, 5) solid-propellant engine, and 6) warhead.

air-defense system. The initial flightpath of the missile was controlled by an inertial guidance system and the terminal flightpath by a radar passive-homing device. The range was 150 km; the mass of its blast-fragmentation warhead was 150 kg. The remaining tactical–technical characteristics were the same as those of the X-15 missile. The same fighter–bombers of the TU series carried the X-15P missile. In 1988, the X-15P missile was added to the arsenal of the air force of the Soviet Army.

Let us consider an air-launched missile Ovod (developed in the Machine-Building DO Raduga), which was intended for hitting ground point targets and small ships. The work was started in 1972 under the direction of the famous Soviet designer A. Ya. Bereznyak, and after his death the work was continued under the direction of Seleznyov.

The X-59 missile was equipped with a sustainer and a booster motor. The latter was placed in the combustion chamber of the sustainer motor. The flight cruise velocity was 860–1000 km/h, and the range was 115 km. The missile length was 5.69 m, the missile body diameter was 380 mm, and the wing span was 1.3 m. The initial mass was 920 kg. The warhead was a shaped-charge-fragmentation or cluster type (with a mass of 280 kg). The cruise altitude was 7 m above sea level or higher, depending on wave height. The flight altitude above the ground was from 0.1 to 1 km depending on the terrain relief. Before the missile launch, the target coordinates were entered into its airborne memory.

During the initial flightpath, the missile was controlled by an inertial guidance system. When the missile approached the target, starting at a distance of 10 km, the television homing device was actuated. The televised picture of the region was transmitted from the missile to the missile carrier. A navigator–operator on the aircraft performed visual target recognition from the televised picture, set cross hairs over the target, and pressed the button of the automatic tracking system. The missile was then automatically guided. The circular probable deflection is about 2–3 m.

In 1980, a system containing an SU-24M fighter–bomber, a control package, and two X-59 missiles was put into service. The SU-17M fighter–bombers were also equipped with the X-59 missile.

In the same Machine-Building DO Raduga, under the direction of Seleznyov, the 3M-80 missile, nicknamed Moskit, was created. The design work started in 1973. This missile has a combined motor, containing an airflowed solid-propellant charge. The missile has a solid-propellant booster placed in the nozzle of a sustainer motor, and when its charge burns out, it is thrown out by an airjet 3–4 s after launch. The control system is combined: The main part of the flight of the missile is controlled by an inertial guidance system, and for controlling its terminal flightpath, a radar active–passive homing device is used. The probability of hitting targets such as boats is approximately 99% even in the presence of enemy electronic countermeasures. If convoys are fired on, the hit probability is about 94%. The cruise altitude is 20 m, and in the region of a target, the missile goes down to 7 m above the wave crests. The length of the missile is 9.4 m, the diameter of the missile body is 760 mm, the wing semispan is 1.3 m, and the wing span is 2.1 m. The initial missile mass is 3950 kg. The range is from 10 to 120 km. The cruise velocity is Mach 2.1. A schematic of the Moskit missile is shown in Fig. 22.

In the State scientific-production center Zvezda, a series of X-25 missiles was developed. The development of this system started in 1970. In 1976, the system entered service. It includes the X-25 missile with a semi-active laser homing device and a laser station Prozhektor-1 for target illumination. The SU-17KG aircraft is used as a carrier. This was the world's first autonomous weapon system of this kind. This variant of the X-25 missile was given the index X-25ML (module missile with a laser homing device). In addition, an X-25MR missile with a radio homing device and an X-25MP missile with a passive radar homing device for destroying operating radar stations were created.

All X-25 missiles have a canard fin scheme. (See the X-25MR missile in Fig. 23.) The missile body diameter is 255 mm, the wing span is 820 mm, the blast warhead mass is 90 kg, and the missiles have a solid-propellant motor. The X-25ML missile is intended for hitting point targets. Illumination of the target can be performed by an aircraft or ground sighting station. The range of the missile is about 20 km, the maximum velocity is 850 m/s, the length is 4255 mm, and the initial mass is 300 kg. There is a variant of this missile for nighttime use, which has an infrared target-seeking device.

The X-25MR missile with a radio homing device is able to overcome intensive electronic countermeasures and is intended for hitting point ground targets and separate surface targets. It has the same parameters as the X-25ML missile, although, its range is shorter, about 10 km.

The X-25MP missile with a passive radar homing device is designed for high-accuracy targeting of radar stations. Its range is 40–60 km. Maximum flight velocity is 900 m/s, the length is 3830 mm, and its initial mass is 390 kg. There is an improved variant of this missile, designated X-25-MPU. This missile has a wider frequency range of reception for the radar homing device. The inertial guidance system substitutes for the radar homing device in the case of loss of a target by the latter, until it catches the target again. The characteristics of the X-25MPU are similar to those of the X-25MP missile, but it has a longer range of 340 km.

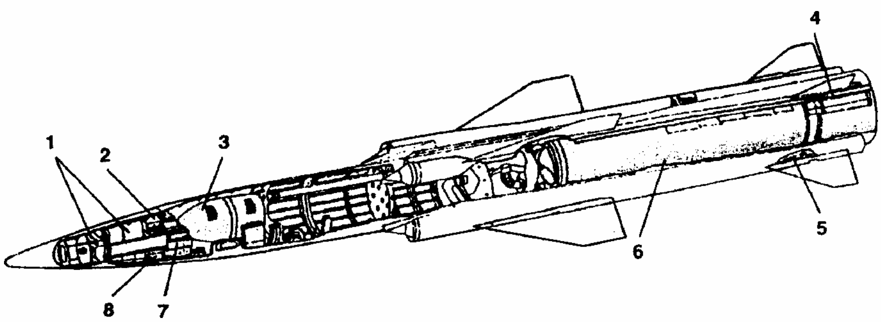

Fig. 22 Antiship Moskit missile (shipborne variant, airborne variant does not have powder accelerator in nozzle of cruise engine): 1) active–passive guidance system, 2) navigation system, 3) warhead, 4) nozzle, 5) control drive, 6) solid-propellant jet engine, 7) battery, and 8) radio altimeter.

