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Nuclear energy for space missions

Yu Ya Stavissky

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Contents

Abstract. **A brief review is given of the 1952 – 1988 research at the A I Leipunsky Institute of Physics and Power Engineering (Obninsk) on the use of nuclear fission chain reactions in developing space vehicles and their on-board power systems. The research was carried out on the initiative of the USSR Academy of Sciences Corresponding Member DI Blokhintsev, Head of the Institute, and enlisted the active support of Academician S P Korolev.**

1. Introduction

Ernest Rutherford discovered the nucleus — the 'pointlike' concentration of the mass of the atom — in 1911 by observing the scattering of alpha particles in gold. Anyone with a modicum of education could conclude from this that the entire energy stored in atoms resides in atomic nuclei and that the electron shells of atoms are responsible for the minutest part of it — for the literally 'atomic' energy. Already in 1915, four years after Rutherford's discovery and at the start of World War I, the great science-fiction writer and sociologist H G Wells published a book *The World Set Free* in which he described a nuclear war. The technical details of this war were inevitably naive — the pilot of a 'flying etagere', something like a Farman biplane, lifted the atomic (nuclear) bomb with his hands, bit off some sort of tube and dropped the bomb overboard. What matters is the result: Moscow, New York, St. Petersburg, London, Berlin, Washington, San Francisco and other large capitals the world over are turned into radioactive ruins behind barbed wire fences...

The idea of conquering cosmic space had been Dmitrii Ivanovich Blokhintsev's dream ever since childhood. He had regular correspondence with K E Tsiolkovsky and, like H G Wells, understood very early the significance of nuclear energy for long-distance space missions — indeed, its energy content is higher by a factor of millions than the best chemical fuels. I was in close contact with Blokhintsev in the second half of his life — in Obninsk after 1950. In June 1950 he was given the post of director of 'Object B' of the USSR Ministry of Internal Affairs (currently the A I Leipunsky Institute of Physics and Power Engineering, LPPI) where he was previously head of theory division. I was also sent to Object B after graduation from the Engineering Physics department of the Moscow Mechanics Institute (MMI). I am convinced that Blokhintsev's choice of physics as his path in life — to study physics, to enroll in the Moscow State University physics department — was stimulated by nothing else but his 'cosmic' interests.

August 6, 1945: Hiroshima. An atomic bomb was dropped on the town, to all appearances against the Japanese, but essentially to demonstrate to the Russians the full power of nuclear weapons. Otherwise, our T-34 tanks would only be stopped by the Atlantic Ocean. No wonder the allies were in such a hurry to explode the first atomic bomb on the Alamogordo testing grounds: the Potsdam Conference that was convened to sum up the results of World War II was to open on July 22, 1945.... I suspect that Stalin learnt about the successful test on July 16, even earlier than the President Truman. Intense unfolding of the Soviet 'atomic project' began. To train specialists for this field of science and technology, a new department was created in September 1945 for the needs of 'new ammunition' at the Moscow Institute of Mechanics of the Ministry of Ammunition — the Department of Engineering Physics. The creation of this unique department — and I do not know of any analog to it — is the achievement of the truly great Soviet physicist, academician of the Ukrainian Academy of Sciences Aleksandr Il'ich Leipunsky.

Our teachers in fundamental sciences at the university level, i.e. physics and mathematics, were outstanding scientists. General physics was taught by Semen Emmanuilovich Khaikin, relativity by Igor Yevgenievich Tamm, electrodynamics by Yevgenii Lvovich Feinberg, methods of mathematical physics by Andrei Nikolaevich Tikhonov, experimental nuclear physics by Lev Andreevich Artsimovich, and so forth. At the same time, the curriculum for the entire student corps

Yu Ya Stavissky Joint Institute for Nuclear Research,
141980 Dubna, Moscow region, Russian Federation
Tel. +49 (0) 961 6 34 15 05. Fax +49 (961) 6 28 56
E-mail: stavss@freenet.de

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included the complete set of technical subjects taught at the best engineering institutes — 12 drawing sheets, courses on the strength of materials, metals technology, technology of materials processing, an extended course on analytical chemistry. The course on the theory of mechanisms and machines (TMM, the Russian acronym that students interpreted as 'be buried here') was given by Ivan Ivanovich Artobolevsky 'himself'. However, we were most impressed with the lectures on machine parts given by Nikolai Nikolaevich Vysotsky, and not so much with their content — they were fairly trivial — as with the manner in which they were presented. The experimental physics practical course ('practicum') presented by Evgenii Sergeevich Trekhov (a war veteran amputee with two prosthetic legs) was very solid. Terekhov's tricky tasks or problems still visit me in my nightmares. These unique features gradually evaporated as the growing new Institute of Engineering and Physics, MIFI, merged the engineering physics departments of the Moscow Institute of Mechanics and Moscow Power Institute. With the passage of time the MIFI was transformed into a giant anthill with narrow specialization in various subfields of knowledge.

Aleksandr Il'ich Leipunsky was one of the 'first' pupils of Abram Fedorovich Ioffe, the founder of the Soviet school of technical physics (Igor Vasilevich Kurchatov was 'first among equals', the favorite). Ioffe sent Leipunsky to Ukraine (in 1928) to set up (together with P L Kapitza and I V Obreimov) in Kharkov (then the capital of the Ukrainian Soviet Socialist Republic) the Ukrainian Physico-Technical Institute — the UPTI (now KhPTI). At the beginning of the 1930s Leipunsky worked in Rutherford's laboratory at Cambridge. In 1934 he experimentally confirmed the existence of the neutrino that Pauli hypothesized to save conservation of energy in the β-decay. The corresponding article was published, on Lord Rutherford's recommendation, in *Proceedings of Cambridge Philosophical Society* [1]. After returning to the Soviet Union and having spent in 1937 the unavoidable six months in prison, A I Leipunsky started at the UPTI an extensive program of neutron physics research, unique in the pre-war USSR, a consistent series of experimental nuclear studies. Rutherford (1871 – 1937), the discoverer of the nucleus, kept repeating until his last years that the nucleus hides gigantic amounts of energy stored in it but that this energy manifested itself only in individual acts of nuclear reactions. However, he insisted, it will never be accessible for human use in 'macroscopic' amounts. Rutherford stopped repeating these words after 1932 when James Chadwick, his student, discovered the neutron....

