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World's First ICBM and Space Launcher: Early Years of R-7 Rocket

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Abstract

The historic first intercontinental ballistic missile R-7 (ICBM SS-6) placed the first artificial satellites into orbit in 1957, ushering in the space age. This Soviet two-stage rocket relied on radio control from the ground during the powered ascent. The control system used two remote radio control posts, RUPs, and an onboard computing unit to steer the missile. This design significantly complicated rocket deployment as a weapon and limited it to launching satellites into orbits with only one possible inclination. The reasons for choosing the implemented radio control and the gradual elimination of its weaknesses are poorly known. The article focuses on the early years of the R-7 and its evolution and trials at the Tyuratam Missile Test Range, also known as the Baikonur cosmodrome, in the late 1950s. Analysis of declassified Soviet government documents, CIA intelligence reports, and Corona reconnaissance photographs led to locating the RUP radio control outposts that supported R-7 launches. The official records of the ICBM tests and launches of the first Earth-orbiting artificial satellites and space probes to the moon and planets in 1957-1960 show the enormous scale and technical challenges of developing and modifying the rocket. The Soviet military operationally deployed the SS-6 only in limited numbers from 1960-1967. The new ballistic missiles relying on storable propellants began to supersede this liquid-oxygen-kerosene ICBM in the early 1960s. The inertial control systems also replaced cumbersome radio control, and the modernized R-7 rocket evolved into a successful family of efficient Soyuz space launchers, placing satellites into orbit to this day.

Keywords: R-7, space launcher, ICBM, flight control, Tyuratam, Baikonur

Acronyms/Abbreviations

CC CPSU	Central Committee of the Communist Party of the Soviet Union
CM USSR	Council of Ministers of the USSR
DoD	U.S. Department of Defense
ICBM	intercontinental ballistic missile
IRBM	intermediate-range ballistic missile
SS	surface-to-surface
TTMTR	Tyuratam Missile Test Range
UDMH	unsymmetrical dimethylhydrazine
USSR	Union of Soviet Socialist Republics
WWII	World War II

Russian Acronyms/Abbreviations/Terminology

BRK	bokovaya radiokorrektsiya (side radio correction)
GRAU	Glavnoe Raketno-Artilleriiskoe Upravlenie (Main Missile and Artillery Directorate)
IP	izmeritel'nyi punkt (measurement [instrumentation] post [site, station])
IPG	izmeritel'no-preobrazovatel'naya golovka (measurement-transducer head)
KB	konstruktorskoe byuro (design bureau)
LKI	letno-konstruktorskie ispytaniya (flight design tests)
NII	nauchno-issledovatel'skii institut (scientific research institute)
MEI	Moskovskii Energeticheskii Institut (Moscow Power Engineering Institute)
MIK	montazhno-ispytatel'nyi korpus (assembly and testing building)
NII	nauchno-issledovatel'skii institut [scientific research institute]
NIIP	nauchno-issledovatel'skii ispytatel'nyi poligon [scientific research test range]
NIP	nauchno-izmeritel'nyi punkt (scientific measurement [instrumentation] post [site, station])
OIS	otdel'naya ispytatel'naya stantsiya (separate test station)
OKB	osoboe konstruktorskoe byuro (special design bureau)
PIK	poligonnyi izmeritel'nyi kompleks (test range measurement complex)
postanovlenie	decree, decision, ordinance
PS	prosteishii sputnik (simplest satellite)
p/ya	pochtovyi yashchik (mail box)
RNII	Reaktivnyi Nauchno-Issledovatel'skii Institut (Jet Propulsion Research Institute)
RUP	radioupravleniya punkt (radio control post [site])
TsSKB	Tsentral'noe Spetsializirovannoe Konstruktorskoe Byuro (Specialized Design Bureau)
UIR	Upravlenie Inzhenernykh Rabot (Directorate of Engineering Works)
UR	universal'naya raketa (universal rocket)
v/ch	voinskaya chast' (military unit)

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1. Introduction

While recovering from the devastation of World War II, the Union of Soviet Socialist Republics (USSR) poured enormous resources into development of nuclear weapons, ballistic and guided missiles, jet aviation, radar, and electronics. The country viewed ballistic missiles as an important asymmetric counterweight to the superior strategic air power of the United States and its allies in the early Cold War. Consequently, achieving an offensive capability of striking the "main adversary," the United States of America, with nuclear weapons from Soviet territory became a top national priority. At the same time, the USSR had also been building air defenses and strategic missile defense [1].

This focus on ballistic missiles with increasing range and reentry vehicle weight (a warhead with a protective enclosure, deployment mechanisms, and possibly guidance systems) led to the first intercontinental ballistic missile (ICBM), R-7 (SS-6). The missile successfully flew on the full range for the first time on August 21, 1957. Two months later, a variant of the Soviet rocket achieved another world's first, placing a satellite into Earth orbit. These accomplishments relied on advances in science, engineering, and manufacturing; creation of the new Tyuratam Missile Test Range (future Baikonur cosmodrome); and formation of specialized military units, reorganized as a new branch of the armed forces, the Strategic Rocket Forces, in December 1959.

This article describes the development of the R-7 rocket in the 1950s, leading to the first operational ICBM and first space launches. Publications usually describe the missile structure, propulsion, and top-level performance characteristics, with very few details about its flight control. They often only mention that the rocket combined inertial ("autonomous" in the Russian terminology) guidance and radio control [2-7]. This lack of details is not surprising because guidance of strategic missiles has always been among the tightly guarded state secrets.

The design bureau of Sergei P. Korolev built the R-7. Its corporate history noted, for example, that "placing launch complexes for firing ICBMs at … [one proposed and very attractive] location [for the new missile test range] would have created unsurmountable difficulties for deploying [remote] posts of the R-7 rocket radio control" [2]. A history of the institute that had designed the R-7 flight control described that "the ground equipment was located at the main and mirror [radio control] posts at distances of 250 km from the launch site on both sides of the trajectory plane" [8]. The publication did not elaborate on the functions of these radio control units and where exactly the military placed them.

The initially implemented guidance system of the R-7 had highly consequential effects on the rocket's performance, operations, and cost. It severely limited its capabilities both as an ICBM weapon and a space launcher. Very little is also known about how and when this flight control system evolved, eliminating many shortcomings.

The article fills this history gap. It relies on scarce information scattered across declassified documents and institutional histories [2,4-7,9-21] and recollections of event participants [22-38]. The article describes the main features of the R-7 radio control and points out likely justifications for the design decisions. It identifies, for the first time, and validates by reconnaissance photographs the exact locations of the rocket radio control posts during ICBM trials and first space launches at Tyuratam (Baikonur).

The sequence of the rocket flights and satellite launches from 1957-1960 shows the scope of the program and rocket evolution. The modifications of the R-7 in the late 1950s, especially changes in the control system, eliminated some original weaknesses and led to its operational deployment as the first Soviet ICBM SS-6. The added upper stages enabled the R-7 to send the first spacecraft to the moon and inner solar system planets and prepared it for a launch of the first cosmonaut to space in 1961.

The comparison with the design and development of the first U.S. ICBM and the R-7 evolution after 1960 are beyond the scope of this publication. The article concludes with a discussion of consequential design decisions of the R-7 flight control under the political and administrative realities and constraints of the Soviet society at the time of the events.

2. Emergence of Soviet ballistic missile establishment

The foundations of modern Soviet rocketry date back to the 1930s. The emerging powerful ballistic missiles belonged to a category of inherently complex and advanced technologies wherein an isolated, creative, and gifted inventor could not succeed. Only the concerted effort of numerous well-organized professional scientists and engineers supported by significant national resources could lead to practical systems [39,40] such as the German ballistic missile A-4 (better known as V-2) of World War II, a technological marvel of its time. The Soviet Union and National-Socialist Germany were the first to recognize the promise of missiles and initiate large-scale rocket development in the early 1930s.

The Red Army embarked on the development of solid- and liquid-propellant rockets on a large scale. On September 21, 1933, Order No. 0113 of the Revolutionary Military Council of the USSR consolidated heretofore scattered rocket research and development in the Jet Propulsion Research Institute (abbreviated RNII in Russian). Another organizing Decree No. 104 of the Labor and Defense Council followed on October 31. By 1934, RNII employed nearly 400 scientists, engineers, and technicians, and 600 people

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one year later [10,41,42]. Political purges of rocketeers soon significantly weakened the Soviet effort.

As World War II drew to a close and the German A-4 demonstrated the extraordinary potential of ballistic missiles, the USSR revitalized its rocket program. During and shortly after the war, the Soviet state created an extensive network of organizations for the pursuit of advanced weapons. These new establishments and their successors provided the foundation for the accelerated missile development in the late 1940s and beyond [40,43].

The leaders of the Soviet Union commonly issued a special top-secret decision (decree, ordinance, resolution), called *postanovlenie* in Russian, to authorize, organize, and marshal national resources for a specific important program in rocketry, weapon systems, and space. The highest levels of the Communist Party and government approved such a joint "*Postanovlenie* of the Central Committee of the Communist Party of the Soviet Union (CC CPSU) and the Council of Ministers (CM) of the USSR," conveniently shortened to "*Postanovlenie* of CC CPSU and CM USSR." The Council of Ministers also issued its additional decrees to organize particular aspects of work.

Depending on the complexity of a program, a *postanovlenie* coordinated the work of many, sometimes up to several hundred, research and development institutions, design bureaus, and industrial plants, managed by various ministries and located across the vast Soviet Union. Such a government decree outlined specific objectives for each involved organization and allocated the funding and other resources [12,14,16,18]. Not fulfilling the tasks assigned by a *postanovlenie* of the CC CPSU and CM USSR could end the career of a chief designer or the director of an industrial plant. The standing of ministers was also on the line.

One year after the end of World War II, the USSR Council of Ministers issued the foundational *Postanovlenie* No. 1017-419ss "Matters of the Rocket Weapons" to organize work on ballistic missiles. Soviet dictator Joseph (Iosif) Stalin signed it on May 13, 1946. The decree identified a specific top priority goal of "reconstruction, using the domestically designed and built materials, of the [advanced German] rockets V-2 (long-range guided missile) and the Wasserfall (antiaircraft guided missile)" [44].

Subsequently, the government established a number of research institutions and design bureaus for this task, at first mostly in Moscow and its suburbs. It also converted many aviation and artillery plants into the centers of rocket development and production. In 1946, the Ministry of Defense activated the new State Central Test Range N. 4 at Kapustin Yar for trials of ballistic missiles and deployed there a brigade of the nascent rocket forces.

Two areas on the outskirts of Moscow, Khimki and Podlipki, soon emerged as the major centers of Soviet rocketry and the future space establishment [40]. Special Design Bureau No. 456 (OKB-456) was organized in the town of Khimki, on the main road to Moscow's future international airport Sheremetyevo. Under Valentin P. Glushko, OKB-456 became the leader in the development of high-thrust liquid-propellant rocket engines. Today, it is NPO Energomash [11].

The area near the suburban railroad station Podlipki (also known as the town of Kaliningrad, today's Korolev) also grew to a particular prominence. Located 25 km north-northeast of Moscow downtown, it boasted, within a decade, the highest concentration of rocket and space research and development organizations.

The foundational decree of 1946 established a new rocket research center, Scientific Research Institute No. 88 (NII-88) at Podlipki. The government made Sergei P. Korolev responsible for long-range rockets at the institute. His Department No. 3 focused on the reconstruction of the German A-4 ballistic missile, using the Soviet-designed and produced parts, components, and materials. By 1948, the Korolev team at NII-88 had built such a rocket, the R-1 [2]. The military accepted it for operational deployment in 1950.

The R-1 became the first rocket in a family of increasingly powerful ballistic missiles designed by Korolev. His new R-2 rocket with a significantly increased range of 580 km would be the next. The Soviet Army operationally deployed the R-2 in 1952.

The work on ballistic missiles in the late 1940s established cooperation among leading research and design organizations and manufacturing plants, which remained the backbone of the Soviet rocket and space programs for many years. In NII-88, Korolev directed the overall ballistic missile development. Glushko's OKB-456 advanced science and engineering of propulsion and built rocket engines. Mikhail S. Ryazansky and Nikolai A. Pilyugin, in the Scientific Research Institute No. 885 (NII-885), concentrated on the radio control and autonomous guidance systems, respectively. Viktor I. Kuznetsov, in the Scientific Research Institute No. 10 (NII-10), built gyroscopes. (Kuznetsov formed a new separate institute, NII-944, dedicated to this technology in 1955.) The State Design Bureau of Special Machine Building (GSKB Spetsmash), headed by Vladimir P. Barmin, designed ground launch complexes and equipment. These leaders and a few others constituted a highly influential council of chief designers, headed by Korolev (Fig. 1).

In 1950, Minister of Armaments Dmitrii F. Ustinov reorganized the growing Korolev's group into Special Design Bureau No. 1 (OKB-1) within NII-88. Then, OKB-1 separated from NII-88, became an independent organization, and combined with the nearby pilot Plant No. 88 in 1956. At that time, the design bureau personnel,

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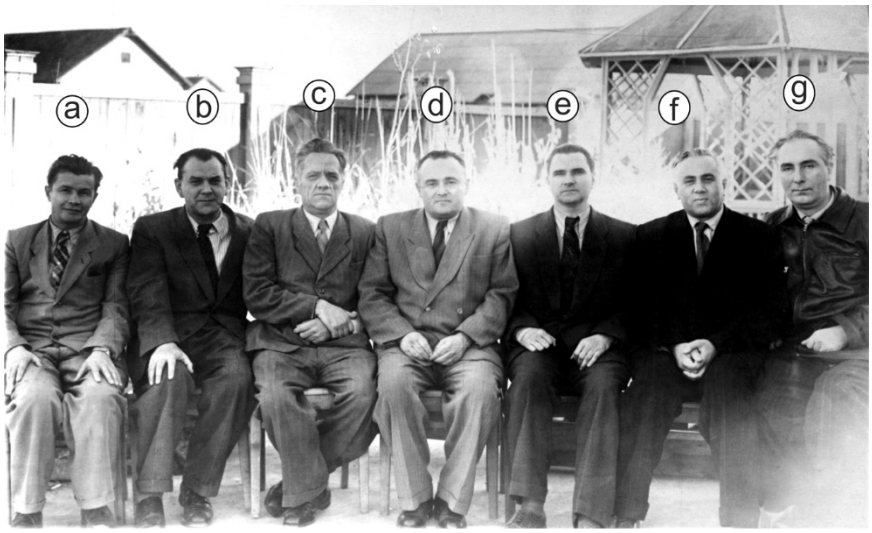


Fig. 1. Leading chief designers of Soviet ballistic missile and space systems and subsystems on October 4, 1957, at Tyuratam after the successful launch that day of the first artificial satellite of the Earth. Left to right (a) – Aleksei F. Bogomolov (1913–2009), space telemetry systems; (b) – Mikhail S. Ryazansky (1909–1987), radio guidance systems; (c) – Nikolai A. Pilyugin (1908–1982), autonomous guidance systems; (d) – Sergei P. Korolev (1906–1966), rockets and spacecraft; (e) – Valentin P. Glushko (1908–1989), rocket engines; (f) – Vladimir P. Barmin (1909–1993), ground launch systems; and (g) – Viktor I. Kuznetsov (1913–1991), inertial guidance and gyroscopic systems. Photo courtesy of NPO Energomash, Khimki, Russia.

without the plant, counted 1500 people. After Korolev died in 1966, this growing establishment became the Central Design Bureau of Experimental Machine Building, or TsKBEM (then Rocket Space Corporation Energia, or RKK Energia, in the 1990s) [2,40].

OKB-1 was not the only enterprise to acquire an open name in the 1960s. While some plants used common names, many industrial scientific research institutes, design bureaus, and manufacturing organizations were known by assigned numbers. This was especially common for establishments in defense-related areas. In the mid-1960s, the Soviet Union introduced "open" names for these "numbered" organizations. In addition to their new designations, many entities retained and continued to use other, so-called "mail box" (*pochtovyi yashchik* in Russian, abbreviated *p/ya*) identifications, particularly in the classified environment.

The Main Missile and Artillery Directorate, GRAU, of the USSR Ministry of Defense had been assigning alphanumeric combinations to armaments, weapons, and equipment. The sequences beginning with "8A" and later "8K" designated ballistic missiles and space launchers. The R-1 ballistic missile was article 8A11. Later, the third and fourth symbols (digits) in this nomenclature, following 8K, referred to rockets developed by different organizations (and their chief designers) and specific models, respectively: 8K6x – for rockets developed by design bureau OKB-586 (under Mikhail K. Yangel, sometimes transliterated as Yangel'), 8K7x – by OKB-1 (Korolev); and 8K8x – by OKB-52 (Vladimir N. Chelomei). The sequence 8K9x indicated solid-propellant ballistic missiles.

A variant of the next R-5 rocket of Korolev's OKB-1, R-5M (8K51), became the first Soviet ballistic missile capable of carrying nuclear warheads. Similar to its predecessors, the R-5M relied on liquid oxygen and alcohol propellants, inherited from the German A-4 design. In 1956, the military launched R-5M, for the first time in rocket history, with a live nuclear warhead and detonated it at the target. The same year, the Soviet Army accepted for deployment this intermediate-range ballistic missile (IRBM) with a range of 1200 km.

The Intermediate-Range Nuclear Forces Treaty (INF Treaty) of 1987 defined intermediate-range ballistic missiles, IRBMs, as those with a range of 1000-5500 km. Intercontinental ballistic missiles, ICBMs, are missiles with a range larger than 5500 km. Table 1 lists the first operational Soviet short-range ballistic missiles and the first-generation strategic ballistic missiles (IRBM and ICBM) built in the 1950s and early 1960s. It also shows the U.S. Department of Defense (DoD) designations (SS, standing for *surface-to-surface*) and NATO reporting names.

The advent of nuclear weapons made geographic concentrations of national assets in strategic technologies especially vulnerable. Consequently, the Soviet Union

Table 1. Early Soviet short-range and strategic ballistic missiles.

	GRAU	DoD	NATO		designer
R-1	8A11	SS-1	Scunner		Korolev
R-11	8A61	SS-1b	Scud-A		Korolev
R-2	8Zh38	SS-2	Sibling		Korolev
First generation of strategic missiles					
R-5	8K51	SS-3	Shyster	IRBM	Korolev
R-12	8K63	SS-4	Sandal	IRBM	Yangel
R-14	8K65	SS-5	Skean	IRBM	Yangel
R-7	8K71	SS-6	Sapwood	ICBM	Korolev
R-7A	8K74	SS-6	Sapwood	ICBM	Korolev
R-16	8K64	SS-7	Saddler	ICBM	Yangel
R-9A	8K75	SS-8	Sasin	ICBM	Korolev

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dispersed important development and industrial facilities throughout the country. In rocketry, it first established series production of Korolev's R-1 (SS-1) ballistic missiles at a plant in Dnepropetrovsk, today's Dnipro in Ukraine, in 1951. (In this article, I use the geographic names common in the Soviet Union during the time of the described events, sometimes adding in parentheses the names used today.) Transfers of other programs followed, creating important new centers in rocketry, propulsion, and satellites in Krasnoyarsk, Kuibyshev (Samara), Miass, Omsk, and other places [40].