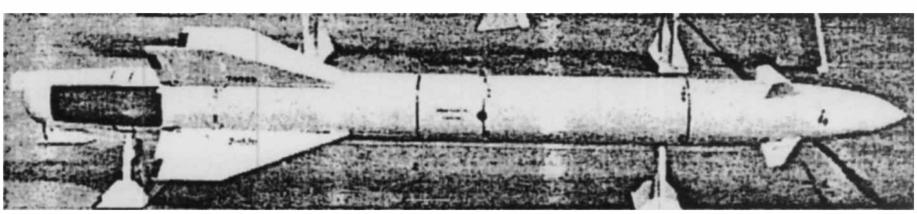

Fig. 23 Airborne X-25MR missile.

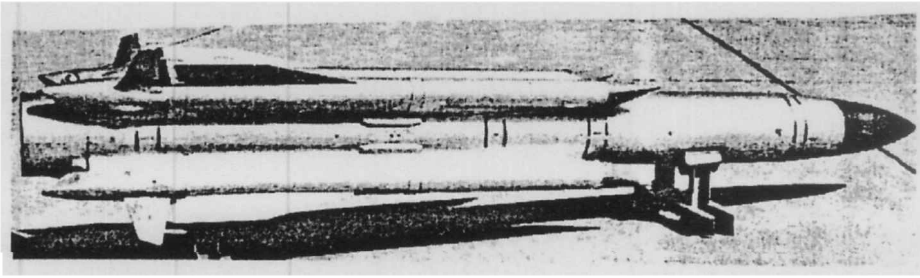

Fig. 24 Airborne X-31P missile with combined athodyd.

The MiG-21, MiG-23, MiG-27, MiG-29, SU-17M, SU-24, SU-25, and YaK-39 aircraft and helicopters are equipped with the missiles of the X-25 series. Russia has been offering the missiles of the X-25 series for export since 1992.

Two other airborne missiles, X-31P and X-31A, were created in the DO Strela (chief designer, Bugaisky) in connection with the U.S.S.R. Cabinet Council resolution of 1971. Both missiles have combined engines: jet propulsion with solid-propellant charge. The booster used in them is placed in the missile engine and is thrown out by the airflow after the booster charge has burned out. The length of the X-31 missile is 4.7 m, the body diameter is 360 mm, the wing span is 780 mm, and the initial mass is about 600 kg. The X-31P missile is shown in Fig. 24. The X-31P missile has a passive homing device, manufactured in the SPA Avtomatika, and a blast-fragmentation warhead weighing 90 kg. Its maximum flight velocity is 1000 m/s, and its range is about 200 km. The X-31P missile is designed for destroying radar stations.

The X-32A missile is equipped with an active radar homing device and is intended for hitting various targets from boats to destroyers. Its range is 50 km, and the maximum velocity is 1000 m/s, as in the case of the X-31P missile.

In 1989, the X-31 missiles were put into service; the MiG-21, MiG-23BN, MiG-27M, MiG-29M, MiG-29K, SU-24M, SU-27M, and SU-27IB aircraft and others were equipped with these missiles. In 1994, the missiles of the X-31 series and the 3M-80 Moskit were bought by the United States.

C. Guided Air-to-Air Missiles

It was this type of rocket that started the history of the solid-propellant rocket production, although, in the beginning they were not guided. In this section, let us consider the solid-propellant missiles of the air-to-air type. Like the missiles of the air-to-ground type, they followed a thorny path of development from imperfect designs to perfect samples of military equipment of the postwar period.

The first missile of this group was the R-5 missile, which began its development in the DO of the Ministry of Defense under the direction of D. L. Tomashevich (1899–1974) in 1951. In 1953, work on this missile was transferred to another Department (under the Ministry of the Aviation Industry) Special DO-2 (chief designer, P. D. Grushin, 1906–1993), where the missile was given the index K-5. It was a missile with a solid-propellant motor with an initial mass of 82.5 kg; its length was about 2.5 m, the body diameter was 200 mm, the wing span was 654 mm, and the fragmentation warhead weighed 13 kg. The missile had a simple beam riding system. After target acquisition, a pilot, flying an aircraft, had to track the target mark into the center of the indicator, that is, to superimpose the longitudinal axis of the aircraft on the direction of the movement toward the target. Then, keeping this position of the aircraft, the pilot had to switch over the airborne radar station into contact mode. After having attained the allowable range, the missile was launched. The pilot had to keep the target mark in the center of the indicator and continue beaming the missile until the missile hit the target.

The missile control system responded to the intensity of beaming of the airborne radar station and corrected the flight of the missile. The K-5 missile maneuverability was not sufficient, and the missile was only used to hit heavy bombers. The operational range of the K-5 missile was less than 6 km and was limited by the capabilities of the airborne radar station of the aircraft. It was the first air-to-air guided missile adopted by the Soviet Air Force. The MiG-17PFU, MiG-19PM, and MiG-21F interceptors were equipped with these missiles. There were a number of modifications of the missile; one of them, the missile with the index RS-2US, was attached to the SU-9 fighter.