In fact, Kurchatov and Leipunsky were the founding members of our 'atomic project' — Kurchatov as its general science head as of February 1943 after the successful completion of Operation Uranus, as Stalin called the plan of defeating the Germans at Stalingrad (after discussing the intelligence reports on atomic weapons research in Great Britain and reading N Flerov's letters with Vernadsky, Ioffe, and Beria in the autumn of 1942). Leipunsky became — after Stalin received a letter from Manfred von Ardenne — the head of nuclear research conducted by a group that included German specialists. In summer 1945 he became deputy for science to Avraamii Pavlovich Zavenyagin, who headed the 9th Directorate of the MVD USSR (Ministry of Internal Affairs) and was a member of the top body of the atomic problem — the Special Committee of the USSR Soviet of Ministers (from August 20, 1945 until July 1953 the Special Committee was headed by L P Beria, who resigned from all his police and military posts in December 1945). Aleksandr Il'ich Leipunsky then commanded four laboratories which employed about 300 German researchers who previously worked in the German atomic project [Laboratories 'A' and 'K' near Sukhumi, currently the Physico-Technical Institute of the Georgian Academy of Sciences, Laboratory 'D' in the Urals in the environs of Kasli, currently the VNIITF, the All-Russian Technical Physics Research Institute, Snezhinsk, and finally, Laboratory 'V' near Moscow, at the Obninskoe railway station, currently the A I Leipunsky Physics and Power Institute, to whose creation and development AIL (the alias by which Aleksandr Il'ich Leipunsky was known in the company of his students) made the decisive contribution]. He worked as director of research of the Institute from 1957 till 1968. Manfred von Ardenne, a well-known German engineer and physicist, in Hitler's Germany had headed the atomic project in the German Ministry of Communications. In his letter to Stalin he proposed on May 15, 1945, a week after Germany capitulated, to apply his and his staff's talents in working for the Soviet atomic project. He had a good idea of the capabilities of Soviet science and technology in this area from a German communist and outstanding physicist, Fritz Houtermans, who escaped from the Nazis in 1933 and worked at the UPTI in Leipunsky's section from 1933 till 1937. Having spent three years in prison as a 'German spy pretending to be an antifascist', Houtermans was turned over to the Gestapo in an NKVD – Gestapo swap deal in 1940. Owing to von Ardenne's efforts, he was released from Gestapo incarceration and for the rest of the war stayed in von Ardenne's institute near Berlin. Houtermans was the first German scientist who, as early as 1941, worked out the plutonium version of the nuclear bomb but kept his mouth shut and his notes in the strongbox until the war ended....

In Obninsk A I Leipunsky began by designing the synchrophasotron — an accelerator for protons designed for energies that at the time were enormous: 10 GeV. V I Veksler, using a clever trick, 'walked away' with this task and constructed the synchrophasotron in Dubna (known at the time as the Hydrotechnical Laboratory of Minsredmash, that is, the Ministry of Medium-scale Machine Building). Roughly after 1949, A I Leipunsky, most probably primed by The Beard (Igor Vasilevich Kurchatov's nickname), started developing in Obninsk 'fast breeders' for the power industry — fast neutron reactors with liquid metal cooling, 'breeding nuclear fuel'. I happened to work on various aspects of the breeding of nuclear fuel in summer 1950 and later (measuring effective neutron capture cross sections in ^{235}U and ^{239}Pu and in design materials, and doing 'macroscopic experiments' [1, 2]), and also on reactor start-up and physical experiments with prototypes of fast nuclear reactors. Fast breeder reactor technology is very likely the only one in Russia in which we are still 'ahead of the entire planet' as a poet said. Its later version — the program BREST being designed at the NIKIET (N A Dolezhal Research and Design Institute) by A I Leipunsky's closest student and follower Viktor Vladimirovich Orlov — is so far the only approach to building an inexpensive, safe, ecologically clean, large-scale power industry with practically unlimited resources of nuclear fuel. Alas, all other tentative attempts were unfortunately hopeless....

[1] Leipunski A I "Determination of the energy distribution of recoil atoms during β decay and the existence of the neutrino" [Communicated by Lord Rutherford] *Proc. Camb. Phil. Soc.* **32** 301 (1936) (*Added by the author in English proofs.*)

An integrated solution to the problem to atomic weapons in the USSR was an example of unprecedented mobilization of energy and resources of the country for solving a problem of truly national importance: how to achieve parity in weapons in a difficult situation of coping with the consequences of the war that brought to Russia destruction on an unprecedented scale. It became possible to create new scientific and technological fields and industries. Matters were additionally complicated by our falling behind badly in the extremely important electrovacuum technology, which constituted one of the fundamental technical causes of the defeats in 1941 — indeed, there was practically no communication between army units in the new conditions of highly mobile warfare.

2. Development of space mission systems at the LPPI (Obninsk)

D I Blokhintsev, who at the end of the 1940s was teaching the foundations of quantum mechanics at the Physics Department of Moscow State University, spotted and invited to work at the PPI (still 'Object V' of the USSR Ministry of Internal Affairs) a young physicist, Igor Il'ich Bondarenko, who literally dreamt of nuclear-reactor-powered space vehicles. However, having arrived in Obninsk in 1949, Igor landed in A I Leipunsky's sphere of interests and was pulled into the first-priority work: fast breeders.