Mikhail Yangel served as director of NII-88 at Podlipki from 1952-1954. In 1954, the government transferred him to Dnepropetrovsk to lead the newly created Special Design Bureau No. 586 (OKB-586) to support the co-located plant for series production of the R-1, R-2, and R-5 missiles. OKB-586 quickly embarked on new independent projects. Also known as the Design Bureau Yuzhnoe (KB Yuzhnoe), it soon became a fierce rival of Korolev in ballistic missiles. In the early 1960s, the "universal rocket," UR, of Vladimir Chelomei's OKB-52 challenged both Korolev and Yangel, leading to another successful family of strategic ballistic missiles and space launchers.

In contrast to Korolev, OKB-586's Yangel and Vasilii S. Budnik focused on rockets using storable (non-cryogenic) propellants favored by the military [11,13,17, 40,45]. Soon, Yuzhnoe developed a highly successful nuclear-capable intermediate-range ballistic missile R-12 (8K63, SS-4, Sandal) with an entirely autonomous (all inertial) guidance system and a range of 2000 km. Already in 1960, the Soviet Union had on active operational duty 172 R-12s, compared to 36 of Korolev's R-5s. The country increased the number of deployed R-12s to 458 and 568 in 1962 and 1964, respectively, while the number of R-5s did not change [9].

The rapid expansion of Soviet rocketry and space activities in the 1950s and the early 1960s enjoyed the enthusiastic support of the supreme leader of the country. Nikita S. Khrushchev had come out as the winner in a power struggle in the Kremlin after the death of Stalin in 1953. He was fascinated by ballistic missiles and their capabilities. Speaking to graduates of military academies in 1958, Khrushchev described, in his memorably folksy way, the new age of automated computer-controlled nuclear-armed missile systems: "It is sufficient now only to press a button, and not only [military] airfields and means of communications of various headquarters will [be hit and] fly into the air but entire cities. Entire countries can be destroyed" [46]. The Soviet leader also viewed ballistic missiles and nuclear weapons as a way to dramatically reduce the conventional ground forces, aviation, and the navy, thus redirecting resources to the economic development of the country (e.g., [47]). One highly-placed veteran of the Soviet rocket industry observed that Khrushchev's "enthusiasm and effervescent activity … without any doubt was conducive to the speeded up development of rocket and space programs in the USSR" [22,32].

A "palace coup" ousted Khrushchev from his office in October 1964. The new Soviet rulers, led by Leonid I. Brezhnev, remained committed to rapid arming of the Soviet Union with numerous and increasingly powerful ballistic missiles, deploying strategic missile defense, and expanding space effort, including antisatellite weapons and the lunar program. Only in the 1980s did U.S. President Ronald Reagan bring to a screeching halt the seemingly unstoppable growth of the Soviet offensive ICBM force by shifting the strategic competition into a highly technological area of ballistic missile defense.

3. Intercontinental weapon R-7

In 1950, OKB-1 worked on the short-range R-2 rocket and studied the bigger intermediate-range R-5. On December 4 of that year, the Soviet government approved the next major step in rocketry, a comprehensive feasibility study (Program N3) of future intercontinental missiles "with the range 5000-10,000 km and warhead mass 1-10 tonne" [2,48]. (The unit "tonne" with the symbol "t" means "metric ton" throughout the text, that is, 1 t = 1000 kg = 2204.6 lb. The same symbol "t" of metric ton is used for both mass and weight.)

The feasibility study had shown progress, and on February 13, 1953, Stalin signed *Postanovlenie* No. 443-213ss of the USSR Council of Ministers "On plan of research and development work on long-range rockets for 1953-1955." The decree authorized further development of a two-stage ICBM with a range of 8000 km, a warhead mass of not less than 3000 kg, and flight tests beginning in 1955. It also stipulated the radio guidance for flight control and emphasized its resistance to jamming and radio interference. The government increased the warhead size to 5500 kg in October of that year [2,12,14]. This large payload requirement led to a rocket significantly bigger than the first U.S. ICBM and a powerful space launcher.

Postanovlenie No. 443-213ss assigned the ICBM development to NII-88 of Ustinov's Ministry of Armaments. It made three specialists of the institute responsible for the program execution: Sergei P. Korolev as the chief designer of the missile, Vasilii P. Mishin as his deputy, and Mikhail K. Yangel as NII-88 director. The same government decree ordered the feasibility studies, under Korolev, of a two-stage intercontinental winged (cruise) missile with a similar range and payload capability. In the 1950s, the U.S. Air Force also pursued concurrent development of intercontinental winged missiles, the supersonic Navaho and subsonic Snark [40]. Both countries would cancel these long-range cruise missile programs by the early 1960s.

As preliminary design (Program T-1) of an intercontinental ballistic missile [48] had shown promise,

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a new decree of the USSR Council of Ministers, No. 956-408ss, approved building the first ICBM on May 20, 1954 [49,50]. The government designated the rocket R-7, GRAU's article 8K71. Many specialists would informally call it "semyorka," which stood for "number seven" with a flavor of affection in Russian.

This important decree by the country's new leadership upheld the national commitment to the top-priority ICBM program one year after the death of Stalin in March 1953. It confirmed OKB-1 under Korolev as the lead development organization and assigned the responsibilities for major R-7 subsystems, such as rocket engines, missile guidance, gyroscope components, power units, ground launch systems, and nuclear warheads [2,49]. The ICBM development became a major national undertaking. More than two hundred research institutes, design bureaus, and plants from 25 ministries contributed to the program [4]. A military scientific research institute, NII-4, located 5 km northeast of OKB-1, became responsible for trials of the missile at a test range and development of associated instrumentation.

On November 20, 1954, the USSR Council of Ministers approved the technical requirements for the R-7 and its preliminary design. The missile had to deliver a 5.5 t (12,100 lb) payload (reentry vehicle with a nuclear warhead) to a distance of 8000 km (4970 miles) with a 10-km (6 miles) accuracy in range and miss distance (side deviation). The planned nuclear device ("special warhead" or "special article," as it was called) weighed about 3000 kg (6600 lb) [2]. It could detonate either on the ground or above in the atmosphere [3]. The government decree stipulated the combined rocket guidance consisting of radio control and autonomous (inertial) systems and required resistance to radio interference and jamming.

The R-7 rocket had a central core section and four side sections attached to it (Fig. 2). Each section, called a block, carried its own engine, propellant tanks, and feed systems. The designers referred to the large central section as Block A and the side sections as Blocks B, V, G, and D [4,37,50], after the first five letters of the Cyrillic alphabet: А (A), Б (B), В (V), Г (G), and Д (D). The rocket engines of all five blocks were started simultaneously on the launch pad. The four side sections (considered the first stage of the rocket) were jettisoned after consuming their propellant in 115 seconds after liftoff. The central sustainer section (the second stage) burned for about 300 seconds.

The required ICBM flight distance and its heavy warhead determined the R-7 size and thrust. The weight of the 34-m-tall rocket was 280 t (617 klb) at liftoff. Together, the main engines of all five sections and additional 12 smaller steering engines provided a total thrust of 403 t (3.95 MN, 888 klbf) at sea level. A report to the Central Committee of the CPSU summarized the R-7 design in 1959:

> Large dimensions and liftoff weight of the [R-7] rocket were mainly determined by the large weight of the special [nuclear] charge available from the Ministry of Medium Machine Building [responsible for nuclear warheads] at the beginning of the R-7 development. The reduction [of nuclear charge weight] became possible only later, with a simultaneous increase of its yield. This [initial]

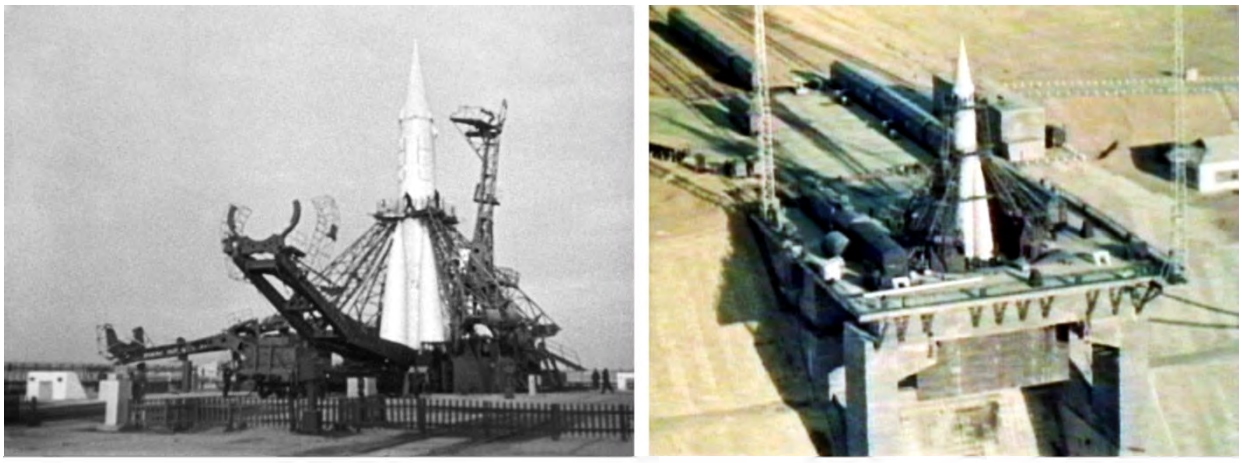


Fig. 2. The first ICBM R-7 at the Tyuratam missile range in May–June 1957. Left: Two tall service towers (shown detached from the rocket body) provided access to all parts of the rocket on the launch pad. Four inclined side masts held the rocket at its "waist," at a point somewhat higher than the rocket's center of gravity. Right: The R-7 launch platform stood out as a cliff over the gigantic flame pit beneath. Two tall masts in the corners of the platform served to illuminate the pad at night. They also protected it against lightning strikes. The military launched the first ICBM, the first artificial satellite, and the first cosmonaut from this position. Originally designed for 25 launches, the installation operated until 2019, launching more than 600 R-7s and its successor Soyuz space launchers. Photographs (Figs. 15.2 and 15.4 [40]) courtesy of Videocosmos.

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> requirement led to the development of an intercontinental rocket with a powerful propulsion system to deliver such a [heavy nuclear] charge to a distance not less than 8000 km. At the same time, [these] large energetic capabilities of the R-7 rocket enabled deployment of heavy satellites of the Earth into orbit and launch of space rockets [from the Earth to the moon and beyond] with large payload weights [49].

The parallel-mounted blocks of the R-7 offered an important advantage. This "packet" design avoided a major technical challenge in rocketry of the 1950s of starting a liquid-propellant upper stage in weightlessness after jettisoning the first stage in a conventional tandem (serial) configuration. Because of the uncertainty of the propellant location in not completely filled tanks of the upper stage, one had to prevent bubbles of the pressurizing gas from covering the propellant outlet. In addition, the rocket's non-hypergolic kerosene and liquid oxygen propellants did not ignite on contact and thus required a separate igniter, complicating the system.

The two-stage R-7 rocket somewhat resembled the first American ICBM Atlas, usually described as the "one-and-one-half-stage" missile. Atlas had two side blocks to be jettisoned after two minutes. Their engines also started simultaneously with the engines of the central sustainer stage on the launch pad. Unlike the R-7, however, the side blocks of Atlas did not carry the propellant and were fed from the tanks of the main central stage [40].

Valentin Glushko's OKB-456 designed and built kerosene-liquid-oxygen engines RD-107 (8D74) and RD-108 (8D75) for the side sections and the central core block of the R-7, respectively [11,51,52]. Maturing technologies of engine cooling made possible the substitution of kerosene for alcohol as fuel, which significantly improved the performance of new engines compared to those of the A-4, R-1, R-2, and R-5 rockets. To overcome the problems with high-frequency instabilities, OKB-456 built RD-107 and RD-108 with four combustion chambers each (Fig. 3, left). The development of an alternative single-chamber engine could not meet the program schedule.

In all R-7 blocks, the upper propellant tanks carried liquid oxygen while the lower tanks contained kerosene [2]. Decomposition of hydrogen peroxide in gas generators powered turbopumps that fed propellants into combustion chambers. In addition to its main engine, each rocket's block included small vernier engines (*steering engines* in the Russian terminology) for thrust vector control. These agile engines could tilt by 45 degrees and provided thrust up to 2.5 t (24.5 kN and 5.5 klbf) each [2,54].

The vernier engines controlled the missile trajectory during powered ascent. They also reduced uncertainties in the final velocity of a reentry vehicle after the cutoff of the main engine of the second stage and its separation. The velocity vector of the separated reentry vehicle determined the accuracy of hitting the target by a warhead. After the RD-108 cutoff, the small vernier engines continued to gently accelerate the missile for several seconds until the desired velocity was achieved. Then, a command turned them off with minimal velocity uncertainty.

A corporate history of OKB-1 notes that overcommitted Glushko's OKB-456 initially declined to build the vernier engines. Consequently, Korolev developed them internally in OKB-1 [2,4,22,32,53]. Later, OKB-456 joined the modification and production of the engines [52].

The successor of the R-7, today's space launch vehicle Soyuz, preserves the main features of the original rocket and engine design. As in the original R-7, there are two vernier engines in each side block and four vernier engines in the central section, respectively (Fig. 3, right). The use of so many engines brought another challenge. Some propellant components remained unused by the cutoff of their engines because of variations in propellant

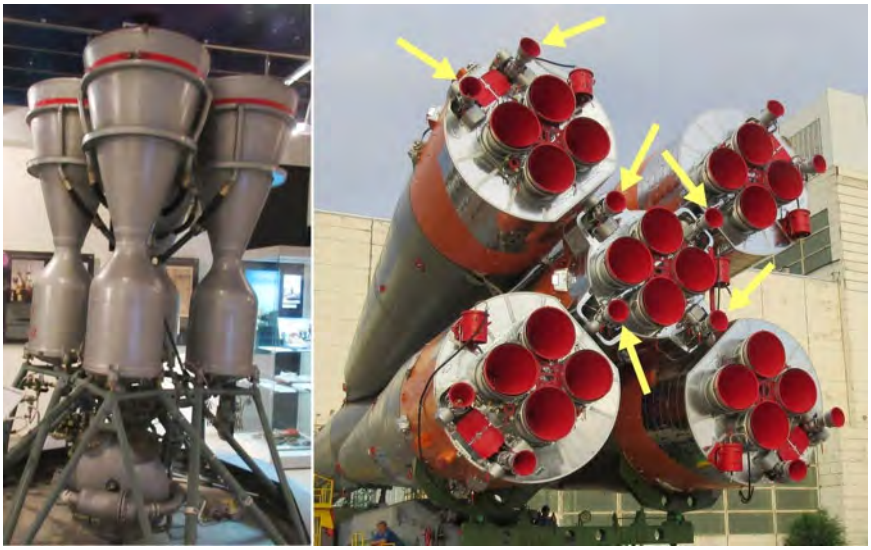


Fig. 3. Left: four-chamber RD-107 (8D74) of a side block of the R-7 in a space museum in Moscow. Right: R-7 successor, modern Soyuz launcher, at the Tyuratam missile range. The arrows point at 4 vernier engines of the second stage (central block) and 2 vernier engines of one of the four side blocks of the first stage. Photographs (July, 2016) by Mike Gruntman.

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pump rates and active control of thrusts during powered ascent. The remaining kerosene and liquid oxygen represented an inert, ballast mass carried by a rocket, thus reducing its throw weight and range. A special effort went into the development of a dedicated system to control the consumption rates and levels of fuel and oxidizer in the propellant tanks, minimizing the mass of unused propellant [2,4,22,32].

The main engines of the R-7 differed in combustion chamber pressures: 60 at in RD-107 and 52 at in RD-108. (1 at is one technical atmosphere or one kilogram-force per one square centimeter, 1 at = 1 kgf / cm^2 = 0.96784 atm.) In addition, their film cooling patterns were not identical but optimized to avoid high-frequency instabilities. The nominal thrusts and specific impulses of the engines at sea level (and in a vacuum, given in parentheses) were 83 t (102 t) and 256 s (313 s), respectively, for RD-107 and 76 t (96 t) and 248 s (315 s), respectively, for RD-108 [11]. (One tonne thrust is 1.0 t ≈ 9.8 kN ≈ 2.2 klbf.) The central core RD-108 could also operate for a longer period of time.

The Soviet Union planned operational deployment of a large number of ICBMs. Similar to setting the series production of the R-1 missile in Dnepropetrovsk, the government created new dedicated manufacturing centers for the R-7 rockets. On September 12, 1957, the Central Committee of the CPSU and the USSR Council of Ministers tasked officials (*Postanovlenie* No. 1125-510) to identify the most suitable industrial facilities for this purpose. Then, on January 2, 1958, *Postanovlenie* No. 2-1 assigned the lead plants for building rockets and their engines in Kuibyshev and the control systems (radio and autonomous) in Kharkov (Kharkiv), in Ukraine [54]. Subsequently, the government converted two large Kuibyshev plants manufacturing bomber planes (Plant No. 1) and aviation engines (Plant No. 24) to series production of rockets and engines, respectively [52,55]. Many other local industrial enterprises would supply various subsystems and components. A large regional center 800 km east-southeast of Moscow on the Volga River, Kuibyshev reverted today to the old prerevolutionary name Samara.

Aviation industry officials, including the highly influential airplane designer Andrei N. Tupolev, tried to prevent the repurposing of "their" aviation plants, but Soviet leader Nikita S. Khrushchev prevailed [34]. The main R-7 rocket production facility in Kuibyshev became known as Plant Progress. To support its work, Korolev opened a co-located unit of his OKB-1, Branch No. 3, under Dmitrii I. Kozlov in 1960 [2,40]. The government reorganized the branch into the independent Central Specialized Design Bureau (TsSKB) in 1974.

At first, the plant assembled the R-7 missiles from parts fabricated and delivered from OKB-1 in Podlipki. Kozlov led this rapidly growing establishment for decades. It modified the original R-7 design and produced numerous Soyuz space launchers. OKB-1 also transferred to TsSKB the task of designing and building image reconnaissance satellites [40]. In addition, Kozlov's enterprise delivered many other spacecraft for remote sensing and space science. By 2010, TsSKB had sent to space nearly one thousand satellites [15].

In 1959, Glushko's design bureau established a dedicated unit, Branch No. 2 or Privolzhskii Branch, in Kuibyshev to support series production of the R-7 engines. At first, the repurposed Plant No. 24 built the original RD-107 and RD-108 engines for the R-7. When the pilot plant of OKB-456 in Khimki had ended production of these engines in 1960, Privolzskii and its plant took over the work on their modifications and improvements. It also began building R-7's steering engines and initiated new rocket propulsion programs [11,52]. Later, the Kuibyshev branch became known as Motorostroitel.