The R-8MR missile with a semi-active radar homing device was produced in the Special DO-4 under the direction of the chief designer, M. R. Bisnovat. It entered service in 1962 as a part of the system consisting of the SU-11 fighter, RP-11 radar homing device, and R-8M missile. The R-8M missile had a solid-propellant motor, was 4.27 m in length, had a body diameter of 275 mm, wing span of 1.3 m, and initial mass of 225 kg. The mass of the target-fragmenting warhead was 35 kg. The missile was designed according to the canard fin scheme, and its range was about 8 km.

In 1965 the K-80 missile was added to the arsenal. It was part of the weapon system that included the long-range TU-128 bomber. There were two modifications of the missile: K-80-R-4R (with radar homing device) and K-80-R-4T (with infrared radar homing device). Both variants had an initial mass of 483 kg, a length of 5.45 m, and a body diameter of 315 mm; the wing span was 1.3 m. The blast-fragmentation warhead with a radio fuze had a mass of 53.5 kg. The K-80 missile hit targets with velocities about of 2000 km/h, at altitudes from 8 to 12 km and at the distances from 2 to 25 km.

In Special DO-4 under the direction of Bisnovat, the development of another solid-propellant missile, R-40, started in 1962. The missile was produced in two variants: 1) with a semi-active radar pulse homing device (R-4OR) and 2) with an infrared homing device (R-4OT). The range of the R-4OT missile was 30 km. The R-4OR missile initially had a range of 50 km, and after it had been modified, its range was 72 km. (The modification index is R-40RD.) The R-40 missile was designed with a canard fin and its length was 5.15 m, the body diameter was 300 mm, and the wingspan was 1 m. The initial mass was equal to 400 kg, of which 118 kg belonged to the solid-propellant charge and 35 kg to the blast-fragmentation warhead, which had a two-channel active radar interference-free fuze. The effective hitting radius was 7 m. In 1970 an interception system consisting of the MiG-25 fighter, airborne radar station, and four R-40 missiles was adopted by the Soviet Air Force.

In 1976, the pilot Belenko escaped to Japan using the MiG-25 air-interceptor, and the Japanese became acquainted with the design of the fighter. In connection with this event, in 1979 the Soviet Army substituted the improved SAPFIR-23 radar station for the previously used SMERTCH-23 airborne radar station and the semi-active homing device with a continuous signal for the semi-active radar pulse homing device. The latter substitution was made to improve the tactical–technical characteristics of the system.

One of the modern air-to-air missiles with a range of 100 km is the RVV-AE missile, or R-77, manufactured in the Machine-Building DO Vympel. This missile was able to hit various targets: aircraft, helicopters, and missiles of the air-to-ground and air-to-air types. The missile can be used at night and in the daytime. Regardless of meteorological conditions, it is capable of overcoming any active and background enemy radar countermeasures. The missile has folding cribrate rudders with small hinge moments for any maneuver and mode of flight, which means that they require a small electric drive.

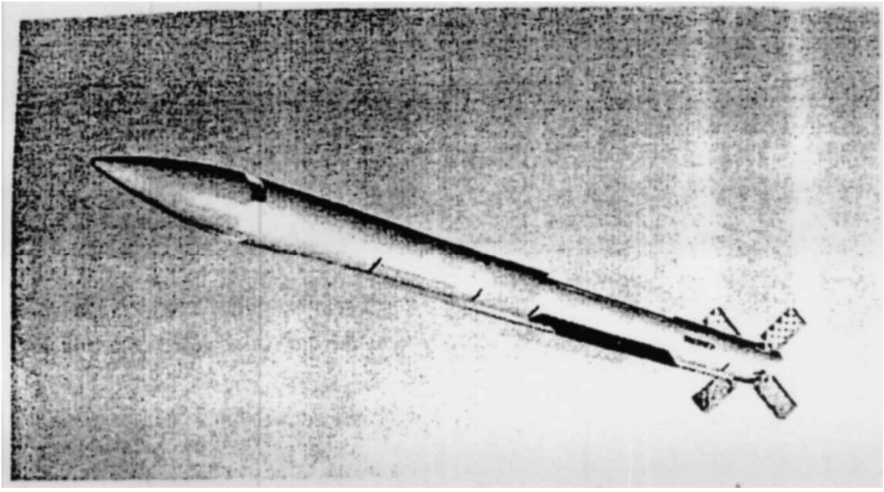

Fig. 25 Airborne RVV-AE missile (R-77).

The flight of the missile can be effectively controlled to angles of attack of 40 deg. The missile is compact, and its flying velocity reaches Mach 4. It hits targets at altitudes from 20 to 30 km, including targets having accelerations to 12 g. The missile guidance is combined: command–inertial guidance is used for the initial flightpath and active guidance is used for the terminal flightpath. Switching to active guidance is performed by a signal from the airborne computer, which determines the distance to the target engaged by the homing device. After the missile is switched to the self-homing mode, the carrierborne computer program creates a mathematical model of the target (the parameters of the target flight). In the case of loss of the target by the self-homing device, the target search is repeated by means of the mathematical model and the radar homing device. The homing device of the missile is capable of performing passive homing on the interference source along with the target. The missile is equipped with a laser fuze beaming the target at the terminal flightpath to determine the optimal moment for the warhead to explode.

In the target attack and defense modes, the micro-shaped-charge continuous rod warhead of the missile literally cuts the target. The warhead mass is 22 kg. The initial mass of the missile is 175 kg, its length is 3.6 m, its diameter equals 200 mm, the wing span is 400 m, and the cribrate stabilizer span is 700 mm. The SU-27 and MiG-29 fighters are equipped with the R-77 missile. The R-77 missile was adopted in 1994. The missile is shown in Fig. 25.