When D I Blokhintsev became director of the Institute, a vigorous group of young people formed around Bondarenko. The subject that brought them together was the problem of harnessing nuclear energy for space flights. In addition to Bondarenko, the group included Viktor Yakovlevich Pupko, Edvin Aleksandrovich Stumbur, and myself. Igor was the principle generator of ideas. At a somewhat later stage Stumbur conducted ground testing of model nuclear reactors for cosmic atomic electric power stations (CAEPSs) — compact fast-neutron reactors with a beryllium reflector. No adequate computer software was available at the time for computing energy distribution along the radius of active zones of such reactors, so I had to run the corresponding calculations by the Monte Carlo method using manual roulette wheels. Month after month I crawled all over sheets of graph paper covering the floor of a classroom of a former boarding school for Spanish children at the Obninsk railway station (Enterprise POBox 276 at that time), playing out and tracing the fate of neutrons created in the active zone. I was gathering statistics.... By that stage, Stumbur had already carried out experimental measurements of energy release in models of reactors with beryllium reflectors of variable thickness — from 5 to 20 cm. This was important to prevent overheating in the extreme active-zone fuel rods closest to the reflector due to fission neutrons slowed down by the beryllium. Pupko was responsible for nuclear and thermophysical computations of various nuclear jet propulsion designs. When he later became Head of the Space Technology Division of PPI, he had to shoulder a great deal of managerial load. I, a born experimenter ('master of breakage' as my father used to call me after I took apart all the clocks and watches in the house), experimented with 'low-thrust' jet motors (in which the thrust was generated by an unconventional ion accelerator — an ion propulsion motor that was to get energy from the on-board space atomic power station, APS). This was in fact part of the program of power-producing fast breeder reactors. The entire research program was very closely supervised by the director — aka DI (as we used to refer to Dmitrii Ivanovich Blokhintsev) — who helped us all he could. Leipunsky never tried to influence our work. In between the two bosses, we steered a comfortable course. The deputy director, Professor Vladimir Nikolaevich Glazanov, also helped a lot. In his time Glazanov, one of the top men in high-voltage electrical technology, had had a month-long business trip to the USA and, on returning in 1938, paid for it by nearly ten years behind barbed wire, the electric current defrosting the permafrost in the labor camps of Norilsk.

Igor Il'ich Bondarenko was an outstanding physicist in a wide range of fields. He had an exquisite feeling for the subtleties of experimenting, his experiments were graceful and efficient, he 'felt' fundamental physics as no other experimenter and only a handful of theoreticians could. I can only find his equal in Enrico Fermi. Always responsive, open, and kind, Igor was truly the darling of the institute. Even now, the PPI continues to survive mostly on his ideas. His life was unfairly short: he died tragically on May 5, 1964 as a result of a medical treatment error. It was as if God, realizing that this man had already accomplished far too much, decided that enough was enough and called it a day...

The story of relations between Blokhintsev and Korolev, who played important roles in the progress of 'cosmic' design at the PPI, is an interesting one. Both Sergei Pavlovich and Dmitrii Ivanovich had the dream of sending a manned rocket into space. The two were in close working contact, and pulled our group into this collaboration, too. However, in the early 1950s, at the peak of the cold war, money was funneled lavishly but exclusively into war-oriented research and design. Rocketry was regarded as nothing more than the means for delivering nuclear charges to a destination, and no thought about artificial satellites was entertained. In the meantime, Igor Bondarenko, who knew from DI about the latest achievements by rocket scientists, was insistent on 'agitating' at every behind-closed-doors meeting for building an artificial satellite of the Earth. No one remembered his role later...

The story of the creation of the P-7 rocket that sent our first sputnik and then Yuri Gagarin into orbit is linked in an unexpected manner to Andrei Dmitrievich Sakharov. He proposed in the late 1940s a combination fission–fusion charge, known as 'sloika' ('layered pie' in Russian) — perhaps independently of Edward Teller. Teller came up with a very similar device that he called 'the alarm clock', three to four years before Sakharov [3]. He could already use a mainframe computer and understood that the alarm clock (the sloika) could not produce a blast of more than 500 kilotons of TNT. This was not enough for him; he wished to create the 'absolute' weapon of unlimited power against the Bolsheviks and thus threw his alarm clock into the bin of crazy ideas...

After Sakharov's sloika was successfully tested in 1953 (its power proved to be equivalent to 400 kt) and its author was elected to full membership of the Academy, he was invited to the office of V A Malyshev, then head of Minsredmash (and former Minister of the Tank Industry), who ordered him to evaluate, without leaving the room, the parameters of the next-generation bomb. Andrei Dmitrievich Sakharov could not do better than give, without any detailed calculations, the anticipated weight of the new, much more powerful, 'grand sloika' [4]. No information was available at the time on the limitations of this design... Malyshev's report was used as the basis for the decree of the Central Party Committee and the Soviet of Ministers, which ordered the team of S P Korolev to design a delivery rocket for this payload. And it was this rocket, coded P-7 and given the name Vostok, that took into orbit both the first sputnik in 1957 and the spaceship with the first cosmonaut, Yuri Gagarin, in 1961. It was never planned to use it as a carrier of heavy nuclear charges, since the evolution of thermonuclear weapons followed a very different path...

In 1956 DI had to leave behind the work that he loved and, on the orders of the bosses in the Central Committee of the Communist Party, to head the creation of the international research center — the Joint Institute of Nuclear Research — as something this country could show as a counterweight to CERN. No arguing was allowed, so he had to drop the job of his life and switch to something very different... Now, on the eve of Dmitrii Ivanovich's 100th birthday we may note that he coped with his new job brilliantly — the JINR remains the best nuclear-physics research complex in Russia, having preserved almost all the traditions instilled into it by Blokhintsev, like regular discussions and voting on research programs, financing by international program committees, annual council sessions, and so forth...

The program of development of cosmic vehicles in the LPPI included the following main design areas:

1. Low-altitude lifting-Wing Atomic Missiles (WAMs) with ramjet nuclear thrusters, in collaboration with the V N Chelomei Design Bureau (KB).
2. Ballistic Atomic Missiles (BAMs), in collaboration with S.P. Korolev's OKB-1.
3. Work on implementation of a gas-phase uranium-hydrogen reactor, in collaboration with V M Ievlev's section (NII-1).
4. Electroreactive thrusters (ERTs) with high ejection velocity and, correspondingly, low thrust.
5. Nuclear power systems for power supply to ERTs, space radiolocation stations, and retranslators. The work was carried out in collaboration with M M Bondaryuk's OKB-670, M Gryaznov's Special Design Bureau Krasnaya Zvezda, S K Tumansky's Special Design Bureau MMZ Soyuz, and S P Korolev's Russian Space Corporation (RSC) 'Energiya'.
6. The development of a prototype propulsion engine of an atomic rocket, in collaboration with the NII-1 in Moscow, A D Konopatov's Voronezh Design Bureau, and a number of technological groups, and testing at the Semipalatinsk testing grounds.