4. Guidance of first Korolev's missiles

By the early 1950s, the work on the first Soviet ballistic missiles had established the engineering and manufacturing foundations for missile guidance. Flight control of the intercontinental R-7 with a much larger range required further advances in technology.

Following the decree "Matters of the Rocket Weapons" of 1946, Scientific Research Institute No. 885 in Moscow emerged as the lead developer of flight control for ballistic missiles [6,8,56,57]. Located 5 km east-southeast of the Kremlin, the institute first reproduced the control systems of the German A-4 missile in the late 1940s. Similar to many other Soviet organizations in the nuclear program, ballistic missiles, rocket propulsion, and air defense [1,40], NII-885 employed specialists forcibly brought from Germany after WWII. More than fifty German scientists and engineers worked in the institute from 1947-1953 [6,22,32].

NII-885 built guidance systems for Korolev's R-1, R-2, R-5, and R-7 ballistic missiles in the 1940s and 1950s. The work of the institute concentrated on two areas: design of autonomous (inertial) guidance in Complex 1, headed by Nikolai Pilyugin, and development of radio control in Complex 2, led by Mikhail Ryazansky [6]. In 1963, the government decree No. 380-138 split the institute into two large independent organizations. It formed the Scientific Research Institute of Automation and Instrument Building (NII AP) under Pilyugin and the Scientific Research Institute of Instrument Building (NIIP, today Russian Space Systems) headed by Ryazansky [6,8,57].

A guidance system controlled rocket flight during the active part of the trajectory, the powered ascent. After the cutoff of the second stage engines, the reentry vehicle separated and continued to fly passively in the gravitational field of the Earth towards its target.

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Similarly, for a satellite launch, the spacecraft separated from the last rocket stage after achieving the desired orbit. For a given ballistic missile flight, a family of trajectories could lead to the target. The guidance system continuously determined the position and velocity vectors of a rocket and steered it during the active part of the trajectory. At the moment when the current position and velocity of the vehicle corresponded to a trajectory hitting the target (or the desired satellite orbit), the guidance system commanded the engine cutoff. The Earth's rotation brought important complications to the required calculations for longer-range missiles such as the R-7.

Missile designers could often divide vehicle guidance into two separate tasks, implemented by two largely independent subsystems. One unit on the ground determined the distance to the rocket and its velocity (range and range rate, respectively), and the other controlled the vehicle position and motion in the lateral (side) direction with respect to the desired trajectory. (The range rate is sometimes called a radial or forward velocity.) The separation of the control functions significantly simplified the guidance of vehicles.

Guidance of the first Korolev's ballistic missiles conceptually resembled the radio-based system of the German A-4. (While German engineers clearly understood the advantages of inertial guidance, "only a few test flights with a pure inertial system took place before the end of World War II" [58].) In the early A-4s, the radio control system included one unit that commanded the engine cutoff. It was positioned at some distance from the launch point (in the flight plane) in a direction opposite to the intended trajectory and measured the missile velocity and distance from the Doppler frequency shift and time delay, respectively, of the radio signals sent back by missile transponders. The missile returned the 30.7-MHz ground signal at the doubled frequency of 61.4 MHz [58,59].

The other unit performed the trajectory side (yaw) control (normal to the trajectory plane), relying on guiding radio beams. Ground antennas transmitted two modulated beams at small angles symmetrically (left and right) with respect to the nominal trajectory. The onboard unit determined the lateral deviation from the flight direction by comparing the received signals of these two beams and steered the missile. On Korolev's R-2, the system of lateral trajectory control, BRK-1, was nearly identical to that of the A-4. The German rocket had relied on a 1.5 kW transmitter 10-16 km behind the missile that alternated radiation emission between "two horizontal dipole antennas … positioned symmetrically 100 m from the flight plane" [36,58-62].

For the next R-5 IRBM, NII-885 implemented a similar flight control concept. To command the engine cutoff, the control unit relied on a pulse transmitter at a frequency of 100 MHz (wavelength 3 m). The designers positioned it 18-30 km behind the launch point and shifted it to the side by a similar distance. Responses of a missile transponder with a turnaround frequency ratio of 3:2 allowed measurements of the distance to the rocket and its velocity with the accuracies of 50 m and 2 m/s, respectively [36].

Placing the transmitter to the side of the trajectory plane kept the angle between the direction to the R-5 and the missile axis within 15-28 degrees during the powered ascent [36]. This minimized the attenuation and phase distortion of radio signals by the plume of the thrusting rocket engine. In 1952, NII-885's Mikhail I. Borisenko experimentally determined that such interference was negligible at frequencies of several gigahertz [56]. (One gigahertz is 1 GHz = 10^9 Hz.) This finding encouraged the transition to higher frequencies for radio control.

The side control system of the R-5, BRK-2, was similar to R-2's BRK-1. Borisenko led the design of these two systems in NII-885 [36,56]. Importantly, he increased the operational frequency to 10 GHz (wavelength 3 cm) in BRK-2, enabled by available electronic components generating short pulses. The use of this high carrier frequency eliminated exhaust plume effects on radio signals and better protected radio control against jamming.

NII-885 placed the BRK-2's transmitter 50 km behind the launch point in a direction aligned with the missile trajectory. A single ground antenna with two separate and shifted emitters in the focal plane produced two guiding beams. Each second, the electronic system generated 500 one-microsecond pulses and alternated them between the two emitters 50 times per second. This created two slightly diverging symmetrical beams on the sides of the desired missile trajectory, enabling flight control not unlike that of the A-4 and R-2 missiles [36]. The use of a single antenna simplified operations by eliminating the need for the operationally inconvenient precise placement of the two transmitting antennas of the R-2 [62].

5. Radio control of intercontinental R-7

The desired 8000-km range of the R-7 led to challenging requirements for velocity vector control during powered ascent. After the engine cutoff and separation, the reentry vehicle would fly for 25 minutes on the passive part of its trajectory to the impact point. Therefore, even a small 1-m/s lateral missile velocity would result in a miss distance of 1.5 km at the target. A similar error in the velocity magnitude after the cutoff could lead to an error of 5 km in distance [36].

By the mid-1950s, all-inertial guidance technology had not yet matured to precisely control trajectories of intercontinental missiles. It could already work, however, on shorter-range strategic missiles. The single-stage intermediate-range R-12 (SS-4) built by OKB-586 (Yuzhnoe) in Dnepropetrovsk became the first Soviet

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strategic missile with an entirely autonomous guidance system [13,17,40]. As early as 1960, the military operationally deployed hundreds of these IRBMs with a range of 2000 km [9].

Leading Soviet specialists had different views on the flight control of long-range ballistic missiles. Boris E. Chertok served for many years as one of Korolev's deputies. Since the early 1950s, he had tried to convince NII-885 to implement all-inertial guidance. According to Chertok, Ryazansky considered such proposals "unrealistic," while Pilyugin "tried to stay out of the arguments but privately … agreed with" Chertok's views [22,32].

The reasoning for the highly consequential design decisions on R-7 guidance, if the related documents are preserved, is buried in "ancient" archives of Soviet industrial research institutions, design bureaus, and the Ministry of Defense. Very few technical details can be found in the public domain in this highly sensitive classified area. Therefore, one can only rely on circumstantial data and rare mentions in recollections of the veterans as well as infer some considerations.

To guide the R-7 ICBM, NII-885 combined the primary radio control and a supporting inertial system, with Ryazansky and Pilyugin as the chief designers, respectively. The radio system controlled the rocket motion at the end of the active part of the trajectory, where the missile position and velocity vectors after the engine cutoff determined the accuracy of hitting the target.

Side control of the R-7 flight presented particular challenges. Sensing a pair of guiding radio beams could work well only for relatively short-range ballistic missiles such as the German A-4 and Korolev's R-2 and R-5, but not for intercontinental missiles. The selected R-7 radio side control would affect the rocket design, location of the missile test range [2,4], associated ground instrumentation sites, launch operations, and cost.

In the 1950s, deputy director of NII-885 Boris M. Konoplev headed the technical development of radio control for the R-5 and R-7. His relations with the institute's chief engineer, Pilyugin, who had been working on autonomous control, deteriorated, and Konoplev had to leave NII-885 in 1955 [36,56]. In 1959, he became head of a new design bureau, OKB-692 (p/ya 67 [5,14]), later known as Elektropribor and then Khartron, in Kharkov. The organization would be building flight control systems for ballistic missiles of Yangel's OKB-586 in Dnepropetrovsk for decades [17,63]. The all-inertial control system of the R-16 ICBM (8K64, SS-7, Saddler) became the first guidance system designed by OKB-692 [17]. Konoplev perished in the "Nedelin accident," the R-16 explosion with numerous casualties at the Tyuratam range in 1960 [19,40,64].

After Konoplev's forced departure in 1955, his deputy Yevgenii Ya. Boguslavsky became the technical lead of work on radio control for the R-5 and R-7 at NII-885. Director and chief designer of the institute Ryazansky continued to keep the title of the chief designer of the R-7 radio control system, but he primarily focused on interactions with government bodies and Korolev [6,36].

The onboard part of the R-7 radio control system was located at the top of the central block of the rocket, above the upper (liquid oxygen) propellant tank. It weighed more than 200 kg [32]. The autonomous guidance system of Pilyugin stabilized the vehicle and provided backup to radio control. The designers installed it in the middle of the rocket's central block between the fuel and oxidizer tanks. They moved this inter-tank unit up to join the radio control system at the top of the second stage in the modified R-7 in late 1958 [2,4].

The autonomous guidance unit stabilized the R-7's attitude and flight motion and controlled the rocket's apparent velocity vector and attitude, according to the flight program. It relied on inertial sensors such as gyroscopes and accelerometers. The system maintained the desired orientation of accelerometers for integration of sensed accelerations to determine the apparent vehicle velocity. It also commanded the rocket engine cutoff in case of a major malfunction, such as the R-7 deviation from the required orientation in pitch, yaw, or roll by more than 7 degrees. In addition, the onboard inertial system provided a backup to terminate engine firing if the radio system failed. It cut the engine off on a particularly important launch of the first cosmonaut Yuri Gagarin in 1961 [36,37], preventing a possible tragedy (see Chapter 7). The autonomous system also operated a propellant management unit to maximize utilization of the fuel and oxidizer.

Radio control is inherently vulnerable to radio interference and jamming by an adversary. The Allies did not jam the A-4s fired at them during World War II [36,59]. However, German engineers designed all missile radio equipment capable of operating at ten different frequencies to overcome possible interference. A fear of jamming of the R-7 radio control affected its design as well. In fact, *Postanovlenie* No. 956-408ss not only specified the details of the R-7 development in 1954 but it also prescribed "the system of rocket control – combined [radio and inertial] and resistant to jamming" [49]. Relying on the R-5 experience, NII-885 built the R-7 radio control at a high frequency of 10 GHz.

The implemented system performed two major tasks in the R-7. First, it measured the distance to the rocket and its velocity and commanded the engine cutoff. The determination of the rocket range and range rate by a ground site relied on missile transponders, with ingenious arrangements to measure Doppler frequency shifts when using pulsed signals.

Second, the radio control system maintained the missile trajectory within the flight plane (side or yaw

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control), which required measuring the vehicle position in the lateral direction. To a significant degree, the state of the art of the available electronic components determined its design. The NII-885 engineers lacked flight-qualified high-power vacuum tube amplifiers for generating continuous microwave radiation at high frequencies of 10 GHz, the continuous wave klystrons. This limitation had important consequences for the R-7.

Scientific Research Institute No. 160, NII-160, had been developing continuous wave klystrons for some time. The Soviet government established NII-160, later known as NII Istok, located in Fryazino, 13 km east-northeast of Podlipki, in 1943 to support the production of radars during World War II. The institute became the country's leading organization focused on the science and engineering of electron vacuum tubes [1]. In particular, it had been working on klystrons since the late 1940s, copying some U.S. designs and developing its own. Similar to other institutions, NII-160 employed many German specialists brought to the Soviet Union after WWII [65,66].

Flight-qualified continuous wave klystrons would have allowed precise determination of the lateral position and velocity of missiles by direction-finding interferometric techniques with receivers separated by mere hundreds of meters [36]. In addition, they would have also enabled convenient Doppler measurements of missile velocities with superior accuracy of a few centimeters per second [36]. NII-160 seemed to have mastered production of pulse sources by that time, but not continuous wave klystrons at 10 GHz. It was not clear to NII-885 when these latter microwave components could become available.

Two fateful decisions on the details of the radio side control significantly influenced the R-7 design and performance. First, NII-885 implemented the pulse-based design using available components [36]. In the second critical decision, the institute chose to rely on the rocket's onboard unit for determining the steering actions, based on radio signals received from the ground. The latter approach conceptually resembled the R-2 and R-5 missiles. The R-7 chief designer Korolev and his OKB-1 must have "blessed" these highly consequential decisions by NII-885 and thus shared the responsibility.

The initial R-7 rocket design called for three radio control posts, two at distances of 250 km in the lateral ("left" and "right") directions with respect to the trajectory and one ("tail post") at a distance of 500 km behind the launch position [3,4,6,8,22,26,30-32,48,67]. The two side sites controlled the missile trajectory in the lateral direction, while the tail post measured the missile distance and velocity and commanded the engine cutoff. The latter post was practically never used [4] because one of the side sites would perform its functions.

The use of continuous wave high-frequency components and interferometric techniques would have allowed placing side control equipment within hundreds of meters from the launch point instead of 250 km. The vulnerable and logistically challenging distant radio control posts made the initial variant of the R-7 poorly suited for deployment as an operational ICBM. They also limited the rocket performance as a space launcher. The design decisions on R-7 radio guidance reminded a story of consequences in an old rhyme, repeated in Poor Richard's Almanack (e.g., [68]), that could be rephrased here as "For Want of a Klystron."

In 1956, the Special Design Bureau of the Moscow Power Engineering Institute (OKB MEI) built an interferometric system, Irtysh, for the instrumentation sites tracking R-7 flights. It relied on an onboard continuous-wave low-power (10 W) beacon, Fakel-M, emitting at a lower frequency of 500 MHz (wavelength 0.6 m) [69]. Irtysh tracked the R-7 flights at distances up to 2000 km but required laborious postprocessing of the received signals. Therefore, it could not control the missile flight in real time but demonstrated the promise of the technique.

The answer to the question of whether the R-7 guidance design decisions could be different, and perhaps better, is likely buried in inaccessible archives today. One could speculate that the R-7 guidance could have been all-inertial and, in the case of radio control, relied on interferometric techniques. In any case, the Central Committee of the CPSU and the USSR Council of Ministers approved the ICBM design and set the program in motion.

Comparison of the ICBM programs of two superpowers is beyond the scope of this article. We only note that the development of guidance for the first American ICBM, Atlas, faced numerous challenges. Many U.S. engineers also viewed radio control as more accurate than maturing inertial guidance. There was a clear understanding, however, of radio system vulnerabilities which ultimately led to placing operationally deployed ICBMs into hardened silos without exposed above-ground components.

During early test launches of Atlas, the so-called radio-inertial guidance system built by General Electric and Burroughs Corp. controlled the initial part of the missile trajectory. The ground systems received the velocity vector parameters from the onboard inertial sensors and sent back the computed corrections. The onboard inertial unit took over missile guidance for the final part of powered ascent. In addition to vulnerabilities to jamming, radio control could not support launches of ICBM salvos. Subsequently, the all-inertial onboard guidance unit (built by American Bosch Arma Corp.) replaced the flight control system for the first U.S. operationally deployed Atlas ICBMs [40,70].

Two R-7's fixed remote radio posts (stations, sites), RUPs, provided missile side control, as initially envisioned [4,6,8,26,67]. The designers placed the main

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RUP A (sometimes referred to as RUP-1) and the mirror RUP B (RUP-2) symmetrically with respect to the launch point on a line perpendicular to the direction of flight (dashed line arrow) (Fig. 4, top left). The main RUP A also performed the functions of the originally planned third (tail) remote station behind the launch site to measure the vehicle distance and velocity and command the engine cutoff.

The side control of the R-7 flight relied on radio pulses (duration 0.1 μs) at the 10-GHz carrier frequency. Figure 4 (left) shows the schematic (based on [36]) of measuring the missile position in the lateral direction. The main RUP A transmitted a pulse (K1), which triggered the missile transponders to send back pulses to RUP A (K2) and RUP B (K3). The RUPs then returned these pulses (K4 and K5) to the missile. The onboard analog device calculated the missile lateral position from the time interval between the received signals, Δt. The entire measurement cycle did not exceed 5 ms (0.005 s) during the powered ascent. The onboard unit determined lateral positions one hundred times each second, derived from them the lateral velocity, and steered the vehicle in yaw.

The main radio control post RUP A also calculated and appropriately shifted the K4 pulse to account for the Earth's rotation for a particular trajectory. High-power

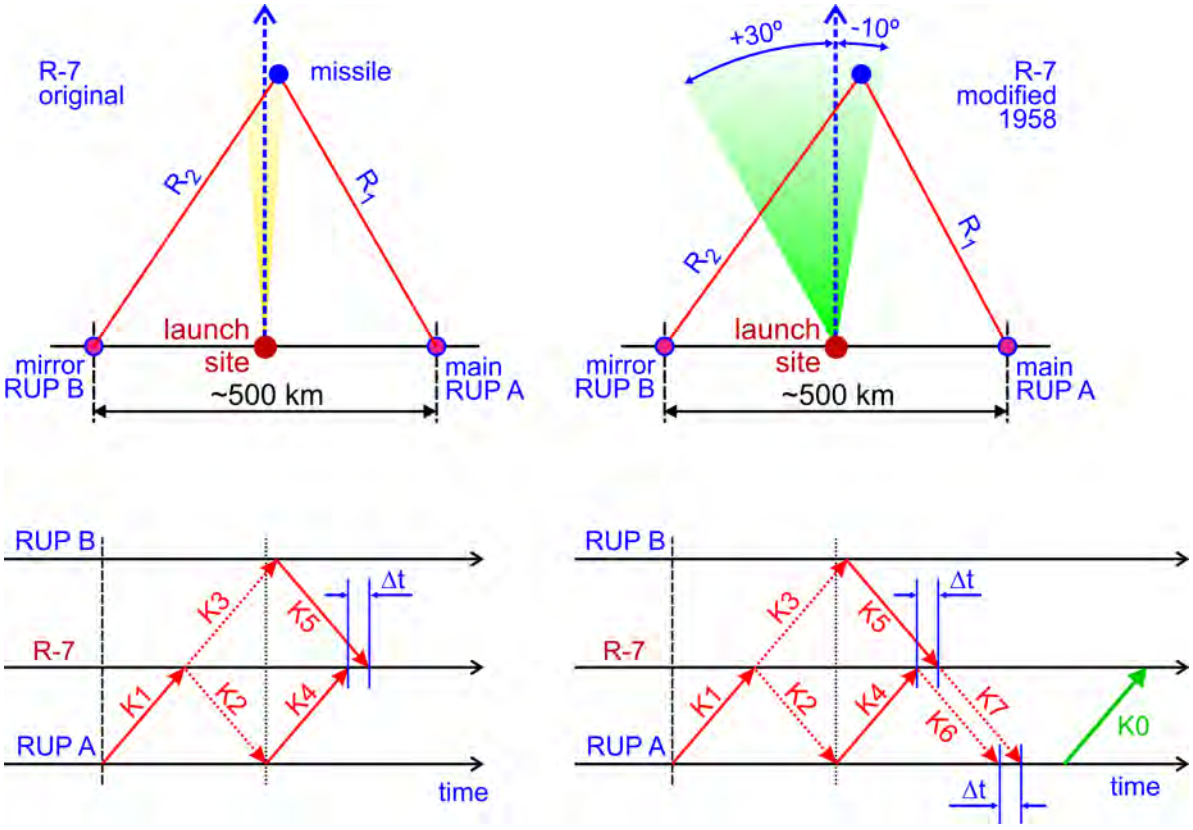


Fig. 4. Schematic (based on [36]) for determining the R-7 lateral position with respect to the trajectory direction (dashed line arrow) in the original design in 1957 (left) and the modified system introduced in 1958 (right). The original R-7 guidance concept (top left) included two distant radio control posts (sites), RUPs (blue-edge red circles) on a line perpendicular to the flight direction. In response to the triggering pulse (K1) transmitted by the main RUP A, the missile transponders sent pulses back to RUP A (K2) and RUP B (K3). The RUPs then returned the signals (K4 and K5) to the missile. The time interval Δt between the received pulses depended on the lateral deviation of the missile from the intended trajectory. The analog onboard control system then steered the missile in yaw according to a sequence of the received time intervals. The early (1957) radio system (left) could guide the missile along its trajectory only within a narrow angular sector (yellow) with respect to the direction perpendicular to the line connecting the RUPs. In the modified R-7 radio control system (right) introduced in 1958, the missile retransmitted the received K4 and K5 pulses to RUP A (signals K6 and K7), where a new, specially designed complex analog computing device, S-416, calculated the steering command in real time and sent its code, K0, to the missile for execution. This new system enabled missile side control on trajectories within a wider 40-degree sector (green), from –10° (toward the main RUP) to +30° (toward the mirror RUP) [3].