In the State Machine Building DO Vympel, a short-range missile, R-73, was designed for close maneuvering combat. Initially it was supposed to be a wingless missile with gasdynamic control only. However, the investigations showed that a wingless missile with gasdynamic control had a number of significant disadvantages. They included a small rate increase for maneuver overloading over the angle of attack and reduction of the operational speed when the engine thrust was reduced. The fact that American rocket makers stopped working on the wingless missile Agile based on the principle of gasdynamic control influenced the Russian rocket-makers to a certain degree.

In fact, the State Machine Building DO Vympel was simultaneously working on two short-range missiles: the R-14 with an all-round looking infrared homing device and the R-73 with an infrared homing device with limited scanning. The R-14 missile was designed based on the R-13M missile. The rocket makers of the Kievsky plant Arsenal suggested making an infrared homing device Mayak capable of marking a target within the angles of target bearing of ±60 deg for the R-73 missile. This innovation made the characteristics of the R-73 and R-14 missiles similar, which led to termination of the development of the R-14 missile.

The R-73 missile was designed with a combined aerogasdynamic control, which had all of the advantages of the missiles with aerodynamic control and the missiles with gasdynamic control. This means that the missile had controllability during the passive flightpath, as well as controllability and stabilization during the flight at large angles of attack, when the engine of the missile is working.

The R-73 missile had much better characteristics than other existing missiles of this type because of 1) the absence of restrictions caused by the modes of flight and the intensity of maneuvers of the carrier; 2) the possibility of firing in collision and crossing courses; 3) the simplicity and operating speed of aiming and target engagement over a whole range of angles of target acquisition, including occasional acquisition during a target search at large aspect angles and at close range; 4) the large maneuvering possibilities; 5) the absolute self-regulation of the missile after launching, which provides complete freedom of movement for the carrier when leaving the attack; 6) the possibility of launching missiles at any angle to attack intensely maneuvering targets; and 7) the high protection of attack and exploding systems against natural and enemy countermeasures.

New technical advances were applied in the development of the R-73 missile. The missile is configured with a canard fin with the traditional cross-shaped arrangement of the aerodynamic surfaces in the nozzle part of the motor, and it is equipped with a gasdynamic control package of the interceptor type. This creates a lateral force due to the deflection of the gas jet of the engine. When the motor is operating, the control and the pitch and yaw stabilization of the missile are performed by connected pairs of four aerodynamic rudders and four gasdynamic interceptors for each channel. After the motor stops, the control and stabilization are performed by aerodynamic rudders. Missile roll stabilization is performed by four mechanically connected ailerons. The missile is supplied with an interference-free small-size passive infrared homing device with high sensitivity and deep cooling of the photodetector. This homing device locks onto the target suspended under the carrier. To increase the probability of hitting the target in crossing courses, the termination point in the homing device is shifted from the nozzle to the body of the target. The main materials used for missile manufacturing are aluminum alloys; the engine body is made of steel. For suspension under the carrier and for missile launching, the P-72 rail launcher with three lugs from the guide rails is used. The assembly of the suspension is fastened to the body of the aircraft with an eye attachment. The built-in equipment in this device enables use of the missile by any modern aircraft without significant updating. The homing device is capable of receiving target acquisition from any information source including radar or optical–electronic systems or a pilot's helmet system, which allows the possibility of further modernization to improve the range, protection against countermeasures, and efficiency. The R-73 missile and its modification R-73E were put into service in 1980s. The R-73 missile is shown in Fig. 26.

The characteristics of the R-73E missile are as follows: The initial mass is 105 kg, the length is 2.9 m, the body diameter is 170 mm, the wing span is 510 mm, and the continuous rod warhead has a

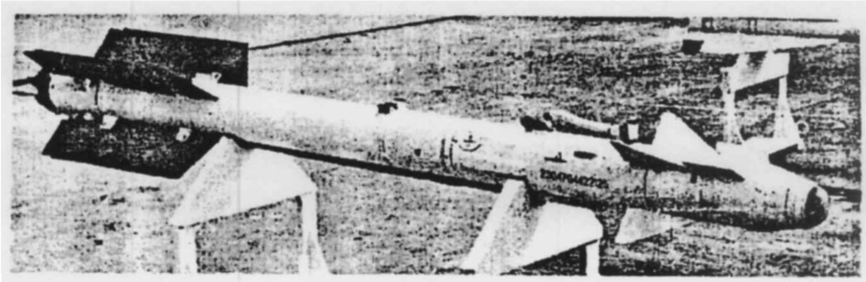

Fig. 26 Airborne R-73 missile.

mass of 8 kg. The R-73E missile is capable of hitting targets flying at altitudes from 20 m to 20 km with overload to 12. The maximum launch range of the missile from the front hemisphere is 30 km, and minimum from the back hemisphere is 300 m. Aircraft such as the MiG-21, MiG-23ML, MiG-29, MiG-29M, MiG-29K, Su-27, Su-27K, and Su-25T can be equipped with the R-73 and R-73E missiles.

Based on the R-73E missile, the State Machine-Building DO Vympel developed a new modernized K-74ME missile with improved maneuverability and a larger range from the front hemisphere (to 40 km). The other tactical–technical characteristics are similar to those of the R-73E missile.