3. Electroreactive thrusters (ERTs)

The parameter that determines if a rocket can fulfill a specific task is the velocity v that the rocket acquires after using up the entire on-board propellant (fuel and oxidizer in the case of a chemical rocket):

$$v = \sigma \ln \frac{M_{\mathrm{i}}}{M_{\mathrm{f}}} .$$

Here, σ is the exhaust velocity of the working medium relative to the body of the rocket and M_{i} and M_{f} are the initial and final mass of the rocket (K E Tsiolkovsky's formula). The exhaust velocity in conventional chemical rockets is determined by the temperature in the combustion chamber and the molecular weight of the combustion product. It was no accident that the Americans used hydrogen as the fuel in the Moon landing module. The combustion product of hydrogen is water, its molecular weight is relatively low and the ejection velocity is about 1.3 times higher than in the case of hydrocarbon fuels. This proves to be sufficient for a landing craft with astronauts to reach the surface of the Moon and then return the astronauts to the orbit of the artificial satellite, where the orbiting rocket is waiting for them... Korolev had to stop working on the hydrogen version of the system after a grave accident in which people were killed, so we lost the race to the Moon.

The way to achieve practically unlimited exhaust velocities is to accelerate matter using electromagnetic fields. I happened to work in this area for nearly 15 years until, with Blokhintsev leaving for Dubna and Korolev dying tragically, this project died a natural death, smothered by the lack of spiritual and material support...

The acceleration of a rocket with an electroreactive thruster is a function of the ratio of the specific power supplied to the thruster by the on-board atomic electric power station (AEPS) to the exhaust velocity. It is unlikely for the specific power of an AEPS to go beyond 1 kW/kg in the foreseeable future. Furthermore, only rockets with low thrust can be created, their thrust being dozens or hundreds of times less than the weight of the rocket, albeit with very low propellant consumption. Such a rocket can only start from a launch platform of an artificial satellite in orbit around the Earth and, at a low acceleration, reach practically unlimited velocities. It was shown earlier [5] that an ERT can yield appreciable gain if the exhaust velocity exceeds ~ 30 km s^{-1}. At the same time, using a realistic electric power supply and exhaust velocities above 200 km s^{-1} would lead to an unacceptably long time to reach required velocities.

In addition to the need of high exhaust velocity, it is necessary to ensure a high efficiency of conversion of electric energy to kinetic energy of the jet of the working medium (about 100%) and low parasitic loss of the working medium.

Exhaust velocities in the indicated range would make it possible — with the specific power of AEPSs available now — to solve the main problems of space flight within the Solar system. As for flights to the stars, we would need systems with exhaust velocities approaching the speed of light — 'photon rockets'. This, however, is the realm of non-science fiction, since for implementing a long space mission of any reasonable duration with a photon rocket, unimaginable specific power of a cosmic electric generator would be needed. We cannot even dream up what physical processes could be used to build them...

Calculations have shown that at the time of a Great Opposition of Earth and Mars, it is possible to realize a flight of less than a year of a manned low-thrust nuclear spaceship to Mars, and return it to an orbit around the Earth. The total mass of such a ship would be around 5 t (including 1.6 t of propellant), a 3-MW AEPS would have a mass of about 3 t, with the jet thrust being provided by a 2.5-MW beam of cesium ions with an energy of 7 keV, which corresponds to an exhaust velocity of ~ 100 km s^{-1}. The spaceship would start from the orbit of an artificial satellite around the Earth and arrives at an orbit around Mars as its satellite. Landing on Mars's surface would require a module with a hydrogen-using chemical engine similar to the one in the American Apollo project.

In those years we considered several ways of designing an ERT — through acceleration of bunched plasma in electromagnetic fields, through acceleration of charged droplets of liquid or microparticles in electric field, etc. However, none of these ideas stemmed from a clear physical basis. Therefore, ionization of cesium atoms on the surface of a medium and heavy metals was a serendipitous find.

Irving Langmuir discovered the phenomenon of surface ionization of atoms of alkaline metals as early as the 1920s [6]. As a cesium atom evaporates from the metal surface with an electron work function greater than the ionization potential of cesium, this atom in very nearly 100% of the cases leaves a weakly bound electron in the metal and becomes a singly charged ion resembling an atom of a noble gas... The surface ionization of cesium, e.g. on tungsten, proved to be the physical process capable of sustaining an ion-acceleration motor with almost 100-percent utilization of the working medium and an energy efficiency of nearly 1. Since Langmuir worked with microcurrents through micron-thin wires, we decided to run experiments under conditions that would simulate those of practical interest. I need to remark that generating a high-density ion beam is not enough. One also has to send it out of the thruster into space. The problem is caused by the space charge of the beam and the charge of the rocket body.

If we consider a planar emitter of ions (e.g. a tungsten plate), it will be necessary to heat it to temperatures at which the cesium atom lifetime on the plate is sufficiently short and for a given influx of atoms the plate remains practically clean, with an unchanged work function. If the surface temperature is too low, the surface becomes covered with adsorbed cesium, the work function drops (ultimately to the cesium ionization potential, ~ 1.6 eV), and the surface ionization of cesium ends. To generate ion beams whose density is limited by the space charge it is necessary to heat the tungsten emitter to ~ 1000 K. In this case, the degree of surface ionization (the ratio of ions to the number of neutral atoms among the particles leaving the surface, decreasing only slowly with temperature) is still very high — around 99.9%. Thermal radiation from the emitter is the main energy loss from the thruster. For a planar emitter and, correspondingly, a planar accelerating system, the maximum specific thrust (per cm^2 of emitter surface) limited by the space charge of the beam is (by the 'three halves power law')