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radio transmitters provided reliable communications between the distant RUPs during launches. The radio control posts became major installations with numerous electronic and communication systems and large technical personnel. Such a bulky system could support rocket trials, but obviously did not meet the operational requirements for deployed ICBM units.

The use of an onboard analog computing device necessarily limited its functions to simplified calculations, which, in turn, required RUPs to be positioned strictly symmetrically with respect to the trajectory. Consequently, this system feature constrained launch azimuths to a narrow angular sector pointed perpendicular to the line connecting the RUP locations (Fig. 4, left). The R-7 ICBMs would thus be able to fly only in one direction. For space launches, such radio control could place satellites into orbits with one inclination only. The requirement of two distant symmetrical radio control posts also prevented locating the rocket test range in a much more comfortable geographic location, instead of inhospitable Tyuratam's desert.

As early as 1955, two specialists at the military scientific-research institute NII-4, Konstantin P. Feoktistov and Gleb Yu. Maksimov, found a way to modify the R-7 radio control concept, which removed the requirement of symmetrical missile control posts. They added to the rocket flight control function additional variables describing the positions of these posts. Feoktistov and Maksimov found such a function that allowed placing the radio control post "practically almost anywhere. Simply, the structure and some parameters of the control function should include the necessary coordinates of the control post" [30].

It was too late, however, for the NII-4 results to change the location of the test range in 1955, as its construction had begun. Feoktistov soon transferred to an important engineering position in Korolev's OKB-1. In 1964, he and a medical doctor, Boris Yegorov, would become the first Soviet civilian cosmonauts to fly to orbit on the Voskhod-1 mission. Maksimov also joined OKB-1, where he played an important role in designing the first lunar missions [71].

Feoktistov noted that the developers of the radio control system at NII-885 were "very pleased" in 1955 with the results obtained by him and Maksimov because they "exonerated the concept of radio control" and improved it [30]. It is not clear why NII-885 did not promptly modify the radio control design according to these consequential findings. The institute waited for three years until 1958 to make changes to address the obvious major operational shortcoming that limited trajectories to a narrow sector of directions.

For a wide sector of launch directions, RUPs no longer had to be symmetric with respect to the trajectory. The side control, however, required much more complex calculations accounting for all six parameters describing missile motion, its three coordinates and three velocity vector components. The NII-4 control approach was thus incompatible with the limited capabilities of the originally planned onboard analog computational device.

NII-885 built the new trajectory side control system in 1958. It enabled launches within a 40-degree sector by shifting the computations of steering commands to the ground rather than performing them onboard as in the original design. The institute also added a large-aperture direction-finding radar (*radiopelengator*) at RUP A to accurately measure the elevation angle of the missile.

The onboard system of the wide-sector capable R-7 returned the received K4 and K5 signals to the main RUP A as K6 and K7 (Fig. 4, right). The specially built ground-based device, S-416, calculated in real time the missile position, determined the steering command (K0), and transmitted its code to the missile. The onboard unit then executed one of the five steering actions in the side direction, "large left" (–3.5° in yaw), "small left" (–1°), "zero" (0°), "small right" (+1°), or "large right" (+3.5°), until the next command received from the RUP [36].

NII-885 built the complex S-416 computational unit as an analog device. Its design presented major challenges. One can only speculate which administrative and institutional considerations and internal politics, as well as the capabilities and limitations of the leaders of OKB-1 and NII-885 and their personal relations, prevented the introduction of digital computers for this task. At that time, the Soviet missile defense program, with different specialists and officials in charge, heavily relied on digital computers [1].

6. NIIP-5 test range and R-7 RUPs

Since the late 1940s, the Kapustin Yar test site supported trials of short-range rockets as well as more capable intermediate-range ballistic missiles such as R-5s and R-12s [1,2,13,40,72]. The R-7 ICBM and intercontinental winged cruise missiles required a much larger range. The R-7's reliance on distant fixed radio control posts, RUPs, with unobstructed communications with rockets in flight, significantly narrowed the choice of possible locations.

On February 12, 1955, the USSR Council of Ministers issued *Postanovlenie* No. 292-181 "On new testing range for the USSR Ministry of Defense" ordering "establishment in 1955-1958 of a scientific research and testing range of the USSR Ministry of Defense for flight development of the articles R-7, Burya, and Buran" [12, 14,40,73]. The work on Burya (*tempest* in Russian) and Buran (*blizzard*) intercontinental cruise missiles would be terminated several years later [48].

The government decree placed the new secret Scientific Research Test Range No. 5 (NIIP-5) "in the Kzyl-Orda and Karaganda administrative regions of the Kazakh SSR [Soviet Socialist Republic]." It also

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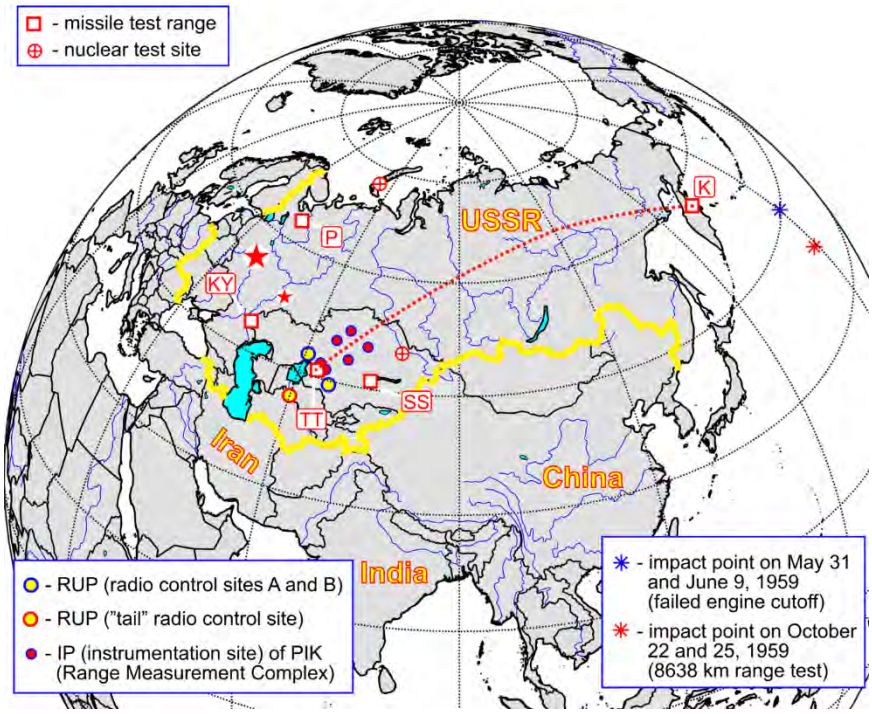


Fig. 5. Main centers supporting development and test flights of the R-7 ICBM and first space launches in the USSR (yellow line state border): NIIP-5 at Tyuratam (TT), Kapustin Yar (KY), Plesetsk (P), Saryshagan (SS), and impact site (K) at the Kamchatka peninsula. Radio control posts, RUPs, guided the rockets during powered ascent. (NIIP-5 practically never used the originally planned tail RUP.) The landmass of the Soviet Union limited the overland R-7 trajectories (dotted line) to 6300 km between Tyuratam and Kamchatka. NIIP-5 later extended missile trials to 8638 km (red asterisk) and then 12,060 km and 12,360 km (not shown), with a flotilla of instrumented ocean-going ships monitoring impacts in the Pacific Ocean.

Six (shown) instrumentation sites, IPs, straddled the active part of the missile trajectory in Kazakhstan. Three additional IPs (not shown) were located close to the R-7 launch point, and six more sites (not shown) surrounded the warhead impact area at Kamchatka. A few more (not shown) scientific measurement posts, NIPs, supported satellite operations and assisted tracking ICBM flights and space launches. A large red star is Moscow, and a smaller star is Kuybyshev (Samara), where the series production of R-7s and their engines was established in the late 1950s.

established "the impact area of head parts of tested articles in the Kamchatka region … near Cape Ozernoi" more than 6000 km away from the rangehead in Kazakhstan (Fig. 5). Even this large distance was not sufficient to demonstrate the ICBM on its required range of 8000 km. Therefore, the government repurposed several ships for monitoring rocket flights to impact points in the Pacific Ocean. The Ministry of Defense referred to NIIP-5 as v/ch 11284. (Each unit in the armed forces of the USSR had its unique identifying number, abbreviated v/ch and standing for *voinskaya chast'*, a military unit in Russian.)

Constructing NIIP-5 in a desolate desert area with harsh climate and no infrastructure was an enormous undertaking. The Ministry of Defense assigned the task to the Directorate of Engineering Works No. 130 (UIR 130), v/ch 12253. At the peak of the construction in the 1950s, more than 20,000 servicemen were building the new missile range [40,73-75].

The first commander of NIIP-5, Lt. Gen. Alexei I. Nesterenko, wrote that, for the first rocket flight trials, it was necessary to build

> [the rocket] launch position, [rocket assembly and test building] MIK with all communications, railroad tracks, concrete automobile roads, water supply lines, system of water reservoirs for firefighting, electric power lines, main communications center and unified time system, [radio] transmitting and receiving centers, separate assembly building for [nuclear] warheads, three RUPs (two base posts at distances of 250 km from the launch position and the tail post at a distance of 500 km), nine measurement [instrumentation] posts in the area of falling first stages, communications relay center in Irkutsk [nearly 3000 km away], six measurement [instrumentation] posts at … [the Kamchatka target area] with a transmitting radio center, receiving radio center, airfields. It was planned to build airstrips at all [remote] sites … [67]

By 1957, NIIP-5 had become a very large active installation [76]. The range deployed, equipped, and staffed more than 30 separate military garrisons across a vast territory. Such a major undertaking could not remain a closely-guarded state secret for too long.

On August 5, 1957, an American deep-penetration reconnaissance flight by a U-2 aircraft (Mission 4035) found and photographed this new missile test range [73, 77,78]. Since that time, the U.S. government documents referred to it as the Tyuratam Missile Test Range

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(TTMTR) after the nearby railroad station Tyuratam. (The name is sometimes rendered in two words, Tyura Tam or Tyura-Tam.) Following the orbital flight of the first cosmonaut Yuri Gagarin in 1961, the Soviet Union publicly identified, in a Cold War deception, the location of the secret space port, the cosmodrome, as Baikonur after a small town 300 km away from the real location of the launch site [73]. "At this point [at Baikonur], there was a concrete pad for firing R-5 rockets in support of missile defense development" [16]. Today, the most widely used catalog of space objects, Space Track (space-track.org), continues to identify the space launch site as TTMTR.

For R-7 trials, NIIP-5 activated a number of measurement posts, IPs, of the Test Range Measurement Complex, PIK, along the active part of missile trajectories in Kazakhstan (Figs. 5, 6). These instrumentation sites tracked the launched rockets by optical instruments, radar, and radio techniques, but did not control their powered ascent. The IPs also captured telemetry from the rockets, monitoring 700 parameters in flight [4].

Figure 7 shows a U-2 photograph of the launch position and nearby supporting facilities of the test range during the first trials in 1957. A rail line and automobile road connected the installation with the Tyuratam railroad station 25 km to the south. The military designated various areas of the range as numbered sites [4,40,73]. For example, Site 1 referred to the first launch pad (R-7, Sputnik, Gagarin); nearby Site 2 hosted the assembly and test building MIK; Site 18 was the main measurement post IP-1. Site 10 referred to the main headquarters and residential area, a few kilometers to the south of the Tyuratam station.

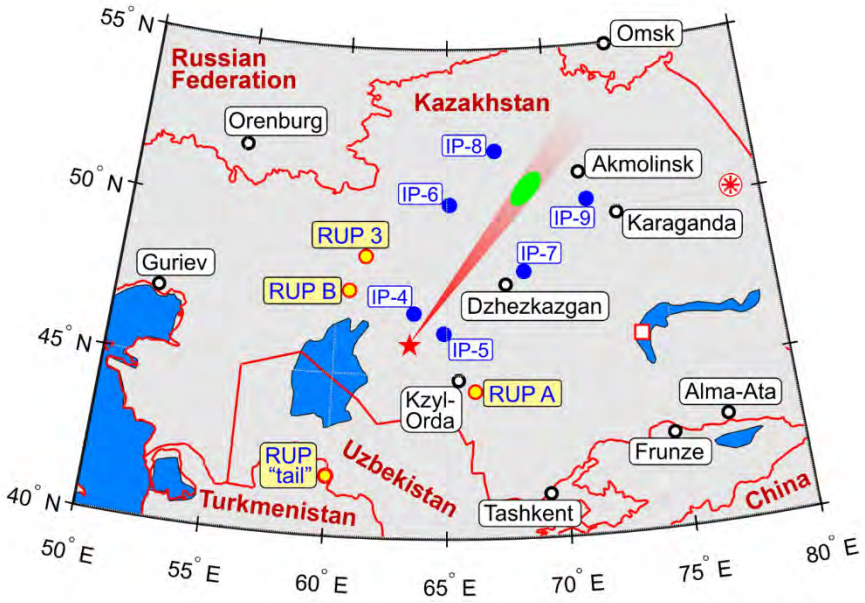


Fig. 6. R-7 related sites of the Tyuratam Missile Test Range in the late 1950s. The red star is the R-7 launch pad, and the northeast-pointed red sector is the rocket flight direction (launch azimuth 37-39 degrees, counted from the north) toward the impact area at Kamchatka and during the first satellite launches. Two radio control posts (red-edge yellow circles), RUP A (main) and RUP B (mirror), guided the R-7s during powered ascent. NIIP-5 used temporary RUP-3 to validate the modified radio control system in 1958 for launches within a wider sector of directions. The green ellipse shows the drop zone of the R-7 first stage blocks. Blue circles are six instrumentation sites, IPs, of the Test Range Measurement Complex, PIK, that tracked rocket flights and received telemetry. Three additional posts (IP-1, IP-2, IP-3; not shown) close to the launch point supported the launches. PIK's IP-4 and IP-5 optically recorded the separation of the R-7 first stages (Fig. 15). Also shown are the locations of the headquarters of the Saryshagan missile defense range (red-edge white square) on Lake Balkhash and the Semipalatinsk nuclear test site (red asterisk in a circle). The names of the main towns are given as commonly used in the Soviet Union: Akmolinsk is Astana (capital of Kazakhstan) today; Dzhezkazgan is often spelled Zhezkazgan; the former capital of Kazakhstan, Alma-Ata, is spelled Almaty; Guriev is Atyrau; and Frunze is Bishkek (capital of Kyrgyzstan).

Very little is known about R-7's radio control RUPs, their locations, equipment, and operations. Corporate histories of OKB-1 and NII-885 only acknowledged the existence of these outposts. Recollections of the program veterans (e.g., [4,36,79] mentioned the location of the main radio control post, RUP A, in the vicinity of a small railroad stop, Tartogai (Tartugai, Turtagai).

In 1962, a U.S. intelligence report identified several instrumentation sites supporting NIIP-5 [80]. Correlation of (i) their locations with (ii) a site observed by a U-2 aircraft mission in 1960 [81] and (iii) an unusually specific distance of 276 km between the R-7 launch point and RUPs listed in one report to the Central Committee of the CPSU in 1957 [82] made possible to determine the locations of RUPs. Space reconnaissance photographs of the Corona program [40,83,84] obtained in the 1960s validated the identifications.

Table 2 shows the geographic coordinates of the R-7 launch point, RUP A, RUP B, and temporary mirror RUP-3 used for testing the modified R-7 radio guidance system that

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enabled missile launches within a wide sector of directions (Fig. 4). (RUP-3 is the author's ad hoc designation of this outpost, since nowhere could its identifier be found.)

The rounded geographic latitudes and longitudes in the table are given with an accuracy of one-tenth of one minute (six seconds), 0.1'=6". On the ground, this accuracy corresponds to a spatial uncertainty of 185 m in the meridional north-south direction and 100-135 m, depending on latitude, in the east-west direction.