Work on the R-27 missile started in the State Machine Building DO Vympel in 1972. Originally, the missile was developed according to the ordinary aerodynamic scheme. Later it was decided to make it based on a canard fin scheme with an asymmetric cross-shaped arrangement of aerodynamic surfaces. Aerodynamic rudders with a complicated configuration were used. The rudders have a large extension, a leading-edge sweep that is variable by sign, and a restricted root part (the so-called butterfly scheme), which allows their use in the differential mode for control and main channels stabilization of the missile, as well as for roll channel stabilization. The configuration of the rudders provides constant rolling moment sign within the whole flight speed range, that is, it excludes the so-called reversal phenomena characteristic of the missiles based on the canard fin scheme. On the bodies of the homing devices, destabilizers are installed in front of the rudders. Because of the change in their area, a constant statistical stability margin is provided for changing types of homing devices.

In the case of the missile modification with the radar homing device, the combined target acquisition technique is used. This enables maximum use of the ballistic capabilities of the missile; its range of locking onto the target by the homing device is 2–2.5 times larger. For the initial flightpath, the inertial guidance of the mathematical target is used, accompanied by the radar correction of its position and velocity during target maneuvers (the information is transmitted via radar link from the carrier). During the terminal flightpath, after locking on the target, homing is used.

The R-27T (ET) missile is a variant of the R-27R (ER) missile. It is equipped with an infrared homing device. When the photodetector cooling system is switched on, its duration is 3 h. The design of this infrared homing device allows system operation when there is no onboard cooling agent carrier before launch (however, the range at which the target can be locked onto is smaller in this case). When lock-on to the target is performed by the informational system of the carrier, the angular designation of the target is transmitted to the missile. When the target is in the viewing field of the coordinator, the missile performs lock-on to the target and target autotrack. If there is no information from the carrier, the missile operates in the self-regulating mode, which is set by the pilot from the cabin. The missile meets the interference protection requirements of the source country and the NATO countries. The characteristics of the R-27 rockets are presented in the Table 11. The characteristics of the homing devices for the R-27ER1 and R-27R1 rockets are presented in the Tables 12 and 13.

Note that the letter T in the index of the missile indicates thermal, and the letter E indicates power available. The missiles with

Table 11 Characteristics of the R-27 missile

Characteristics	R-27ER1	R-27R1	R-27ET1	R-27T1
Initial weight, kg	350	253	343	254
Missile length, m	4.7	4.0	4.5	3.7
Body diameter, mm	230	230	230	230
Engine diameter, mm	260	230	260	230
Wing span, m	0.8	0.77	0.8	0.77
Rudder (jet) span, m	0.97	0.97	0.97	0.97
Target flight altitude, km	To 27	To 25	To 30	To 24
Possible overloads of target	8	8	8	8
Launch range, km				
Maximum (from front hemisphere)	130	80	120	72
Minimum (from back hemisphere)	0.5	0.5	0.5	0.5
Warhead mass, kg	39	39	39	39

Table 12 Characteristics of the homing device of the R-27ER1 missile

Characteristics	Value
Launch range (for R-27 when effective radar surface of target is 5 m^2), km	To 70
Lock-on range when effective radar surface of a target is 5 m^2, km	Not less than 20
Radio correction range channel (aircraft MiG-29 weapon control system), km	To 50
Readiness time after preliminary cut-in during 2 min, s	Not more than 1.5
Weight (without nose dome), kg	Not more than 14.5
Diameter, mm	200
Length (without nose dome), mm	600

Table 13 Characteristics of the homing device of the R-27R1 missile (9B-1101K)

Characteristics	Value
Lock-on range when the effective radar surface of the target is 3 m^2, km	25
Time of inertial guidance with radio correction (at maximum distance from carrier of about 25 km), s	30
Body diameter, mm	219
Length (from nose dome), mm	1173
Weight, kg	33.5
Weight of apparatus, kg	21.5

indices containing the letter E are equipped with a more powerful solid-propellant engine, with a diameter larger than that of the main part of the body. The missile is mainly made of a titanium alloy; the engine body is made of steel. For attachment to the missile-launching aircraft and for the launching of both modifications of the missile, the same rail launcher and catapult launcher are used. The APU-470 rail launcher is used for attachment of the missiles under aircraft wings, and the catapult launcher, AKU-470, allows attachment of the missiles under the body or the wings.

The R-27 and R-27E missiles entered service in 1984–1985. They are used with the MiG-29K, MiG-29M, MiG-29C, Su-27, and Su-27K aircraft. The R-27ER missile is shown in Fig. 27.

In the early 1970s, design work was begun of the R-33 long-range missile in the State Machine Building DO Vympel. This was in response to the development of the F-14a fighter with the AIM-54A Phoenix missile in the United States. The R-33 missile together with the MiG-31 fighter were to constitute a multichannel system for long-range interception, Zaslon. The aerodynamic scheme of the missile is a standard one. The upper pair of rudders is deflected outward when the missile is attached to a carrier–aircraft. The R-33 missile has inertial control and semi-active radar homing in the terminal flightpath. The MiG-31 fighter is equipped with an onboard radar station with a phased antenna array, capable of guiding four missiles simultaneously to four targets, flying at different altitudes. The whole control system was developed at the SPA Fazotron under the direction of the chief designer V. K. Grishin. In 1980, the R-33 missile was adopted (for the MiG-31).

The R-33E modification was made later (designated R-37). The R-33E missile hits targets at altitudes from 20 to 50 m over different surfaces having a range of 26–28 km and velocity to Mach 3.5, flying ±10 km lower or higher than the carrier–aircraft. It is capable of hitting four targets at once at different altitudes and intervals. At the MAKS-95 exhibition, its range was indicated to be 120 km, but some data received from abroad suggest that it is 160 km. A schematic view of the R-33 missile is given in Fig. 28. The tactical-technical characteristics of the R-33F missile are presented in the Table 14.