$$F = 0.8 \times 10^{-3} \left(\frac{v}{d} \right)^2 \quad \text{g/cm}^2 .$$

Here, v and d are the accelerating voltage (in V) and the width of the accelerating gap (in cm), respectively. However, the space charge does more than just limit the ion beam density. It also blocks the emergence of the beam into open space. V R Bursian was the first to consider the effect of space charge on the motion of a flow of charged particles, having a given initial velocity, through space with a zero electric field (the drift space) [7]. He was able to show that the current that can be 'pushed' through the drift space is a quadratic function of the space length L and is proportional to $1/L^2$, i.e. for a beam of positive ions to emerge into open space, the space charge needs to be canceled out by electrons. This would simultaneously solve the problem of neutralizing the rocket body's charge. This is how the three-electrode circuit of the ion propulsion motor with surface ionization of cesium came about: the first electrode is a tungsten plate ion emitter at the potential $+7$ kV relative to ground, the second electrode is an accelerating grid at -3 kV, which simultaneously locks the electron current from the second grid kept at zero potential (the emitter of compensation electrons) to the ion emitter plate. To carry out integrated checking of the physical processes in the three-electrode circuit and to learn more about working with cesium in the atmosphere and in a vacuum at high voltage, the circuit was recreated 'in metal' and tested in a vacuum at $\sim 10^{-6}$ (Fig. 1, [8]).

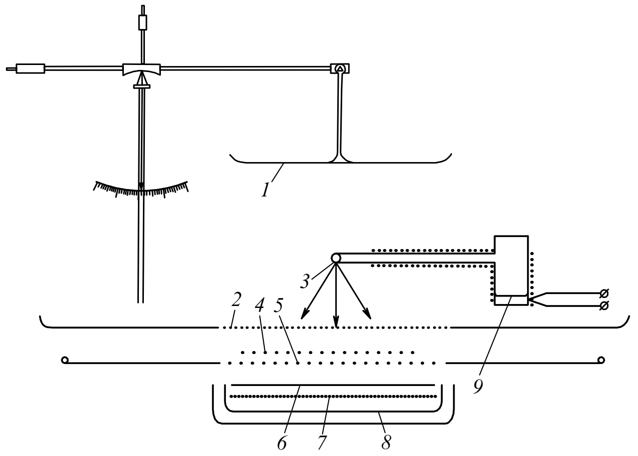

Figure 1. Schematic diagram of model ion drive thruster: *1* — mobile system for thrust measurement; *2* — screen grid; *3* — orifice for inflow of cesium vapor; *4* – grid for electron emission; *5* — locking grid; *6* — ion-emitting surface; *7* — emitter heater; *8* — heat shields, *9* — cesium evaporator.

The tungsten ion-emitter plate was heated by the radiation from a tungsten heating coil; the source of the cesium atomic beam was a molecular gun; the first and second grids were heated by passing direct current: the first grid (made of tungsten) in order to remove the cesium deposit and thereby suppress elevated thermoelectron emission, and the second, made of thoriated tungsten, in order to provide electron emission to compensate for the space charge of the ion beam. Fuzed quartz was used to fabricate the insulators. To measure loads and forces (the thrust) in the compensated ion beam we used a calibrated balanced plate (the 'balance') located at a distance of ~ 40 cm from the model. The force measured by the deflection of the plate in the conditions described above was 0.5 ± 0.1 g. The calculated value of thrust was 0.66 g.

The process of compensation of space charge was analyzed by Igor Pavlovich Stakhanov and his team. It was shown that as a result of interaction between electrons emitted by the second grid and the space charge of the ion beam, oscillatory movement of electrons is generated. The corresponding intense microwave radiation was detected by using industrial-grade ondometers. Radiation frequency as a function of current density and accelerating voltage was found to be in good agreement with the calculations by I P Stakhanov's group (Fig. 2, [9]).

This first experiment was followed by nearly ten years of detailed study of individual processes in the three-electrode circuit.

We studied the degree of cesium ionization as cesium was diffusing through porous emitters made of tungsten and molybdenum (see, e.g. [10]). Using such emitters made it possible to ensure a uniform supply of cesium to the surface and to eliminate large losses that occurred with external feed from a molecular gun. Cathode sputtering of construction

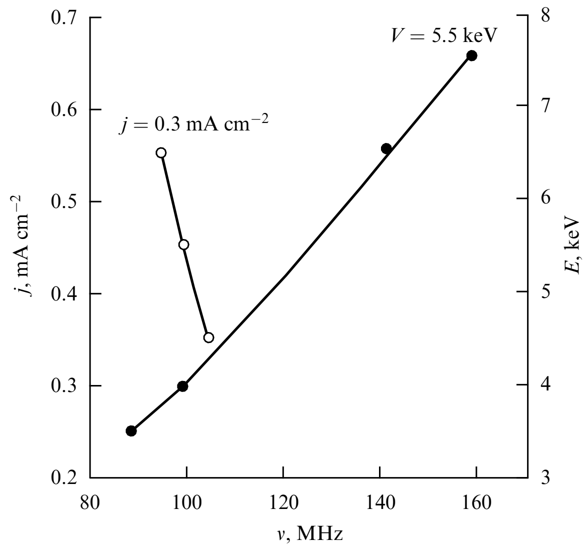

Figure 2. Frequency as a function of current density and energy of ions.