Table 2. Geographical Coordinates of R-7 launch point and RUPs.

	latitude	longitude
launch pad	45°55.2' N	063°20.5' E
RUP A	44°30.0' N	066°14.4' E
RUP B	47°24.2' N	060°25.1' E
RUP-3	48°37.5' N	061°13.5' E

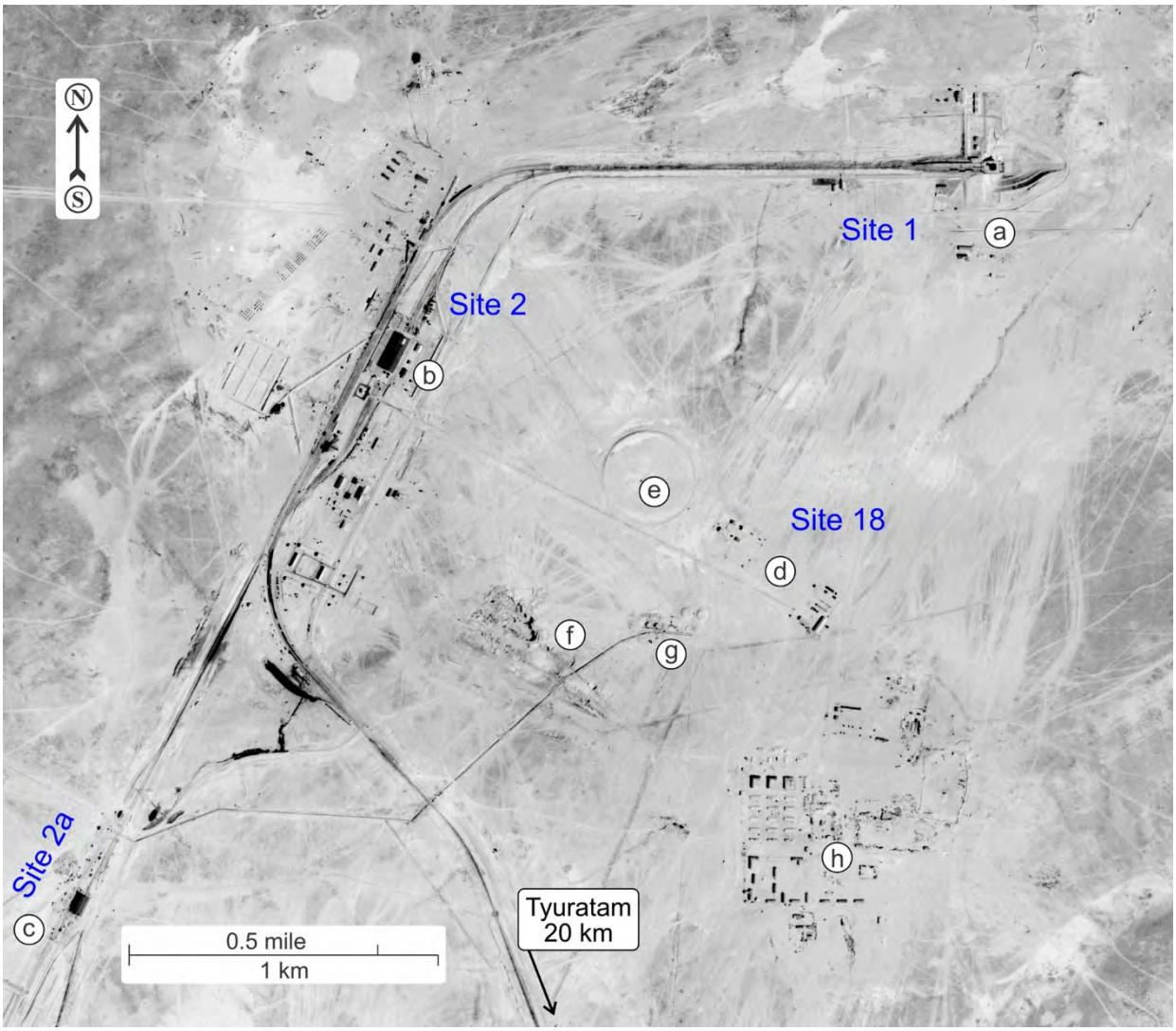


Fig. 7. U-2 photograph of the rocket launch area at the Tyuratam missile range one week after the first successful flight of the R-7 ICBM to Kamchatka on August 21, 1957. (a) – launch pad with a flame pit, TTMTR Site 1; (b) – rocket and spacecraft assembly and test building, MIK, at Site 2; (c) – assembly and test building of special (nuclear) warheads, Site 2a; (d) – PIK's IP-1, Site 18; (e) – direction-finding interferometer Irtysh; (f) – borrow pit; (g) – water storage facility; (h) – headquarters and barracks (1955-1957) of the 2nd Engineering-Construction Brigade that built Sites 1, 2, 2a, and 18 (the barracks later accommodated units of rocket forces). A rail platform with a fully assembled ICBM or space launcher rolled from the MIK building to the launch pad.

Original reconnaissance photograph by U-2 aircraft (Mission 4058, August 28, 1957), National Archives and Records Administration (NARA); photograph identification, interpretation, and processing by Mike Gruntman.

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The main radio control post, RUP A, was located 65 km southeast of a regional center, Kzyl-Orda (Fig. 6), and 5 km north-northwest of a small railroad stop, Tartogai. This large technical position housed numerous sophisticated electronic and communication systems to control R-7 flights (Fig. 8). The nearby supporting residential area included barracks for enlisted servicemen, quarters of officer families, and dormitories for visiting engineers and technicians from industry.

Figure 9 shows the buildings, called *pavilions*, of large-aperture missile-tracking radars (*radiopelengator*). NIIP-5 used a tethered balloon (Fig. 10) for calibrating radar and communications electronics as well as for adjusting the antenna pointing of interferometric missile flight control systems [33]. A 90-m-tall self-supporting lattice tower (Fig. 8, top right) had a dome-shaped electronic system on top. A military unit, 71st Separate Test Station (OIS 71, v/ch 25642) of radio control, operated RUP A. Another unit, 72nd Separate Test

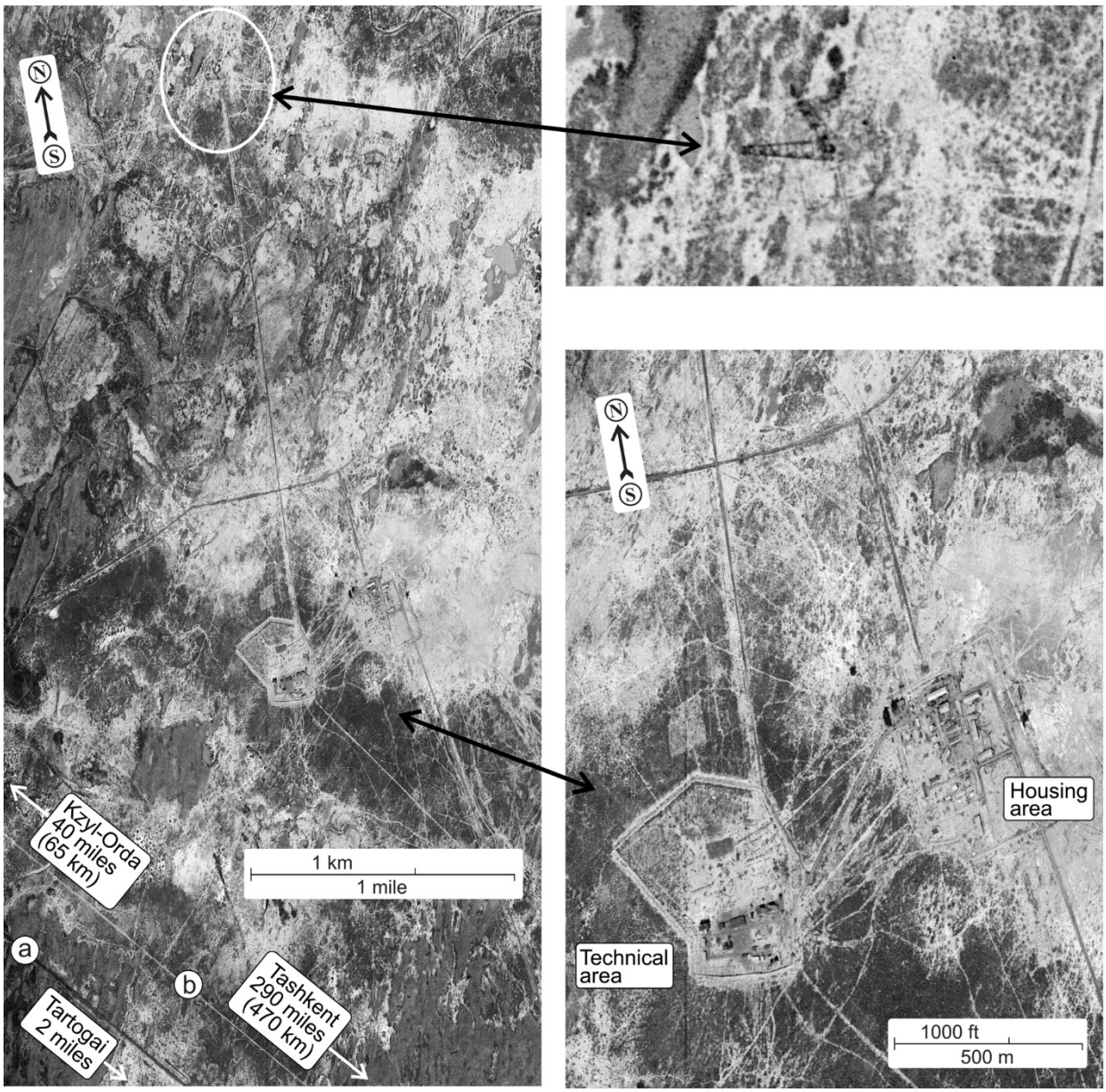


Fig. 8. Satellite photograph of the main R-7 radio control post, RUP A, 5 km north-northwest of Tartogai (left). It included the technical and housing areas (bottom right) and a 90-m tall self-supporting lattice tower (top right) with a dome-shaped object on top. (a) – railroad Orenburg-Tashkent; (b) – automobile road (highway) Orenburg-Tashkent. Original satellite reconnaissance photograph by KH-7 camera (Mission 4007; April 25, 1964), U.S. Geological Survey; photograph identification, interpretation, and processing by Mike Gruntman.

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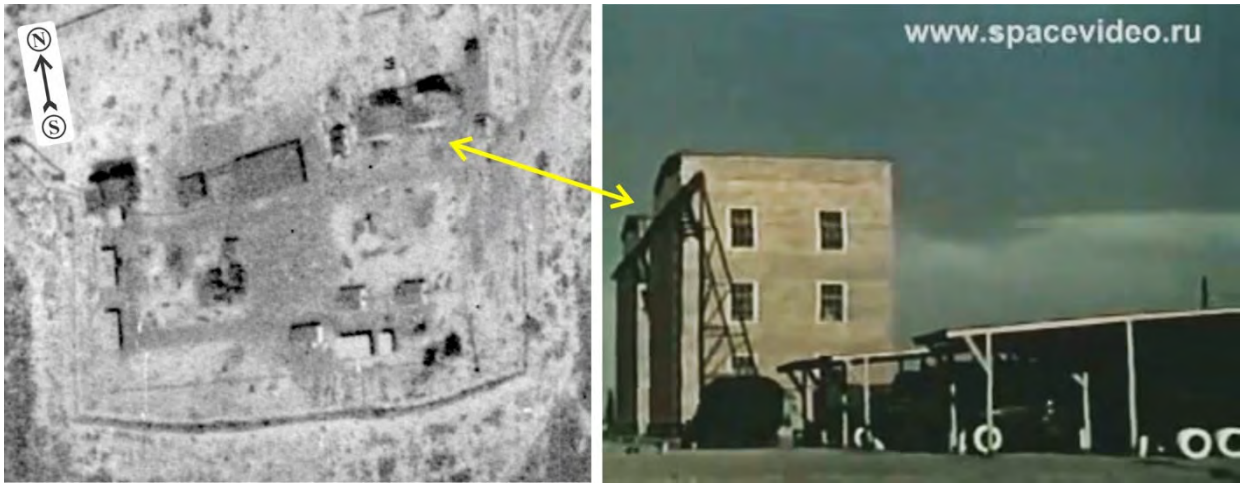


Fig. 9. Satellite photograph (left) and a film frame (right) of two buildings (pavilions) housing trajectory radars (*radiopelengator*) at RUP A. Original satellite reconnaissance photograph (left) by KH-7 camera (Mission 4007; April 25, 1964), U.S. Geological Survey; photograph identification, interpretation, and processing by Mike Gruntman. Frame (right) credit: [76].

Station (OIS 72, v/ch 14094), was in charge of RUP B. In 1962, the Strategic Rocket Forces changed the identifying numbers of these units while preserving their duties [85].

U.S. outposts in Turkey and Iran had been collecting electronic and communications intelligence on activities at the Tyuratam range for many years [1]. In addition, deep-penetration reconnaissance missions by U-2 planes photographed NIIP-5 on August 5 and 28, 1957 (Missions 4035 and 4058, respectively), July 9, 1959 (Mission 4125), and April 9, 1960 (Mission 4155) [73,78]. Based on the gathered information, CIA analysts correctly determined some features of the R-7 radio control. By July 1959, they had identified the involved instrumentation sites RUP A (CO5B in CIA documents), RUP B (CO5D), and RUP-3 (CO5E) [80,86].

One CIA report concluded that the "preponderance of evidence … tends to support the [missile and space launcher] guidance" as a possible function of CO5A (RUP A). It also noted that from "a purely technical point of view, it is feasible for a station at this location to perform guidance functions, as COMINT [communications intelligence] and photography suggest … [A U-2 photograph] locates CO5D [RUP B] in an area on the opposite side of the rangehead where it could have the same spatial relationship to the rangehead and the line of fire as CO5B [RUP A], it is possible that these two stations represent a part of a long-base-line guidance/tracking system." The report cautiously stated

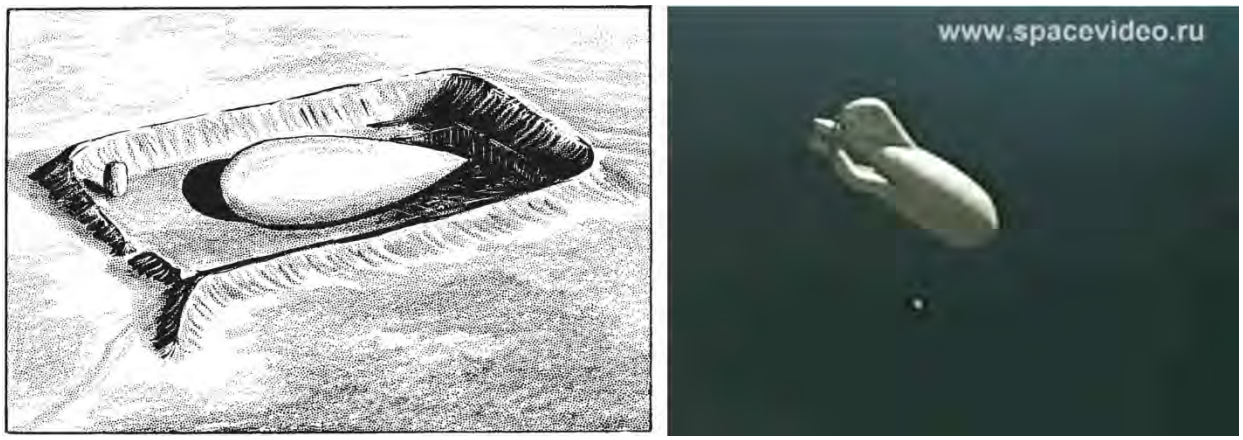


Fig. 10. Left: CIA's rendering of a tear-shaped 6-by-25 m balloon in an enclosed earthen revetment observed 1.2 km north of the residential area of RUP A (Fig. 8) by U-2 Mission 4125 on July 9, 1959 [86]. Right: film frame of a balloon in flight (credit: [76]).

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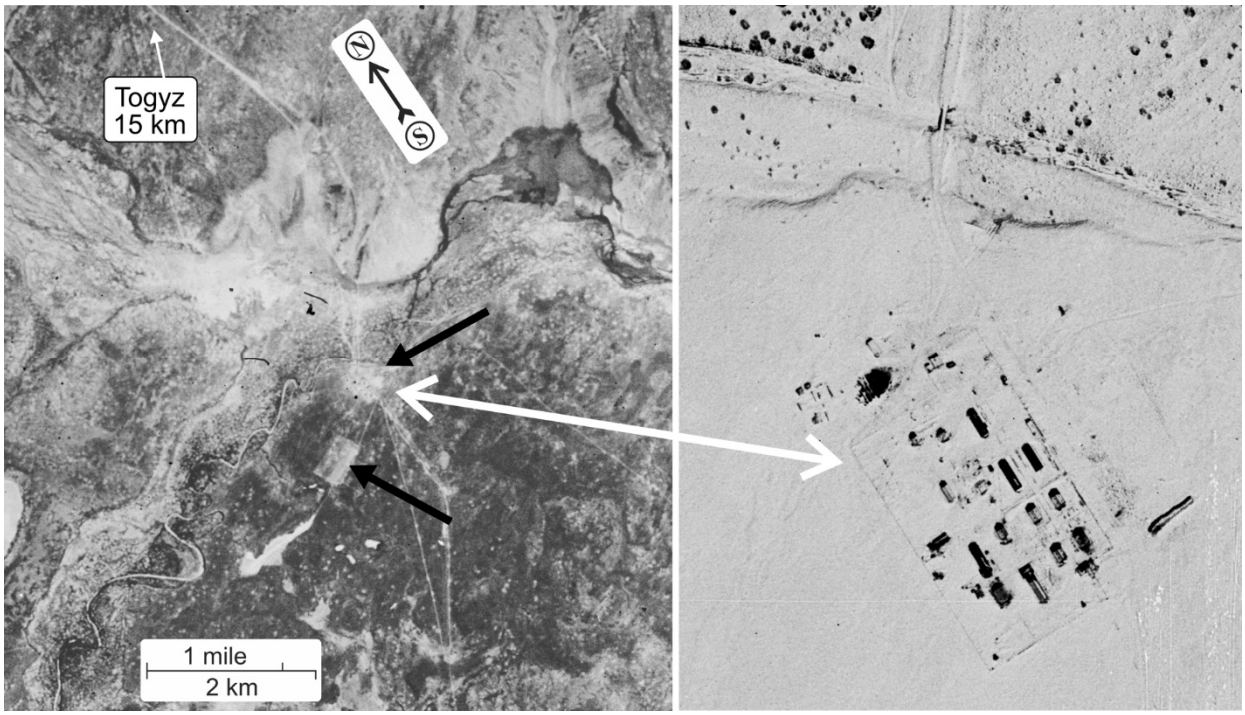


Fig. 11. Satellite photographs of R-7's mirror radio control post, RUP B. Located in a desert 15-20 km southwest of the small town Togyz in Kazakhstan, it included the operations and housing areas (black arrows, left). A winter photograph (right) provides a high-contrast image of RUP's buildings. Original satellite reconnaissance photographs by KH-4 camera (Mission 9044; August 29; 1962, left) and KH-7 camera (Mission 4016; March 15, 1965; right), U.S. Geological Survey; photograph identification, interpretation, and processing by Mike Gruntman.