The short-range (infighting) R-60 missile was developed in the State Machine Building DO Vympel. It was the first and the last infighting missile made in Russia. The R-60 missile had an aerodynamic canard fin scheme with a destabilizer. The missile length was 2100 mm, the body diameter was 120 mm, and the wingspan was 390 mm. The initial weight was 45 kg. The weight of the warhead was 3.5 kg. The warhead was equipped with radar and optical or combined fuze. The missile had an infrared homing device. The range at high altitude equaled 0.5–10 km, at low altitude the range was 0.3–1.5 km. The R-60 missile entered service in 1974 and could be carried by all types of fighters, including the MiG-21, MiG-23M, MiG-25PD, MiG-29, MiG-29C, MiG-31, Su-24M, Su-25T, and Yak-38. The R-60M and R-60MK missiles are modifications of the R-60 missile; they were adopted in the late 1970s. In the second-half of the 1980s in Soviet Army workshops, the Me-VV helicopters were equipped with the R-60 missile. A schematic view of the missile is presented in Fig. 29.

Table 14 Tactical–technical characteristics of the R-33E missile

Characteristics	Value
Length, mm	4150
Body diameter, mm	380
Wing span, mm	900
Rudder (jet) span, mm	1180
Initial mass, kg	490
Warhead mass, kg	47
Warhead type	Blast-fragmenting
Maximum launch range, km	120
Peak altitude of targets, km	0.05–28

At the end of this section, let us consider the information on one more air-to-air solid-propellant missile, the R-23, which until 1982 remained superior to its foreign analogs in efficiency in complicated informational situations, in interference protection against various types of interferences, and in the presence of reflective surfaces during attacks on low-flying targets.

In 1982, the U.S. AIM-7M missile with Doppler pulse homing device attained the level of efficiency of the R-23 missile. The R-23 missile was designed according to a standard aerodynamic scheme with a destabilizer (Fig. 30). The length of the missile was 4.46 m, the body diameter was equal to 200 mm, and the wingspan was 1.0 m. The initial mass of the missile was 223 kg, the warhead mass was 25 kg, and the range was from 25 to 35 km. The missile was capable of hitting targets at altitudes from 40 m to 25 km. It had a RGS-23 radar homing device with signal monopulse processing. Two modifications of the missile were made. One, R-23R, had a radar homing device, and the other, R-23T, had an infrared homing device. The R-23T modification has a smaller mass, about 217 kg, and its length was 4.18 m. The MiG-23M, MiG-23MR, MiG-23ML, and MiG-23MLD aircraft were equipped with the R-23R and R-23T missiles.

D. Air-Defense Guided Missiles

In the Soviet Union, antiaircraft guns were no longer used against flying targets after the period of the Korean War. Work on creation of air-defense guided missiles had begun immediately after World War II.

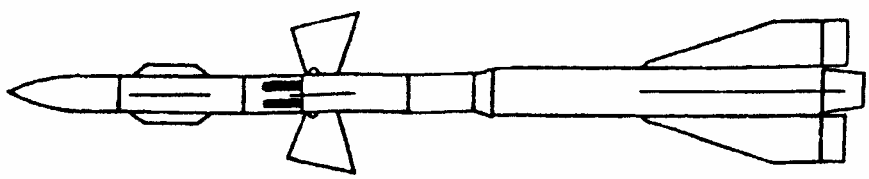

Fig. 27 Airborne R-27ER missile.

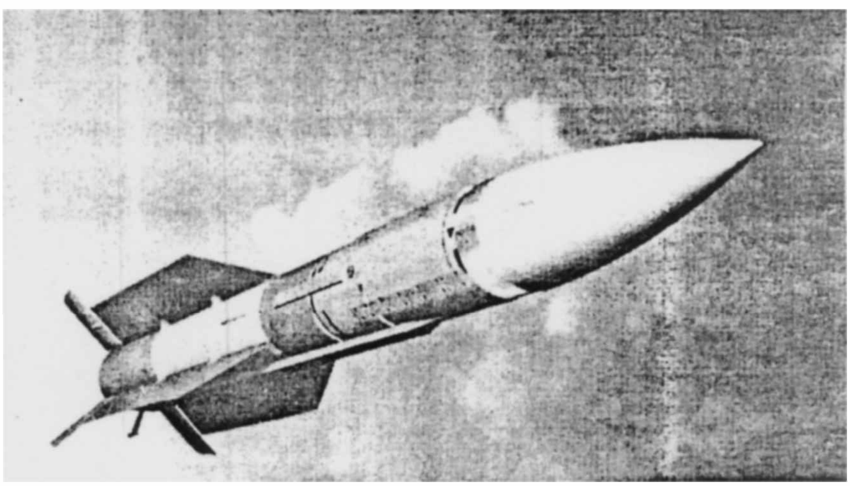

Fig. 28 Airborne R-33E missile.

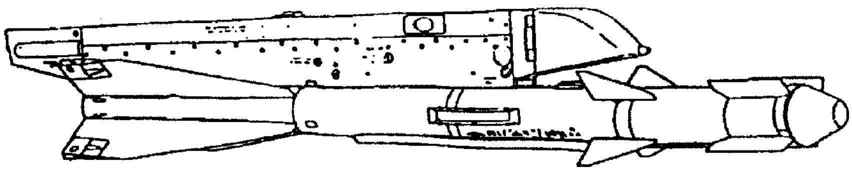

Fig. 29 Airborne R-60 missile.

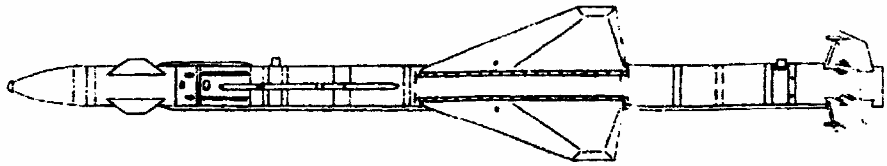

Fig. 30 Airborne R-23R missile.