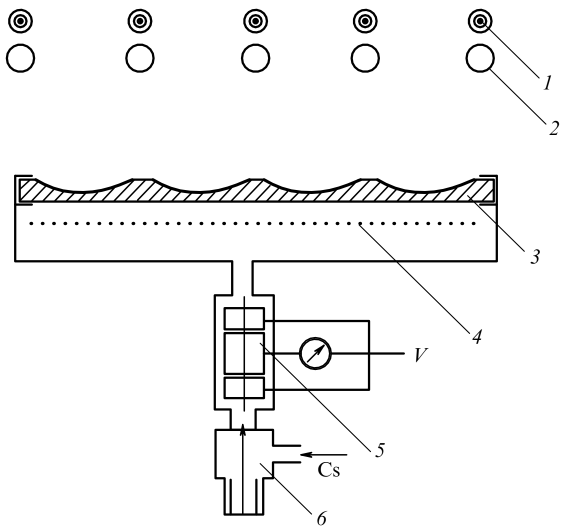

Figure 3. Schematic diagram pf a model of an ion thruster with a porous emitter: *1* — compensation grid (set of oxide cathodes); *2* — locking grid (air-cooled steel tubes); *3* — emitter (a plate of porous tungsten); *4* — emitter heater; *5* — cesium vapor pressure gauge measuring the current of surface ionization to the central filament; *6* — needle valve — cesium vapor dispenser.

materials in beams of accelerated cesium ions was studied [11]. We also investigated ion optics by simulation on conducting paper, studying various designs of models. One of the latest versions, with a porous emitter made of profiled tungsten, a first grid made of air-cooled steel tubes, and a second grid with oxide cathodes (Fig. 3), was tested in 1965 and provided a 'thrust' of about 20 g with an ion beam current of 20 A; the coefficient of energy transfer to the beam was about 90% and the cesium utilization coefficient was $\cong$ 95%.

4. Nuclear power sources

We know of no straightforward way of converting the energy of nuclear fission to electric energy so far, and there is still no path obviating the need to incorporate the intermediate stage — the thermal machine. As its efficiency is always below unity, the 'non-converted' heat needs to be disposed of somehow. This is not a problem on the ground, in water, or in the air. In space we only have one way — that of thermal radiation. Therefore, an APS in space cannot function without 'refrigeration by emission of radiation'. As the radiation density is proportional to the fourth power of the absolute temperature of the emitting surface, the temperature of the radiational refrigerator needs to be as high as possible. This serves to reduce the area of the emitting surface and correspondingly diminish the mass of the power engine. We suggested using the 'direct' conversion of nuclear heat to electricity, without a turbine or generator; this appeared to be more reliable for prolonged operation at high temperatures.

From the literature we knew about the work of Abram Fedorovich Ioffe, who pioneered semiconductor research in the USSR. Hardly anybody remembers now the power supply devices he developed, which were used in the times of the Second World War. Quite a few guerrilla units had radio communications with the 'Larger Land' by using 'kerosene TEGs' — Ioffe's thermoelectric generators. A 'crown' of TEGs (in fact a string of semiconductor elements) was lowered onto the glass of a powerful kerosene-fueled lamp and its output wires were connected to the transmitter-receiver. The 'hot ends' of the elements were heated by the flame of the kerosene-fueled lamp while the cold ends were cooled by the ambient air. The heat flux propagating through the semiconductor generated an emf and the current was sufficiently high for a reception session, while in between sessions the TEG was charging a battery in order to power the transmission session. Ten years after the victory we paid a visit to the Moscow TEG factory and discovered that these devices were still in demand. Many villagers had at the time an efficient radio receiver, Rodina, with directly heated vacuum valves requiring a battery power supply. Ioffe's TEGs were often a good replacement for batteries.

The trouble with the 'kerosene' TEG is its low efficiency (about 3.5%) and rather low working temperature ($\sim$ 350 K). However, the simplicity and reliability of the system were attractive for developers. For instance, silicon-carbide-based semiconductor converters developed by I G Gverdtsiteli's group in the Sukhumi Physico-Technical Institute of the Georgian Academy of Sciences found useful applications in cosmic nuclear power units of the BUK series.

At some point, A F Ioffe also suggested a 'vacuum' thermoemission converter: a diod placed in a vacuum. A hot cathode emits electrons with the Maxwell energy spectrum. Some of them overcome the anode potential and do work in the load of the circuit.

It was expected that a system of this type would produce a considerably higher efficiency (up to 20 – 25%) at operating temperatures above 1000 K. Furthermore, in contrast to a semiconductor device, a vacuum diode is neutron-irradiation-proof and can be used in the same assembly with a nuclear reactor (a semiconductor converter has to be placed outside a reactor and use a heat carrier to transfer heat to it). Alas, we realized that the idea of a vacuum converter is practically infeasible. As in the case of the ion thruster, the barrier is the space charge, but this time not for ions but for electrons. A F Ioffe proposed using in the vacuum converter microns-wide gaps between the cathode and the anode, but in the conditions of high temperatures and thermal strains this is extremely difficult. This is where cesium proved of great use: one cesium ion created through surface ionization on the cathode cancels out the space charge of about 500 electrons.

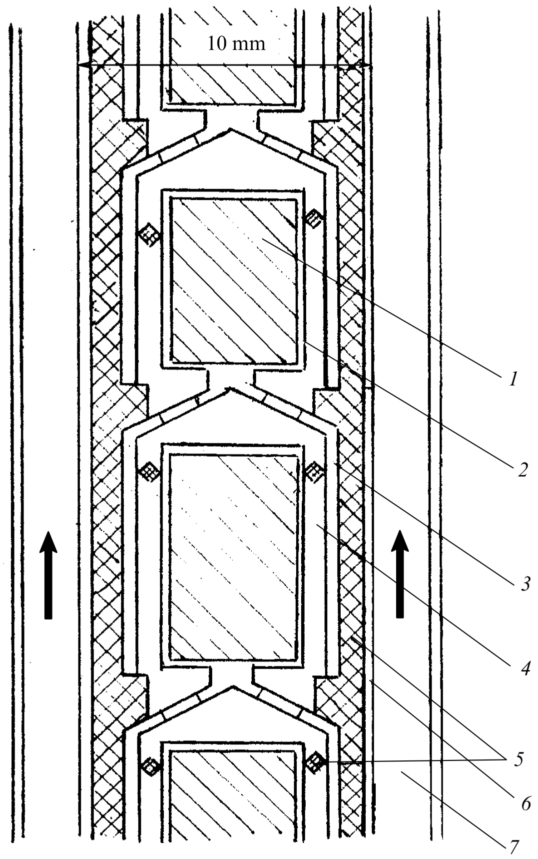

Figure 4. Schematic diagram of a thermoemission electric energy generating channel (V A Malykh's 'garland'): *1* — enriched uranium oxide core; *2* — cathode (molybdenum, tungsten); *3* — anode (niobium); *4* — vacuum gap with cesium vapor; *5* — insulation (beryllium oxide); *6* — body (steel); *7* — heat carrier (sodium – potassium).