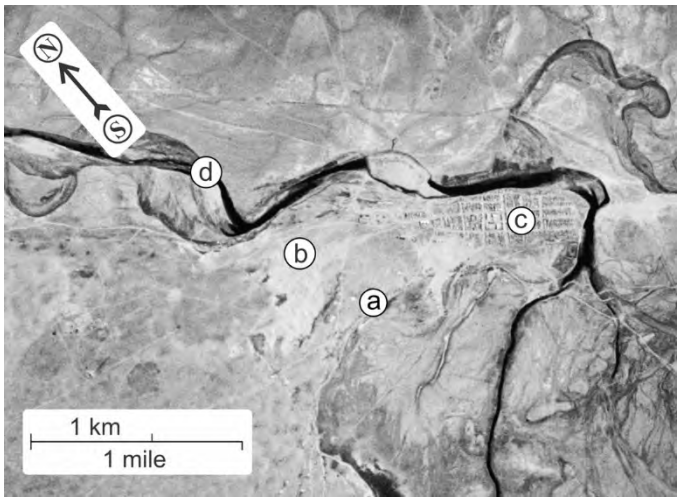


Fig. 12. "Temporary" mirror RUP (CO5E in CIA reports) near settlement Irgiz, 340 km from Site 1 at Tyuratam. This radio control post served to validate the modified R-7 radio control system, enabling launches in a wide 40-degree sector of trajectory directions. a – technical position, b –air strips; c – settlement Irgiz; d – Irgiz river. Original satellite reconnaissance photograph by KH-4 camera (Mission 9044; August 29, 1962), U.S. Geological Survey; photograph identification, interpretation, and processing by Mike Gruntman.

that "no signals have so far been received [intercepted] which would tend to confirm this theory" [86].

NIIP-5 placed the mirror RUP B radio control post 276 km from the launch pad in a desert 15-20 km southwest of a railroad stop, Togyz (Toguz, Tuguz). Figure 11 shows reconnaissance satellite photographs of RUP B in 1962 and 1965. Temporary RUP-3 (Fig. 12) with technical and residential areas and an airstrip near Irgiz (Yrgyz) supported some R-7 launches in 1958 to validate the modified radio system controlling flight trajectories within a wide 40-degree sector.

In the late 1950s and early 1960s, all three RUPs hosted newly formed military units (v/ch 13973, 14117, 14162 [87]) for training in preparation for their deployment at the operational (combat) R-7 ICBM positions at Plesetsk. Military crews concluded their training by rocket launches on July 30, September 18, and November 21, 1959. At least one of these launches, on September 18, demonstrated ICBM firing from the "readiness state No. 1" within 80 minutes after the command [14,87]. Then, the Strategic Rocket Forces transferred the trained units to radio control posts at Plesetsk. Two mirror RUPs complemented each main RUP at operational positions there to provide

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a wide range of possible directions of firing [19,79]. The northern ICBM base at Plesetsk (Fig. 5) would also become a very busy space port in the mid-1960s.

NIIP-5 placed the tail RUP 530 km southwest of the launch position in the vicinity of the town of Tashauz in Turkmenistan (Figs. 5, 6). This radio control post was practically never used because RUP A assumed the function of commanding the engine cutoff [4]. A CIA report noted that this installation near Tashauz "would be compatible with a description of a guidance program used on ICBM/space vehicles" as it appeared, and was spotted by the analysts, in the December 1957 issue of the Soviet magazine *Tekhnika Molodezhi* (Technology for the Youth) [86]. This highly popular technology-oriented monthly publication reached half a million subscribers. Only three months after the announced first successful ICBM flight in August, an article in this magazine discussed the powered ascent of a rocket guided by radio beams from the ground, including one from behind the launch point, as well as the use of an onboard transponder for engine cutoff [88].

7. R-7 trials and rocket evolution

OKB-1 delivered sections of R-7 rockets to Tyuratam from Podlipki (and later from Kuibyshev) by rail. The officers and soldiers of NIIP-5, together with engineers and technicians from industry, assembled rockets horizontally and thoroughly tested them in an assembly and testing building, MIK, at Site 2 (Fig. 13).

At an important meeting in November 1954, government officials and designers agreed on transporting R-7 blocks by rail and their horizontal assembly [4]. This consequential decision limited the size of factory-built components and shaped many features of the rocket. From the MIK building, a rail platform with a fully assembled ICBM or a space launcher slowly rolled to the launch pad two kilometers away (Fig. 7). There, the ground crews erected, fueled, tested, and launched the rocket. The R-7 successors, the Soyuz space launchers, have been repeating this procedure hundreds of times throughout many decades (Fig. 14).

After the rocket liftoff, the side blocks (the first stage of the rocket) separated in 115 seconds at an altitude of 40-50 km. At that moment, the R-7 velocity was 2100-2200 m/s. The central block continued to fire for more than three minutes. At its engine cutoff 300-320 seconds after the liftoff, the ICBM reached a velocity of 6380-6390 m/s [2,4].

NIIP-5 officers and specialists from industry conducted launches from a blockhouse near the



Fig. 13. Assembly and test building, MIK, of rockets and spacecraft, at Site 2 of the Tyuratam range. Top: MIK construction in 1956 (view from the west). Middle: completed building (view from the south). Bottom: R-7 horizontal assembly inside MIK. Credits: top – Russian State Archive of Scientific and Engineering Documents; middle and bottom – frames from film [76].

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Fig. 14. Rail platform with a fully assembled Soyuz space launcher rolling to the launch pad from MIK in 2016. The process has not changed from the early days. Photograph by Mike Gruntman.

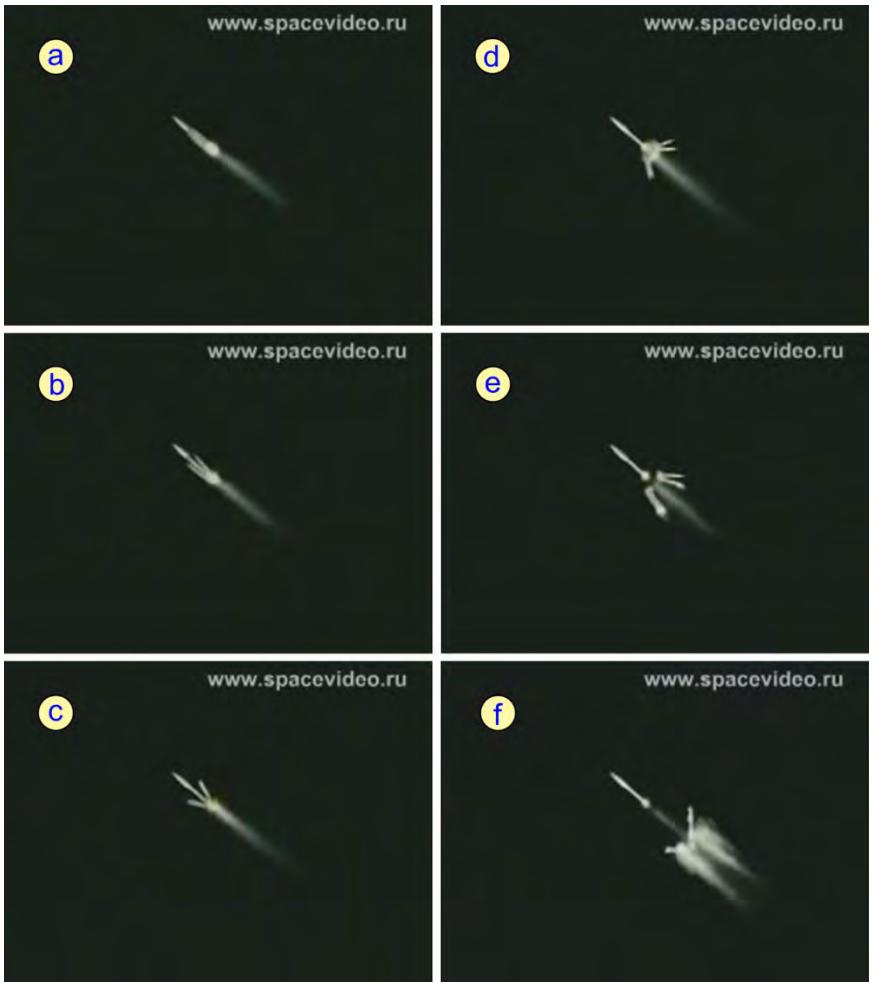


Fig. 15. Separation of R-7 side blocks 115 seconds after the liftoff at 40-50 km altitude. The central block (second stage) continues to operate for more than three minutes. The Test Range Measurement Complex, PIK, captured separation events on film by KST-80 cinetheodolites at its measurement posts IP-4 and IP-5. Credit: frames from film [76].

launch pad. The main and mirror radio control posts, RUP A and RUP B, controlled the vehicle flight during its powered ascent. The reentry vehicle (or satellite) separation followed the cutoff of the second stage engine. Nine PIK's measurement posts, IPs, captured telemetry and tracked rocket position and velocity by optical and radio equipment and radar. IP-4 and IP-5 had agile optical telescopes with 80-cm diameter apertures, cinetheodolites KST-80. They recorded the launch-critical event of stage separation on film (Fig. 15). The operating crew of each cinetheodolite consisted of one officer and three soldiers.

The main instrumentation post, IP-1, 2 km from the launch pad (Fig. 7), coordinated operations of remote IPs. In early 1957, 28 officers and 54 sergeants and soldiers served at IP-1 [89]. In the early days, each R-7 launch involved more than 1000 officers, 300 sergeants, and 2500 soldiers as well as numerous engineers and technicians from industry [4].

The R-7 development program went through three phases of ground and flight tests [49]. The first phase lasted from September 1956 to March 1957 and focused on ground firing of rocket engines at special stands, many at Branch No. 2 of NII-88 (future NII-229), 90 km north-northeast of Moscow. Then, NIIP-5 conducted 13 rocket launches during the second phase from May 1957 to July 1958. It consisted of 9 ICBM launches (6 being successful or partially successful) and 4 satellite launches (three successful, deploying Sputnik 1, 2, and 3 into orbit). Finally, the third phase from August 1958 to November 1959 included 16 ICBM launches (two failed) and 8 space launches (three successful). The tests of a

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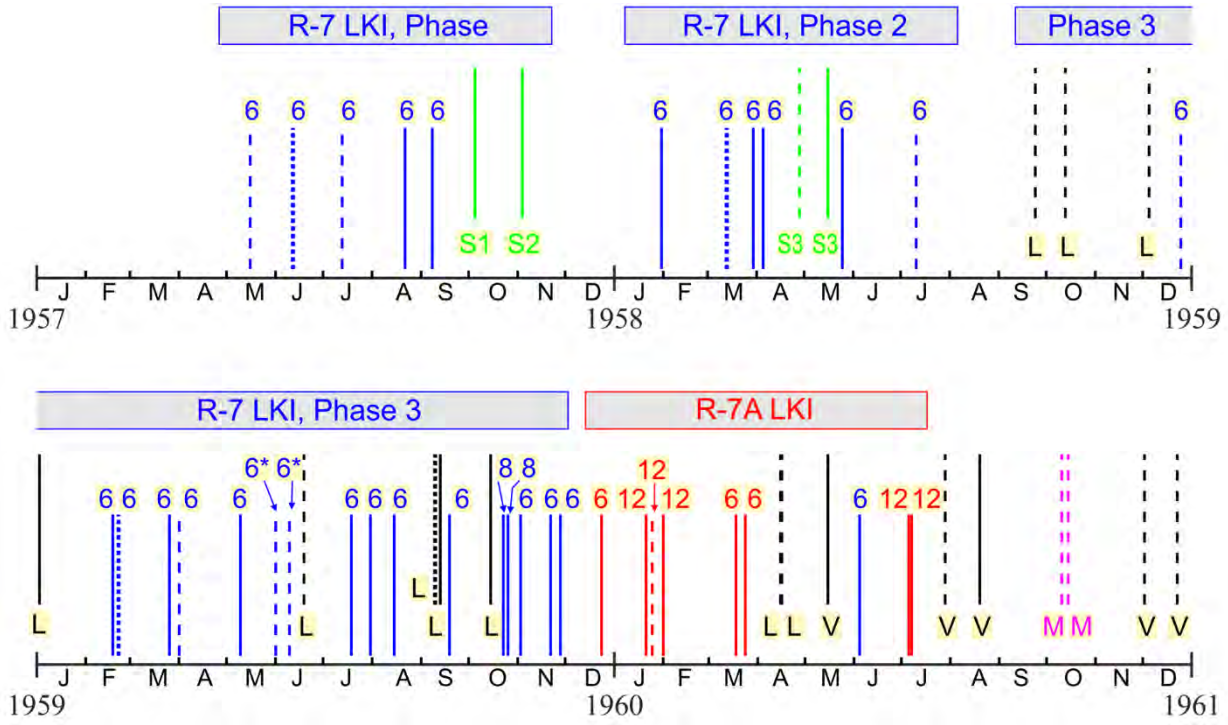


Fig. 16. Phases (campaigns) of OKB-1/NIIP-5 flight design tests, LKI, of the R-7 and its derivatives at the Tyuratam Missile Test Range from 1957-1960 (based on [2,49,90,93]). The vertical lines, which begin near the horizontal time axes and have the marks (numbers) above them, show launches of the R-7 (blue) and R-7A (red) ICBMs. The vertical lines, which originate at a larger distance above the horizontal axes and have the symbols (letters) beneath them, represent R-7 space launches. The solid and dashed lines correspond to successful and failed launches, respectively; the dotted lines are scrubbed launches when the rockets did not pass tests on the launch pad and were removed.

ICBM tests. Marks 6 identify the ICBM launches to a nominal range of 6314.5 km (sometimes 6307.25 km, 6310.96 km, or 6318 km) to the target site at Kamchatka. Marks 8 and 12 are the flights to nominal distances of 8637.53 km and 12059.4 km (and 12, 359.1 km), respectively, to target points in the Pacific Ocean. Marks 6* show the launches on May 31 and June 9, 1959, when the cutoffs of the second stage engines failed, and they burned until all the propellant was consumed. As a result, the warheads overflew the target point by two thousand kilometers and splashed in the Pacific Ocean (Fig. 5).

Space launches. The green lines are the first three successful satellites, Sputnik 1 (S1, R-7 PS), Sputnik 2 (S2, R-7 PS), and Sputnik 3 (S3, R-7 8A91). The black lines show the launches by a three-stage R-7, 8K72, to the moon (marked L) and the development flights of the Vostok spacecraft for human spaceflight (marked V), some carrying dogs. The magenta lines are the launches of spacecraft to Mars (marked M) by the four-stage 8K78 (Molniya) variant of the R-7.

significantly modified rocket variant, R-7A (8K74), followed in 1960 (Fig. 16).

The defense industry conducted flight trials of new missiles as *flight design tests*, or LKI. NIIP-5 and Korolev's OKB-1 divided the R-7 LKI at Tyuratam into three distinct phases or campaigns [2]. The second phase of the R-7 development, described above [49], comprised LKI's Phases 1 and 2. The third development phase was Phase 3 of the LKI trials.

The first LKI campaign consisted of 6 launches in 1957 (Fig. 16). All ICBM tests were on the nominal distance 6314 km, with the impact point at Kamchatka [49,90]. NIIP-5 and an industrial team attempted the first R-7 launch on May 15, 1957. The crews had been learning how to prepare a large and complex rocket, and the prelaunch ground testing lasted almost ten days. Checking electrical systems alone took more than 110 hours. The rocket successfully lifted off and flew nominally for more than one minute before the onboard fire developed.

A report to the Central Committee of the Communist Party summarized the accident:

> A fire took place because of … [a leakage] in high-pressure kerosene pipes of the power plant.

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> Development of fire on the 97th second of the flight led to the termination of the functioning of the engine of one [side] block and its separation from the rocket on the 98th second of flight. (Nominally, side blocks should separate on the 115th second.) Because of this [separation of the side block], the accident termination system turned off other engines of the rocket [91].

Search teams found two rocket blocks 300 km downrange and 10 km to the left of the nominal trajectory ground track. The investigation of the rocket failure involved examination of the telemetry recorded on oscilloscope photographic films 20 km long [92].

NIIP-5 tried the second R-7 launch unsuccessfully three times on June 11, 1957. Frozen liquid oxygen valves aborted the first two attempts. Then, the incorrectly mounted valve for nitrogen purge of liquid oxygen pipes led to failure. The rocket was safely removed from the launch pad and returned to the assembly building.

The ground crews made the third attempt on July 12. The liftoff was again successful, but the rocket was destroyed after 33 seconds because of uncontrollable spin caused by electronics failure. Finally, the fourth launch on August 21, 1957, succeeded, and the missile reached its target area at the Kamchatka Peninsula. The simulated warhead disintegrated during reentry into the atmosphere. The engineers attributed the latter occurrence to the warhead's likely collision with the rocket second stage after separation [4,25,40].

Six days after this first full-range flight of the R-7, the official Soviet news agency TASS declared to the world that the USSR had demonstrated the ICBM. Simultaneously, it also announced positive results of the recent nuclear tests. The Soviet Union had thus realized the nuclear-tipped ICBM [2,40].

The next successful full-range rocket flight followed on September 7, 1957, but the warhead again disintegrated. In these first two ICBM launches, the military estimated the impact points as the centers of the reentry vehicle fragments found at Kamchatka.

NIIP-5 concluded the first LKI campaign by two space launches that placed the first artificial satellites of the Earth into orbit, Sputnik 1 on October 4 and Sputnik 2 with dog Laika on November 3. OKB-1 modified R-7 rockets, designated 8K71PS, for this task. The rocket length was slightly shortened, but its diameter and general design remained the same (Fig. 17). A participant of the events noted that such space launches "did not present any difficulties… [T]he launch of the R-7 rocket with the first satellite onboard did not differ in its appearance to us [in missile control] from other launches during the R-7 trials at the range" [36].

The correspondents of the world press stationed in Moscow largely ignored earlier publications in the Soviet Union that had clearly pointed to forthcoming satellite launches. The first satellite "surprises" in October and November of 1957 led to a public uproar in the United States [40], driven and amplified in part by internal politics [94].

Following the first R-7 LKI campaign, OKB-1 corrected the identified technical problems. In particular, it prepared three new types of warhead thermal protective layers to test on future launches. The engineers also modified the reentry vehicle design, improved the separation system, and increased the delay between the main engine cutoff and separation from 6 to 10 seconds to avoid possible collision [4]. In addition, they installed a new onboard slit antenna for the missile tracking and telemetry system Tral [2].

The second LKI phase lasted from January to July of 1958, ending with the last rocket firing on July 10, 1958 (Fig. 16). During this campaign, the launch on March 29 demonstrated the first completely successful ICBM flight, with the warhead reaching the impact area without disintegration. It created a crater 32.5 m in diameter and 13.2 m deep [49]. In the next partially successful ICBM flight on April 4, radio control of the engine cutoff failed. The onboard integrator of the apparent velocity in the backup inertial guidance system turned the engine off with an inbuilt small delay, resulting in a 68-km overflight [49]. The trials provided important technical data, which remained, however, insufficient for addressing rocket structural oscillations and collecting the statistics on the impact point scatter to determine ICBM accuracy [2].

During a flight of this campaign, OKB-1 and NII-885 introduced the first major change in the R-7 radio control. The modified guidance system widened the angular sector of launch directions to 40 degrees (Fig. 4, right). A new "asymmetric" RUP mirror site at Irgiz (RUP-3 in Fig. 6; Fig. 12) controlled the rocket together with the main RUP A. The flight validated the approach that NII-4's Feoktistov and Maksimov had outlined in 1955 [30]. After the second LKI campaign, OKB-1 moved the autonomous control unit of the rocket from its position between the propellant tanks to the top of the R-7 central block, next to the radio control system. In addition, the engineers increased the thrust of steering engines [2].