Air-defense missiles were first made with liquid-propellant rocket engines, and solid-propellant rocket motors were used as boosters. However, starting with the S-300 system, air-defense missiles used only solid propellants. Grushim dreamed (see Ref. 16) of creating a missile that would not demand any special maintenance. Only solid-propellant missiles were capable of meeting this requirement. Russian designers had managed to make air-defense guided missiles with solid-propellant motors before the S-300, that is, before the 1970s. For instance, the V-757 missile developed by the DO of Grushin was a solid-propellant missile. The development of the missile started in 1958. The V-757 missile had a booster, a sustainer rocket engine, a control system, and other components of the payload. The sustainer rocket engine contained a solid-propellant gas-generator fueled ramjet. The engine had a specific impulse of 500 kgf · s/kg. The flight velocity of the V-757 missile was Mach 3.7, and the average flight velocity was 820–860 m/s when the range of the active flightpath was equal to 40 km. The maximum flight altitude was 23 km. The mass of the missile ranged from 2635 to 3045 kg. This missile was radio-controlled. The missile was never adopted for use.

The V-600P missile entered the one-channel air-defense rocket system S-125 having a 3-cm band. In this system, control (or governing) commands were formed based on the projection of forces in one direction and not three directions as it should have been done. The system was designed to hit pilotless and piloted air targets at low and high altitudes. The V-600P missile was a solid-propellant missile with a sustainer rocket engine and a booster rocket engine. The booster had folding fins. The range was from 6 to 20 km. The peak target hitting altitude was 12 km; the minimum altitude was 200–300 m. The length of the missile was 6.09 m, the body diameter of the main stage was 0.375 m, and the diameter of the launch stage was 0.55 m. The initial mass of the missile equaled 912 kg. The missile was capable of hitting targets with a speed up to 1500 km/h, and it was equipped with a warhead having a mass of 60 kg. The missile was radio controlled. The missile was adopted by the Soviet Army in 1961 (Fig. 31).

The S-125M system, a variation of the S-125 system, is one of the most successful late developments. The S-125M system contained the television guidance system Karat 2 and a two-stage V-601 solid-propellant missile; it was put into service in 1970. The system had target interception altitudes from 50 to 18,000 m, and its V-601 missile was capable of performing maneuvers at up to 6-g acceleration.

The next version of the S-125 system is the S-125M1, which was adopted in 1978. It contains the V-601PD missile. This air-defense system has a short-range limit of air target interception equal to 3.5 km, and the minimum altitude of interception is 20 m. The mass of the warhead of the missile was increased up to 72 kg, and the launcher equipment ammunition has 16 missiles instead of 8. The initial mass of the V-601PD missile is 980 kg. After 30 years of service, this system is still operational, and it has the potential to remain operational in many countries of the world until 2020–2030 (Ref. 17). This system has been exported to 35 countries.

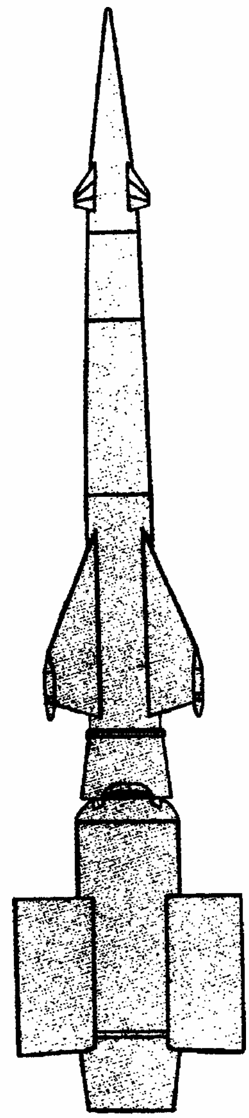

Fig. 31 Missile 5V24 (V-600P).

By 1978, the multipurpose S-300PT system with one-stage solid-propellant guided air-defense missile having a command–control system had been developed. In 1979, a new air-defense system was put into service. It contained the V-500K missile, which was transported in a transport–launch container. Before launch, the lid of the container is dislodged by the gases of the solid-propellant gas generator, and the missile is catapulted out of the transport–launch container to an altitude about 20 m. At this stage (1–2 s after catapult

Fig. 32 Missile 48N6.

actuation), the sustainer rocket engine switches on, and the missile turns and moves toward the target carrying out the ground-to-air commands. The initial mass of the missile is 1480 kg, the range is from 8 to 50 km, and the firing altitude is in the range from 25 to 25,000 m. The warhead mass of the missile is 130 kg, and the firing duration is 8–10 s.

The S-300PT system operates in self-regulating mode. It fulfills the following tasks: target acquisition, target tracking, distribution of targets, missile launch, target lock-on, target autotracking, guidance, and result evaluation. The operator's functions consist of performing control over the operation of the technical means used. The system is able to operate under conditions of intensive interference and can realize control over a large set of flying targets by the command system. Besides the V-500K missile, the S-300PT system includes illuminating radar and radar guidance, a command system, a radar acquisition device, a multiprocessor digital computational center, a communication system, about 12 launchers, and about 40 missiles, which are ready to be launched. The command–control system allows operation of about six systems at a time. Each system is capable of firing at 6 targets at a time, guiding about 12 missiles to the targets. The S-300PT system was made under the direction of B. V. Bunkin. The chief designer of the V-500K missile was Grushin (see Ref. 16).