The Ioffe vacuum converter filled with cesium is essentially an 'inverted' ion thruster. The physical processes in the two are very similar.

One of the consequences of the work in Obninsk on thermoemission converters was the creation (and start of an industrial production run) by an outstanding technologist, Vladimir Aleksandrovich Malykh, in his subdivision of fuel rods for the Topaz conversion reactor executed as a string ('garland') of converters connected in series (Fig. 4). Such fuel rods generated up to 30 V — about a hundred times higher than single-cell converters designed by the 'competing' research teams, such as M B Barabash's group in Leningrad and later by a group in the Atomic Energy Institute. It was therefore possible to 'feed off' the converter reactor with a power greater by a factor of several hundred. However, the reliability of a system composed of thousands of thermoemission elements caused suspicion. We therefore also looked at the classical scheme, the steam turbine conversion of nuclear fuel to electricity.

In space voyages to remote destinations, a turbogenerator would have to work for a year or two, maybe for several years. To reduce the wear, the turbine rpms must be as low as possible. On the other hand, the turbine works efficiently if the velocity of molecules in the vapor is close to that of the turbine blades. Therefore, we began by considering the use of the heaviest vapor — that of mercury. What stopped us was the intense radiation-stimulated corrosion of the iron of stainless steel in mercury. In the absence of radiation, mercury boils for decades in the bodies of vapor jet high vacuum pumps made of conventional steel. But in high-density radiation fields in a mercury heat carrier, corrosion 'ate up' Armco-iron shells of plutonium fuel rods at the Argonne fast reactor in two weeks (Clementine, USA, 1949) and shells made of stainless steel 1X18H9T of a similar reactor in LPPI (BR-2, USSR, 1956).

Potassium vapor looked very promising. A fast reactor with ceramic fuel (uranium oxide ceramics) cooled by boiling potassium and similar to the BR-5 LPPI research reactor with sodium cooling was the basis of the designed power unit of the low-thrust spaceship. Potassium vapor rotated the electric turbogenerator. This 'machine' technique of conversion allowed us to achieve efficiencies of up to 40%, while actual thermoemission systems had efficiencies of only about 7%. However, the evolution of the AEPS with machine conversion of energy stopped there. It all ended with writing a detailed report, in fact, of 'physics notes' to the technical project of a low-thrust spaceship for a manned mission to Mars. The project itself has never materialized.

In my opinion, the interest in space missions using rockets with nuclear thrusters simply petered out. After Sergei Pavlovich Korolev's tragic death, the work by the PPI on low-thrust systems became much less intense. The new head of the OKB-1 was Valentin Petrovich Glushko, who was quite indifferent to such systems. Dmitrii Ivanovich Blokhintsev put down roots in Dubna but the work on designing a space mission AEPS with direct conversion of nuclear-generated heat to electricity still continued. The aim, until perestroika came along, was to create power supply units for powerful communication satellites (radiolocation and TV-broadcasting stations).

Between 1970 and 1988, about 30 radiolocation satellites were launched, with nuclear reactors and Gverdtsiteli semiconductor converters (BUK systems, Fig. 5) and two with Topaz thermoemission conversion reactors (Fig. 6).

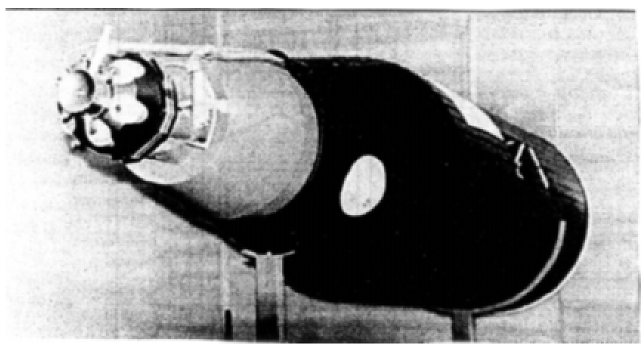

Figure 5. BUK, nuclear energy driven system for radiolocation satellites, with semiconductor conversion reactors.

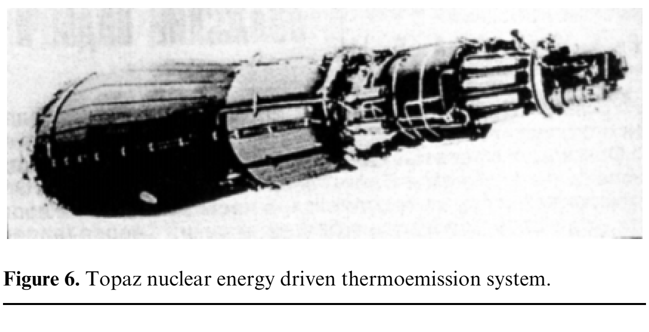

Figure 6. Topaz nuclear energy driven thermoemission system.

A BUK was essentially Ioffe's TEG which, instead of a kerosene lamp, used a fast reactor of up to 100 kW as the heat source. The total load of highly enriched uranium was about 30 kg. Heat was transferred from the reactor to converters by the circulating sodium – potassium eutectic. The operating lifetime of a BUK was 1 to 3 months. In case of failure, the BUK was maneuvered into a long-life orbit at an altitude of about 1000 km and left there. In almost 20 years of launches, these satellites have crashed to the Earth thee times — twice into the ocean and once to the ground, in Canada, in the vicinity of the Great Slave Lake. The satellite was the Cosmos 954 launched on January 24, 1978. It worked for 3.5 months. The uranium power cells of the satellite burnt up completely in the atmosphere. The only parts found on the ground were what remained of the beryllium reflector and semiconductor batteries (these data can be found in the joint report of the Canada and USA commissions on operation Morning Light).

The Topaz thermoemission nuclear-energy-driven system used a thermal-neutron reactor with a total power of up to 150 kW. The total on-board amount of enriched uranium was considerably lower than on a BUK — about 12 kg. The basis of the reactor was comprised of fuel elements forming electricity-generating garlands that were developed and manufactured in V A Malykh's division. They constituted a string of thermal elements, the cathode being a 'thimble' made of tungsten or molybdenum filled with enriched uranium oxide and the anode being a multilayered niobium tube cooled by a sodium – potassium eutectic. The cathode temperature reached 1650 K, the electric power of the reactor was 10 kW.