Sergei Khrushchev, the son of the Soviet leader Nikita Khrushchev, worked in the rocket design bureau of Vladimir Chelomei and closely followed the developments in ballistic missiles. He recalled that after Phase 2 of LKI in the middle of 1958, top defense officials briefed his father on the projected costs of the ICBM program. Not only was the industrial production of the R-7 expensive. Sergei noted that the enormous costs of operational deployment of these large rockets with gigantic launch installations and remote control sites especially unsettled the Soviet leader.

Khrushchev's son pointed out that several design flaws of the R-7 came into focus at this time, the

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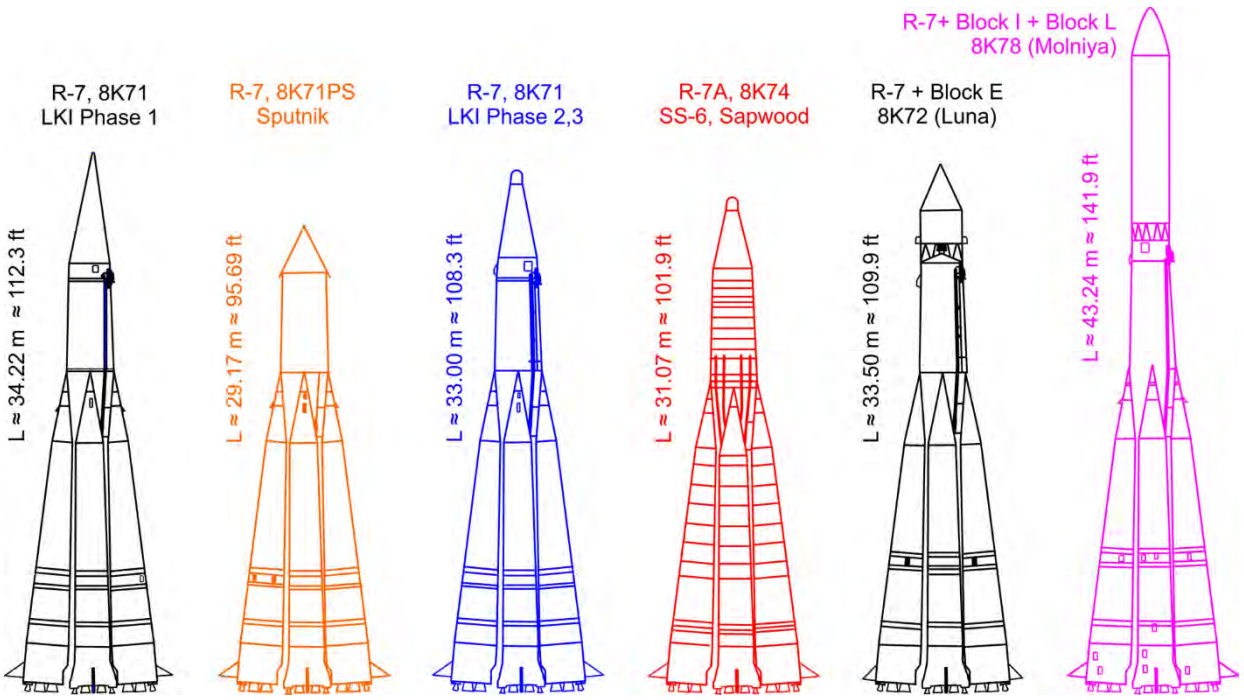


Fig. 17. Early R-7 ballistic missiles and their adaptation for space launches. The crude schematic sketches are roughly to scale. The rocket lengths L varied, depending on the number of stages and the length of the payload. The diameter of the core stage remained the same, determined by the fabrication tooling. From left to right: R-7 (8K71) ICBM (black) and R-7 (8K71PS) variant for the first two space launches (orange) during the first LKI phase in 1957; R-7 (8K71) ICBM during the second and third LKI phases of trials (blue); R-7A (8K74) ICBM (red); basic R-7 with the third stage Block E (8K72) enabling spacecraft launches to the moon (black); and four-stage R-7 (8K78) with Blocks I and L for early missions to Mars (in 1960) and Venus (1961) (magenta).

shortcomings that, in his words, "some [in the government and industry] did not see while the others tried not to notice" [34]. The need to replenish continuously boiling off liquid oxygen and to periodically perform delicate recharging and recalibration of onboard acceleration integrators especially stood out. Difficulties of building ICBM launch bases with remote radio control posts in desolate areas without roads and electric power lines tempered enthusiasm.

The Soviet leader also understood that the presented to him estimates of half a billion rubles (1958 currency; reformed in 1961) for each R-7 launch position were "only a beginning" because "any construction project [in the country] costs a few times more than the initial projections" [34]. To put this number in perspective, one billion rubles equaled 0.6% of the entire annual defense-related expenditures of the country in 1960, which consumed 7.5% of the gross national product [19,95].

In the middle of 1958, Nikita Khrushchev met with Sergei Korolev to consider possible alternatives and solutions. According to Khrushchev's son, Korolev totally rejected the idea of building ICBMs based on storable propellants such as nitric acid oxidizer, arguing that it would corrode all tanks, pumps, and valves.

Note that the competitor of OKB-1, Yangel's OKB-456 in Dnepropetrovsk, had been working on the development of such an ICBM, R-16 (8K64, SS-7, Saddler), at that time. The Council of Ministers authorized the program by *Postanovlenie* No. 1596-807 on December 17, 1956 [96]. The rocket relied on unsymmetrical dimethylhydrazine (UDMH) and nitric acid. Already in 1961, the military operationally deployed 10 of the R-16 ICBMs, with their number growing to 172 in 1964 [97].

The son of Khrushchev recalled that Korolev had also surprised the Soviet leader by promising at their meeting that

> they [OKB-1] will eliminate distant radio control posts, and soon it will be possible to control the rocket without radio, autonomously. The father gasped at this unexpected statement. "Why did we then plunge so much money into building a new test range at Tyuratam? The autonomous[ly guided] 'semyorka' [R-7] could have been launched from a well-established [existing range at] Kapustin Yar," he uttered with reproach. Korolev did not argue but

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> explained that when [the construction of] the new test range was being decided on, he did not think [that] the autonomous control system [would be realistic]. In everything else, Korolev remained unbending. … Unlike in their previous meetings, they [N. Khrushchev and Korolev] parted … with a feeling of dissatisfaction [34].

Facing enormous costs and logistical challenges, the Soviet leader decided to significantly scale down the ICBM deployment plans to three positions: one new separate launch pad at Tyuratam (future Site 31 of the range) and two sites at Plesetsk.

In another important development, Soviet nuclear institutions had concluded by 1958 that a thermonuclear charge could be made smaller than was originally planned for the R-7. Consequently, the same R-7 rocket could deliver a lighter warhead to a distance much larger than the 8000-km range.

On July 2, 1958, several decrees of the Central Committee of the CPSU and the Council of Ministers of the USSR shaped the directions of ballistic missile programs for several years [98]. First, the authorities ordered (*Postanovlenie* No. 718-342 and No. 725-347) building two operational ICBM launch positions, called "object Angara," at Plesetsk. Another *Postanovlenie*, N. 724-346, approved work on the modified Korolev's longer-range lighter-warhead R-7 ICBM, designated R-7A (8K74; the U.S. DoD and NATO retained the SS-6 and Sapwood names for this rocket variant). The decree stipulated a 12,000-km range with an accuracy of 10 km for the new missile.

Also on that day, *Postanovlenie* No. 726-348 initiated development by OKB-456 of a new inertially-guided intermediate-range ballistic missile using storable propellants, R-14 (8K65, SS-5, Skean). Two months later, a new decree (No. 003-476, August 28, 1958) accelerated work on another Yangel's storable-propellant missile, the R-16 (SS-7) ICBM.

The main goal of the next, third phase of the R-7 LKI in 1959 was to demonstrate the readiness of the rocket for operational deployment as an ICBM and conduct launches of series-manufactured (at Kuibyshev) missiles by trained military combat crews. The campaign lasted from December 24, 1958, till November 27, 1959, and included 16 rocket launches. In addition, several modified R-7s with third stages sent spacecraft to the moon, three being successful [2,90,99].

Based on the R-7 LKI trials in 1959, a report to the Central Committee of the CPSU on December 29, 1959, determined that "the development of the strategic intercontinental ballistic missile R-7 had concluded with general positive results" and that the rocket had met "the range and accuracy requirements … of the Ministry of Defense of the USSR". The report noted that the series-production plant in Kuibyshev built half of the tested ICBMs. It also emphasized that the military had activated the first operational (combat) R-7 launch position, Angara, at Plesetsk, with the second position to be ready in January 1960 [49]. On January 20, 1960, *Postanovlenie* No. 60-20 of the CC CPSU and CM USSR accepted the R-7, article 8K71, for operational deployment [19]. Each ICBM launch position at Plesetsk included one main RUP and two mirror RUPs [79,100].

The son of the Soviet leader Khrushchev remembered that the first deployed ICBMs targeted "one New York and the other Washington, D.C. The targets for two other rockets were supposed to be Chicago and Los Angeles." He "did not see the maps with the targets, but there were many conversations among rocketeers about city hostages on the territory of the United States. The father [Nikita S. Khrushchev] also mentioned them" [34].

During the third, final LKI campaign of the R-7 trials in 1959, another consequential development took place that would soon significantly change and simplify the rocket. As Sergei Korolev told Nikita Khrushchev at their meeting in the summer of 1958, the maturing technology made it possible to eliminate remote radio side-motion control sites. At that time, OKB-1 was already working on the modified version of the rocket with a lighter warhead and longer range, R-7A (8K74). Now, this missile could be further improved by drastically changing its flight control. Importantly, the cost of its operational deployment that had unsettled the Soviet leader so much could be significantly reduced.

On July 23, 1959, top defense industry and military officials summarized the developments in a report to the Central Committee of the CPSU:

> A possibility has emerged during trials of the article R-7 to significantly simplify the system of radio control of the [being developed] article R-7A, which would allow a significant reduction of the cost of operational launch positions of the article R-7A as well as improve the performance characteristics of this article.
>
> NII-885 … conducted the analysis of the accuracy of control of side motion of the R-7A by an autonomous [inertial] control system, which showed a possibility of achieving the required flight accuracy of this article [missile] without radio control in the side direction. In that case, the ground equipment of R-7A radio control would be deployed [consolidated] in a single position near the launch point. The cost of an equipment set [for one launch position] would decrease from 52 million rubles to 23 million rubles. The cost of the construction of radio control posts of one operational [launch] position, including communication systems, would decrease by 80 million rubles. The expenses on the [military] personnel operating the radio control system would decrease by about 9-10 times [101].

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Soon, the Central Committee of the CPSU and the Council of Ministers of the USSR (*Postanovlenie* No. 997-434, August 22, 1959) approved these consequential changes for the R-7A [14].

It is not clear from the report wording in heavy bureaucratese whether the improved inertial guidance technology alone or a better design by NII-885 based on the existing autonomous unit enabled this dramatic simplification of missile flight control. As is common for complex systems, a combination of advancements likely contributed to the rocket modifications. Personal rivalry among leaders of ballistic missile development, institutional competition, parochial interests, and access to the decision makers also likely played important roles in how exactly this change happened.

One participant in missile control work since the mid-1950s recalled that "some respected specialists believed [at that time] that an autonomous control system [of ballistic missiles] would not be able to achieve the accuracy of hitting a target provided by radio control systems [in the 1950s]" [102]. Another top specialist noted that "the position taken by some leaders of the institute [NII-885] who claimed that there was no alternative to radio control systems was slowing the new development [of inertial systems]" [63]. The latter observation clearly referred to internal disagreements within NII-885 between proponents of radio and inertial systems.

Korolev's deputy Chertok also wrote that, in the early 1950s, Konoplev in NII-885 believed that "ballistic missile control systems should move away from unwieldy and complicated radio systems… One time, Konoplev let it slip to me [Chertok] that, if it had been up to him, he would have completely redone the system developed and put into production for the R-7." Guidance specialists at another research institute, NII-49, in Leningrad have also been arguing that advances in accelerometers should allow achieving the desired missile accuracy "without a radio system" [33].

Outspoken Feoktistov observed that the personalities of leading program participants, especially their abilities to operate in a cumbersome totalitarian system, played a decisive role in the R-7 program. He described that many

> global decisions [in rocketry] were made not by CC CPSU and not by the government [Council of Ministers] but by [a very senior defense industry official Dmitrii F.] Ustinov and Korolev. By hook or by crook, they later sought to formalize their decisions by the "cognizant [responsible government] bodies." In this troubled milieu of the state monopoly [on everything] and without a czar at its top, in a system of not [firmly] codified rules that could change at any moment, both Ustinov and Korolev felt themselves as fish in water [30].

Nikolai Pilyugin's team at NII-885 had been building inertial units of the combined control systems for Korolev's rockets since the late 1940s, beginning with the R-1. They realized the shortcomings of "pendulum accelerometers with inductive transducers of moving element angles" used in the German A-4 and initiated development of alternative devices. The referred-to German sensor was likely an electromagnetically-constrained pendulum cross-range accelerometer developed in the A-4 program [58].

Gennady V. Semenov began to work at NII-885 in 1955 and later served in a high-level position in the overseeing ministry. He recalled that Pilyugin's team

> soon understood that they [pendulum-type accelerometers of the A-4] were unsuitable for normal and side stabilization [of intercontinental missiles] because of low measurement and transducing accuracies. … [T]herefore, we [at NII-885] began development of our [new] devices to form controlling signals for the system of normal-and-side stabilization, which were proportional to the side and normal components of apparent velocities. We called these devices measurement-transducer heads (IPG [in Russian abbreviation]). We [also] began to design similar IPGs for the system controlling the [missile] range …
>
> [D]evelopment of IPGs established a possibility of building [inertial missile control] subsystems … that, in turn, enabled control of the R-7 rocket and other rockets with the required flight accuracy without using radio systems for range and side control [103].

Following the first successes in IPG development, the government organized their series production at plants in Kharkov in Ukraine and Omsk in Siberia. The first-generation IPG sensor, V142, would be used in the autonomous control system of the R-7. Plant No. 634 in Omsk, today's Elektrotochpribor, manufactured thousands of the second generation IPGs, F142, D139, D142, and D242, for IRBMs and ICBMs [103-105].

In the meantime, as inertial guidance technology was still maturing, LKI flights of the improved R-7 rockets, R-7As (8K74), began at Tyuratam on December 24, 1959, and lasted until July 1960 (Fig. 16). NIIP-5 launched 8 rockets, with 7 being successful. The missile had a lighter warhead and relied on radio control for its engine cutoff. The new autonomous (inertial) system performed trajectory side control. Therefore, missile guidance did not require the mirror RUP B anymore, and the main RUP A was moved to the vicinity of the launch site. It became known as a "near-start" or "near-launch-pad" (*pristartovyi*) RUP.

The single consolidated RUP controlled only the range, range rate, and the elevation angle of the missile position using radar and onboard transponders. Rocket flight control relied on the engine cutoff radio system only during the critical final stage of the powered ascent. Consequently, one fixed onboard antenna replaced two

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mechanically articulated agile antennas of the original radio system communicating with the missile from after its liftoff. This significantly simplified the operations and further reduced the ground equipment. The pulse signals for side control (Fig. 4) were completely eliminated. During tests, NIIP-5 conducted several R-7A launches to a 12,000-km range (Fig. 16), with impact points in the central Pacific Ocean monitored by instrumented ocean-going ships. The government accepted the R-7A ICBM (8K74) for operational deployment by *Postanovlenie* No. 1001-416 on September 12, 1960 [19].

The ballistic missile technology continued to advance, and Korolev's OKB-1 introduced many innovations in its next R-9A ICBM (8K75, SS-8, Sasin). In particular, significant effort went into improving the thermal insulation of cryogenic components and handling of liquid oxygen. The introduction of supercooled liquid oxygen made its longer storage possible. Its lower viscosity also shortened the loading time into rocket propellant tanks from 20-30 min to 3-8 min, which did not exceed the time needed for spinning up gyroscopes of the missile guidance system in preparation for launch [2]. The military deployed this Korolev's new kerosene-liquid-oxygen ICBM in silos in the mid-1960s. The missile was 3.5 times lighter at liftoff than the R-7 and carried a more powerful nuclear warhead with a 5-mt yield [106].

Radio control had also been improving. The industry now produced flight-qualified continuous-wave klystrons, which enabled missile control based on interferometric techniques. By the end of 1960, NII-885's Borisenko had built such an interferometric system for ballistic missile flight control.

In the late 1940s, OKB-1 and NII-885 established a practice of testing new radio control systems on flights of older missiles. For example, the engineers tried the original R-7 radio control on the R-5 flights, where the units under development were installed instead of warheads. NII-885 first tested a prototype of the new interferometric system in such a passive, payload mode on the R-7 during the memorable flight of the first cosmonaut Yuri Gagarin to space on April 12, 1961. The interferometric unit did not control the vehicle flight but only used the launch to verify its performance [36,56].

NII-885 successfully completed the development of this new interferometric radio control system, which had two perpendicularly oriented pairs of receivers to measure the direction to the vehicle in elevation and azimuth [36]. It continued to rely on transponders and Doppler frequency shift for the determination of the rocket range and range rate during powered ascent. Some variants of the operationally deployed Korolev's R-9A ICBMs used the direction-finding interferometric technique for guidance. While NII-885 built similar systems for Yangel's R-36 (8K67, SS-9, Scarp) and Chelomei's UR-100 (8K84, S-11, Sego), the military fielded these ICBMs with all-inertial guidance systems [6,8,33,36].

The inertial guidance unit of the R-7 provided the backup for cutting off the main engine with some delay after the nominal time, if the radio control command failed. It performed this critical function for the first time in the launch on April 4, 1958. Another rare failure of radio control happened during Gagarin's launch. A power converter of the onboard radio system malfunctioned, and it did not command the engine cutoff. The backup autonomous system terminated its firing with an inbuilt one-second delay that resulted in a slightly higher velocity of Gagarin's spacecraft. Consequently, the orbit apogee was 40 km higher than nominal [24,33,36,37]. This could have resulted in a tragedy.

After one orbit, the Vostok vehicle with the first cosmonaut fired an onboard braking engine to reduce its velocity. Typically, one needs to lower the spacecraft velocity by 100-150 m/s to reenter the atmosphere and land (e.g., [107]). A veteran of instrumentation sites of the Tyuratam range, Vladimir Kraskin, explained:

> The orbit of the satellite [Gagarin's spacecraft] was chosen such that, in case of malfunction of the braking engine during reentry, the vehicle would land in 5-7 days due to the natural braking [due to friction] in the upper atmosphere. The life support system of the reentry vehicle was designed for this duration [of flight]. The increase of [orbit] apogee by 40 km increased the time in orbit to 10-12 days [and the cosmonaut would have perished as a result]. But the braking engine did work, and the man who accomplished the first human spaceflight remained alive [37].