In 1981, the V-500K missile in the S-300PT system was replaced by the V-500R missile, and the updated system was put into service. The V-500R missile has a semi-active homing device-converter, its initial mass was 1665 kg, and the maximum range was 75 km. The firing altitudes could be varied from 25 to 27,000 m.

Another variant of the S-300 system is the S-300PM. It was developed under the direction of Bunkin. It has heightened interference protection. The illuminating radar, guidance radar, command system, acquisition radar, launcher, and 40U6 multiprocessor computational complex were new. Also, a new solid-propellant, one-stage 49N6 missile was developed. The chief designer of the missile was Grushin. The development of the S-300PM system was finished in 1988. In 1989, the missile was adopted. The 48N6 missile together with the traditional warhead can be supplied with a powerful warhead causing detonation of the warheads of a ballistic missile. The range of the 48N6 missile is 150 km. The missile is supplied with a semi-active radar homing device, which transmits target information to the ground by radio. The control commands for the missile originate in a ground digital computational center; they are based on analysis of the data transmitted from the missile and from several guidance and viewing radar stations. They are then transmitted to the missile. As can be seen, this is no longer an air-defense missile; it is rather an antimissile system capable of annihilating the warheads of approaching ballistic missiles (Fig. 32). The S-300P system can be exported.

At present, development of new of means air defense is being continued. The development of the long-range S-400 system has been completed. Its missile range is 400 km. However, using a different type of a missile for this system gives it the capability of hitting targets at smaller distances. The standardized system equipped with short- and long-range missiles is designated Triumph. Its testing on the pad at Kapustin Yar started in 1993. In general the work on this system was performed under the direction of A. A. Lemansky. The development of the Triumph system has been conducted under the direction of V. G. Svetlov. The development of other types of air-defense and antimissile missiles is being conducted together with the development of the Triumph system.

VI. Conclusions

This paper on the history of solid-propellant rocket weapons in Russia in the 20th century is, by necessity, abbreviated. To give a full description of each missile or missile system, several volumes would be required. This paper describes some characteristics of some of the best-known missile systems to give a general idea of their development, function, and use. The author did not try to describe all existing solid-propellant missiles.

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References

[1]Wimpress, R. N., *Internal Ballistics of Powder Missiles*, Izdatelstvo inostrannoy literatury, Moscow, 1952.

[2]Gazenko, V., "The Birth of 'Katyusha,'" *Technika i vooruzheniye*, No. 2, 2001.

[3]Kiselyov, A. M., *The Matter of Great Importance*, Izdatelstvo DOSAAF SSSR, Moscow, 1983, p. 96.

[4]Zabelin, L. V., *From the History of the Russian Powder Industry, Short Biographical Essays*, Central Research Inst., Scientific–Technical Inst. of KPK, Moscow, 1997, p. 80.

[5]Bratukhin, A. G. (ed.), *Aircraft Building in Russia*, Mashinostroyeniye, Moscow, 1995, p. 392.

[6]Glushchko, V. P. (ed.), *Cosmonautics Encyclopedia*, Izdatelstvo Sovetskaya Encyclopedia, Moscow, 1985, p. 528.

[7]Vernidub, I. I., "The Contribution of Research Institute-6 in the Creation of RS30 BM-13 ('katyusha')," *The Pioneers of Rocketry, Andrei Grigorievich Kostikov*, M. V. Keldysh Research Center, Moscow, 1999, pp. 185–200.

[8]Sadovsky, I. N., "The Development of the First Russian Solid-Propellant Strategic Missiles 8K95, 8K98, 8K98P," *From the History of the Russian Powder Industry*, edited by, L. V. Zabelin and I. D. Skvortsov, Central Research Inst., Scientific–Technical Inst. of KPK, Moscow, 1997, pp. 13–29.

[9]Karpenko, A. V., Utkin, A. F., and Popov, A. D., *Russian Strategic Missile Systems*, Saint-Petersburg, 1999, p. 288.

[10]Kalabukhov, G. V., and Smirnov, L. A., *A Brief History of the Creation of the Composite Solid Propellants*, MIChM, Moscow, 1998, p. 74.

[11]Zhukov, B. P. (ed.), *Energy Condensed Systems. Concise Encyclopedic Dictionary*, 2nd ed., corrected. M.: Yanus-K, 2000, p. 596.

[12]Shpak, V. S., "The Contributions of the State Institute of Applied Chemistry and Some Other Organizations of the Leningrad Region to the Development of the Production of Composite Solid Missile Propellants and Solid-Propellant Engines," *From the History of the Russian Powder Industry*, edited by L. V. Zabelin and I. D. Skvortsov, Central Research Inst., Scientific–Technical Inst. of KPK, Moscow, 1997, pp. 30–44.

[13]Chertok, B. Y., *Rockets and People, Recollections*, Vols. 1 and 2, Mashinostroyeniye, Moscow.

[14]Mazurov, N. P., Vinogradov, A. N., and Agafonov, V. N., "From Shells to Missile Systems," Collection of Articles and Documents Dedicated to the Centenary of A. G. Kostikov, edited by Y. G. Demyanko, Moscow, 1999, pp. 160–169.

[15]Makarovetz, N. A., "From 'Katyusha' to 'Smertch,"' Collection of Articles and Documents Dedicated to the Centenary of A. G. Kostikov, edited by Y. G. Demyanko, Moscow, 1999, pp. 170–176.

[16]Shirokorad, A. G., *The History of Aviation Weapons. Brief Essay*, Harvest, Minsk, Belarus, 1999, p. 559.

[17]Pervov, M., "Anti-Aircraft Missile Weapon of the Anti-Aircraft Defense of the Country," Aviarus-XXI, Moscow, 2001, p. 309.