The first flight-ready pilot model — the Cosmos 1818 satellite carrying a Topaz unit — was placed in orbit on February 2, 1987 and worked faultlessly for six months until the on-board cesium was spent. The second such satellite, Cosmos 1876, was launched a year later and remained operational almost twice as long.

The principal developer of the Topaz system was the Soyuz Special Design Bureau of the Moscow Mechanical Plant (OKB MMZ) headed by S K Tumansky (formerly of A A Mikulin's aircraft motors design bureau).

Thermoemission conversion reactors whose development was supervised by the LPPI constituted a first-class achievement of science and technology in Russia — an achievement without analogs.

The success of the Topaz design stimulated work on other projects with conversion reactors, including a unit with electric power up to 500 kW using a lithium-cooled reactor. It was developed jointly by LPPI and Russian Space Corporation (RSC) 'Energiya', which was headed by an experienced rocket expert, S P Korolev's colleague Mikhail Vasilevich Melnikov. In conclusion I simply have to share with the reader my impressions of the work of his division on developing the lunar thruster — a motor based on chemical fuel for the third stage of the rocket designed for orbiting and landing on the Moon. This was in the late 1950s in Podlipki (now Korolev) on the No. 3 mounting pad of OKB-1. The floor of an enormous production unit (3000 m^2 in area) was full of dozens of desks with German-manufactured six-beam loop oscillographs (impounded as reparations) recording onto 100-mm wide paper rolls (one desktop PC would suffice today...). At the front wall of the building you saw a bench for assembling the combustion chamber of the engine. Thousands of wires connected the bench to oscillographs — from the sensors of gas velocity, pressure gauges, tensometers, etc. Each day started at 9:00 with the ignition of the engine. It worked for about 20 min. Immediately after switching it off, the team of mechanics (morning shift) dismantled it, scanned the parts carefully and measured the combustion chamber. At the same time, the computation team conducted an analysis of oscillographic records. Recommendations were formulated on modifying the design and operation mode. During the afternoon shift the designers, engineers, and workers of the production unit implemented the modifications proposed; during the night shift a new combustion chamber with diagnostics equipment would be assembled on the bench. Exactly 24 hours later, at 9:00 the next session would begin. And this went on seven days a week, for weeks, months, years on end. More than three hundred versions of the engine a year. That was the style of elaboration of the engines of chemical-fuel rockets that were designed to work for 20 – 30 minutes. Nuclear-energy-powered systems and ion-jet thrusters were to work non-stop for months and years. Hence, the required full-scale testing of materials and structures must last for a comparable time. This means that the choice of radiation- and corrosion-resistant materials and optimal designs takes years to complete. These impressions of Melnikov's 'production unit' proved very useful. They stimulated work on proposals of accelerated rapid testing of materials for nuclear technologies, up to studies of resistance to radiation damage of construction materials in focused beams of high-energy protons from high-current medium-energy accelerators — the so-called meson factories [15].

5. High-thrust systems

I did not have a chance to really work in this field, so I will limit this part to a brief review [14].

At the initial stage of the nuclear-powered space mission the LPPI was developing the lifting-wing cruiser missile KAR in collaboration with the design bureau of V N Chelomei. This stage of development had a short life and ended with calculations and the testing of elements of the thruster designed in V A Malykh's division. The goal was to create a non-piloted aircraft with a straight-flow air-breathing nuclear engine carrying a nuclear warhead (a sort of a nuclear analog of the 'buzz bomb' or 'doodlebug' — the German V-1). The system was to be launched with solid-fuel rocket boosters. After the required velocity was reached, the thrust would be produced by atmospheric air heated by the fission chain reaction in the honeycomb cells of beryllium oxide saturated with enriched uranium.

The main area of efforts in developing high-thrust rockets was in designing thermal nuclear-driven rockets. In our case these were ballistic atomic missiles (BAMs) with a range of several thousand kilometers (a joint LPPI – OKB-1 project), and in the case of the USA, similar KIVI type systems. The thrusters were tested at testing grounds near Semipalatinsk and in Nevada. The hydrogen in such systems is heated in a solid-fuel reactor to a high temperature, is atomized, and is ejected from the rocket in this form. The exhaust velocity is then increased more than four-fold in comparison with the chemical hydrogen-using rocket. The calculated temperature of hydrogen was ~ 3000 K.

At NII-1, whose science supervisor was Mstislav Vsevolodovich Keldysh (then President of the USSR Academy of Sciences), V M Ievlev's division was researching, in collaboration with the LPPI, a totally fantastic proposal — a gas-phase reactor in which the chain reaction would take place in a gaseous mixture of uranium and hydrogen. The exhaust velocity of hydrogen flowing from such a reactor is about ten times higher than from a solid-fuel engine, and uranium is separated and remains in the active zone. One of the ideas was to use centrifugal separation when the hot gaseous mixture is 'twisted' by the cold inflowing air, which results in the separation of hydrogen and uranium as this happens in a centrifuge. Ievlev thus tried to directly reproduce processes occurring in the combustion chamber of a chemical rocket using for an energy source not the heat released by the burning of fuel but a fission chain reaction. However, problems with purely hydrogen exhaust containing a small admixture of uranium remained unsolved, not to mention the problems of confinement of hot gas mixtures at a pressure of dozens of atmospheres.

The work by the LPPI on ballistic atomic rockets ended in 1969 – 1970 with a 'trial by fire' at the Semipalatinsk testing grounds of a prototype rocket engine with solid-fuel batteries. It was developed in cooperation with A D Konopatov's Voronezh KB, Moscow NII-1, and a number of technological groups. A thruster generating 3.6 t of thrust was based on a nuclear reactor IR-100 with fuel batteries of uranium carbide and a zirconium carbide solid solution. The hydrogen temperature reached 3000K, and the reactor generated 170 MW of power.

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