The fundamental weakness of using cryogenic propellants in Korolev's ballistic missiles R-7 (8K71), R-7A (8K74), and R-9A (8K75) could only be eliminated by transition to storable propellants. Yangel's OKB-586 built such an ICBM, R-16 (8K64), which was also almost twice lighter than the R-7A. Its corrosive nitric acid and UDMH propellants improved missile readiness but still had limitations. Despite their shortcomings, the Soviet Union was quickly deploying these imperfect first-generation ICBMs (Table 3) as they became operational in the early 1960s [108].

Table 3. Operationally deployed first-generation ICBMs

	R-7	R-7A	R-16	R-9A
	SS-6	SS-6	SS-7	SS-8
1960	2	2	0	0
1961	0	6	10	0
1962	0	6	50	0
1963	0	6	114	2
1964	0	6	172	11

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With the introduction of the universal rocket UR-100 (8K84, SS-11, Sego) developed by Vladimir Chelomei, the second generation of liquid-propellant strategic ballistic missiles overcame many of the most challenging problems of the first-generation ICBMs. Then, many years later, solid propellants would replace the liquid propulsion of Soviet ICBMs.

8. To low Earth orbit and beyond

OKB-1 modified two R-7 rockets to launch the first satellites during Phase 1 of LKI in 1957. A rocket variant, 8K71PS, successfully placed into low Earth orbit Sputnik 1 and Sputnik 2 in October and November of 1957. The launch of the first "simplest satellite" (PS), Sputnik 1, required the development of techniques for jettisoning the protective fairing and separation of the satellite. The second satellite, Sputnik 2 with the dog Laika onboard, was not designed to separate, and it orbited the Earth joined with the second stage of the rocket [2].

After development delays, the originally planned first Soviet satellite, Object D, was finally ready in early 1958. OKB-1 had optimized thrust time dependences of R-7's main and vernier engines for this launch. The military assigned the identification 8A91 to the launcher. The first attempt to send Object D to space on April 27, 1958, failed on the 93rd second of flight due to structural longitudinal oscillations (pogo effect) of the launcher. On May 15, 1958, the R-7 successfully deployed this large 1322-kg satellite, known as Sputnik 3, into orbit. The spacecraft had numerous scientific instruments [109] and carried solar cells to generate electrical power. It remained in orbit for almost two years until April 6, 1960.

On March 20, 1958, a government decision approved the development of a three-stage variant of the R-7, 8K72, capable of sending spacecraft to the moon. Going beyond low Earth orbit represented a high-priority step in the space race between the superpowers. This space launcher consisted of a basic R-7 and the added third stage, Block E, on top (Fig. 17). It became the first Soviet rocket with a separation of sequentially installed stages, unlike the side blocks of the R-7 mounted in parallel. A series of spacecraft for exploration of the moon had the letter E in their designations, such as E1, E1A, E2, etc. [2,110,111].

Another government decision authorized building two competing liquid-propellant engines for the new Block E upper stage [110]. The primary engine, RD-119 of Glushko's OKB-456, included several important innovations. In particular, it used UDMH instead of kerosene as fuel in combination with liquid oxygen as oxidizer. Engineers anticipated the increase in the engine's specific impulse by 8-10 s [11].

Concurrently, Special Design Bureau OKB-154, led by Semen A. Kosberg, began work on a backup kerosene-liquid-oxygen engine, 8D714. This engine inherited the design and propellants of the vernier engines operating with RD-107. A division of OKB-1 that had designed these steering engines for the R-7 also joined work on 8D714 [2,11,110]. Later known as the Design Bureau of Chemical Automation (KB KhimAvtomatiki), OKB-154 was located in the town of Voronezh, 400 km south of Moscow.

Facing development difficulties, OKB-456 could bring its new RD-119 to an operational status only by the middle of 1959. Korolev's OKB-1 then decided not to wait and declined the use of Glushko's RD-119 in its 8K72 [11]. It chose Kosberg's 8D714 engines based on familiar propellants for Block E of its lunar missions. In the meantime, the RD-119 engine of Glushko soon proved its value and performance. Nearly 170 space launches by other rockets relied on this upper-stage engine in the 1960s and 1970s.

Valentin Glushko was not happy with this contentious episode about R-7's upper-stage engine, undermining his dominating position in rocket propulsion. This led to a souring of his relations with Sergei Korolev [99]. Later, a rivalry between these two prominent leaders in the Soviet space establishment had a major effect on the development of the N-1 space launcher for the manned lunar program. Head of the country Nikita S. Khrushchev recalled that

> the differences of opinion [between Korolev and Glushko] started to pull them apart, and the two of them couldn't seem to work together… I wanted them to make peace with each other, so that they could devote more of their knowledge to the good of the country, rather than dissipate their energy on fights over details. It seemed to me that they were both talented, each in his own field [112].

Starting the engine of the 8K72 third stage, Block E, in conditions of weightlessness presented a challenge because of the uncontrolled motion of propellants in tanks. Therefore, OKB-1 introduced a procedure, called a "hot start," to initiate firing of the third stage engine before the final cutoff of the second stage engine. The continuing vehicle acceleration by the lower stage settled the propellant at the bottom of the tanks in Block E. Only after the third stage engine began firing, Block E and the spacecraft on top separated from the second stage below. (Such separation is commonly referred to as "hot staging.")

To implement the hot start on the R-7, the engineers placed the third stage of the rocket at a distance from the second stage. An open beam truss between the stages allowed engine exhaust to freely escape to space before separation. This design resembled the interstage truss of the second stage of OKB-1's next ICBM R-9A (8K75) already in development, with Kosberg's OKB-154 building its second stage. The present-day Soyuz space launcher preserves this open interstage gap inherited from 8K72 and R-9A (Fig. 18).

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At the beginning of the third LKI campaign of the R-7, the new three-stage space launcher, 8K72, attempted three times, unsuccessfully, to send spacecraft to the moon (Fig. 16). The first two launches, on September 23 and October 12 in 1958, failed due to the pogo effect. A technical investigation identified the cause of the longitudinal structural oscillations and developed mitigating solutions [2,113]. A malfunction of a hydrogen peroxide pump terminated the third flight. Finally, on January 2, 1959, the fourth 8K72 successfully launched the 361-kg spacecraft, E1, to the moon. The mission objective was to impact the lunar surface. The vehicle exceeded, however, the required Earth departing velocity by 41 m/s and missed the moon by 6000 km from its surface [114]. Consequently, the spacecraft became the first human-made object orbiting the sun with a period of 450 days and orbit eccentricity of 0.15.

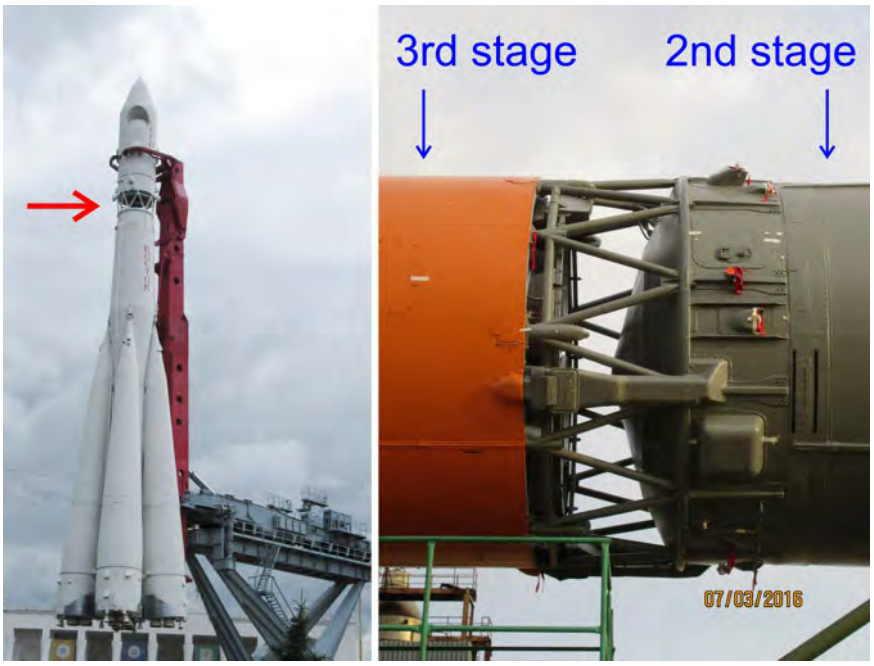


Fig. 18. Left: open beam truss (arrow) between the second and third stages in the replica of the R-7 (Vostok) rocket that launched the first man into space on display (installed in 1967) in Moscow. Right: interstage open beam truss of the modern-day Soyuz space launcher. Photographs (2016) by Mike Gruntman.

With the secrecy surrounding the space program, the Soviet Union claimed the mission success and called the E1 spacecraft Luna-1 and Mechta (a dream in Russian). The batteries powered this space vehicle and enabled communications with the ground for 62 hours. The science payload functioned until a distance of 500,000 km, with reliable data transmitted from at least 200,000 km. The instruments made pioneering measurements outside the magnetosphere, including the solar wind detection [99].

A NIIP-5 veteran, Vladimir V. Poroshkov, participated in this launch to the moon. He attributed the miss of the target to irresponsible carelessness by officers and engineers at the R-7 radio control RUP caused by the New Year celebration less than two days before the launch:

> On January 1 [1959], a representative of the developer organization of the [R-7] radio control system set the elevation of the planes of the RUP [A] antennas with an error of 2 degrees, at 44 degrees instead of [correct] 42. Nobody checked him (because of the [New Year] celebrations [previous night and the resulting lack of sleep and hangover]). The data from a [missile tracking] radar were [properly] fed to the computing unit during the [powered ascent of the rocket] flight. But they indicated, because of the error in elevation, that the trajectory was lower than nominal. Therefore, the computing unit did not cut off the second stage engine [at the right time], waiting for the elevation to reach the [erroneously set] required value… The cause of the error was confirmed by a later check of the [equipment at] RUP, where the set parameters were preserved [4].

Two more 8K72 missions to the moon succeeded in 1959. One spacecraft, Luna-2 launched on September 12, impacted the moon. The other, Luna-3 launched on October 14, flew around the moon and obtained the first photographs of its far side [2,49,90,99].

The R-7 third stage provided higher velocities to spacecraft and made it possible to send them to the moon. It also enabled placing heavier vehicles into low Earth orbit, which was indispensable for developing capabilities for the planned human spaceflight in the future. The three-stage R-7 with Block E (known as Vostok) in these flights carried the 8K72 designation. With a different upper stage, Block I (Soyuz), the military referred to the launcher as 11A511 [2].

For the first planetary missions, OKB-1 built a four-stage variant of the R-7 (8K78). Sometimes called Molniya, it weighed 305 t on the launch pad. The third stage was a new Block I, essentially a modified second stage of Korolev's R-9A ICBM. It relied on the engine of Kosberg's OKB-154. For the fourth stage, Block L, the

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propulsion division of OKB-1 built a new engine, S1.5400 (11D33). This engine had a more complex and more efficient closed-cycle design with a titanium combustion chamber, providing higher specific impulse [2]. (In a closed-cycle engine, a gas-generator powering the turbopump sends its exhaust into the combustion chamber rather than dumps it into the surrounding environment.) Multistage variants of the R-7 preserved the basic design of the rocket but were longer (Fig. 17).

Overcoming a major technical challenge of the time, the last stage, Block L, could restart in weightlessness. The first three stages and the first burn of the fourth stage of an 8K78 rocket placed a spacecraft into a low Earth parking orbit. Then, the second burn of the fourth stage could send a 1.5-t spacecraft on a trajectory to the moon or a 1-t spacecraft to nearby planets, Mars or Venus [99]. (The velocity increments for propelling spacecraft to Mars and Venus are, within 10%, the same, e.g., [107]).

The first two launches of 8K78 to Mars failed because of a malfunctioning third stage [2,16] in October 1960 (Fig. 16). Then, NIIP-5 attempted two 8K78 launches to Venus in February 1961. The fourth rocket stage did not work properly in the first launch. Finally, the rocket performed nominally during the second launch to Venus, but the spacecraft failed after ten days [2,16,99]. The full success in reaching a planet would come only in 1967.

9. For war and space – conclusions

Development of the historic R-7 rocket in the 1950s led to the first intercontinental ballistic missile and launches of the first artificial satellites of the Earth. The rocket's flight control combined autonomous (inertial) and radio systems. The initially implemented R-7 guidance had highly consequential effects on the rocket design and operations. It severely limited its capabilities both as an ICBM weapon and a space launcher, and drove up the cost.

The justifications for the selected R-7 flight control remain buried in inaccessible government and industrial archives. Scarce information in the public domain allows, however, identification of the flight control shortcomings. The main questionable design decision was the insistence on radio control for the operational ICBM rather than accelerating the development of all-inertial guidance.

Several specific features of the implemented radio control that impacted the R-7 performance included: (a) use of pulse techniques for side (yaw) control of rocket motion, which placed the radio control posts hundreds of kilometers away; (b) dependence on an onboard side-control computational unit with inherently limited capabilities, which required symmetric locations of distant radio control posts for a selected trajectory and prevented widening the launch sector by a control function with more complex calculations; and (c) reliance on analog computational units for flight control.

While NII-885 developed and built the flight control system for the R-7, OKB-1 shared the responsibility for decisions to rely on radio control for the operational ICBM and its specific features. Many influential leaders of NII-885 believed that "there was no alternative to systems of radio control" [63] and OKB-1 insisted at the time "that the specified [by the requirements] target accuracy could only be achieved if ICBMs were controlled from the ground via radio link" [48].

Later, the designers justified the need to use the existing proven technology by the time pressure and the existential rivalry with the United States in the Cold War [36]. At the same time, many of them knew that the initial schedule of the R-7 development was too optimistic. For example, *Postanovlenie* No. 443-213ss in February 1953 called for R-7 flight trials in 1955 [14]. It took twice as long for the first missile to lift off the ground.

One could speculate whether OKB-1 and NII-885 should have first accelerated development and maturing of IPG sensors for inertial guidance and microwave components for radio control. Such advances could have saved time at later stages of the R-7 development and resulted in achieving the operational ICBM earlier and at significantly lower cost.

Even a very limited deployment of the R-7 ICBMs in 1960 became possible only after OKB-1 and NII-885 made the first important changes in the original radio control concept. In 1958, they shifted the computation of the side control commands to a ground post, modified exchanges of pulses between the missile and RUPs (Fig. 4), and introduced a new control function. This design eliminated severe restrictions on the trajectory directions and orbit inclinations. Scientists at NII-4 had identified this possibility already in 1955 [30], which could have been implemented at that time.

As the Central Committee of the CPSU and the USSR Council of Ministers blessed the R-7 design and set the program in motion, changing technology and key missile features could only come with major administrative effort and at a penalty to the approved schedule. Consequently, the program leaders pursued such modifications reluctantly and after exhausting band-aid solutions. The R-7 development history shows, however, that major adjustments were possible. In late 1954, the government approved, for example, a highly consequential decision to assemble the rocket horizontally at MIK rather than vertically on a launch pad as it had been envisioned earlier [2].

Non-technical considerations likely played a decisive role in the program execution. It is not known whether the leaders of the R-7 program had ever brought the stark development choices to the attention of the top officials in the Communist Party and government. Perhaps, they feared that such approaches would not be welcome. Or, rivalry among the country's leading missile designers and competing institutional interests prevented honest

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considerations. A totalitarian state, by its nature, offered very few opportunities for truly independent analysis and deliberations, often relying on personal access to the country's leaders for decision-making on proposed developments. Institutional inertia must have also played a role as well as personal considerations of the chief designers, some of whom had unforgettable Gulag experiences earlier in their lives. The consequences of falling out of favor with the country's rulers remained especially severe in a society where all individuals depended on the state for the necessities of their lives and favors, including places of residence, living conditions, education, medical care, and retirement.

The R-7's onboard analog device worked out steering commands for side control from the received radio pulses transmitted from the ground. It is unclear why a radio control RUP could not perform this function on the ground instead. It is unlikely that the designers tried to minimize the signal exchanges between the missile and the ground units (Fig. 4) to protect against possible radio interference and jamming. Reliance on fixed remote outposts made the R-7 ICBM radio control inherently vulnerable in any case.

One can also speculate that a rigid administrative system did not promote innovations with an associated risk of failure. Perhaps this prevented basing control on flight-qualified continuous-wave klystrons or IPGs, which were still being developed in the early 1950s. Pursuing programs with uncertain outcomes could jeopardize the personal standing and professional future of chief designers and their overseeing ministers. Therefore, the inherent institutional inertia encouraged the use of the already proven, even if inferior and obsolete, radio control concepts successfully working on the R-2 and R-5 ballistic missiles.

Dependence on analog computing represented another important R-7 shortcoming. NII-885 and OKB-1 apparently viewed the emerging digital computing as not mature [36]. The designers did not introduce a digital computer, even in a modified ground radio control unit of the R-7, in the late 1950s. In contrast, Soviet strategic missile defense, also being advanced at the same time, relied from the outset on a ground digital computer for much more demanding real-time tasks in missile interceptions [1].

One could speculate that the compartmentalized structure of the Soviet industry perhaps explained the use of analog computing in ballistic missiles. Two partially overlapping, partially independent, and often rival establishments directed the development of ballistic missiles and missile defense in the country. Responsible for ballistic missiles and space, the Ministry of Defense Industry and later the Ministry of General Machine Building were dominated by highly influential rocket designers specializing in structures, gas dynamics, propulsion, and heat transfer, with electronics playing a supporting role. In contrast, the Ministry of Radio Industry, which built air and missile defenses, was responsible for radars and related applications, with its primary expertise in electronics. Consequently, it was more confident in relying on new digital computing.

Insights into the described history of the R-7 (SS-6) ICBM development carry additional importance today because of the current geopolitical environment. The inner workings of the Soviet Union in this program may enhance understanding of the decision-making process and policies of the People's Republic of China (PRC), a space and military superpower. Both countries, the USSR in the past and the PRC today, operate under totalitarian systems with similar roles of the ruling communist parties. The one-party state structures share fundamentally similar governing ideologies. As China is returning to a traditional way of communist governance for the life of a supreme ruler, the historical similarities in decision-making processes could become more pronounced.

After many changes and with all its shortcomings, the historic R-7 rocket became operational as an ICBM in limited numbers in 1960, but not for long. Ballistic missiles with all-inertial guidance and non-cryogenic propellants replaced it in a few short years. As inertial guidance matured, NII-885 terminated all work on ICBM radio control in the late 1960s [6]. The R-7 rocket evolved into a successful family of reliable space launchers that continue to place satellites and cosmonauts into orbit to this day.

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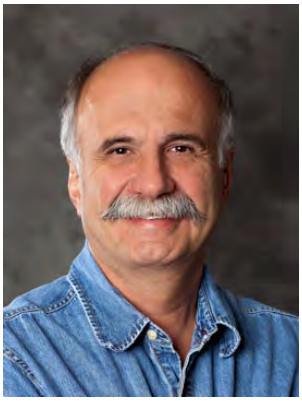
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