Superconducting Magnets For Space Application Nuclear Power and Propulsion Systems

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Developments in Russia

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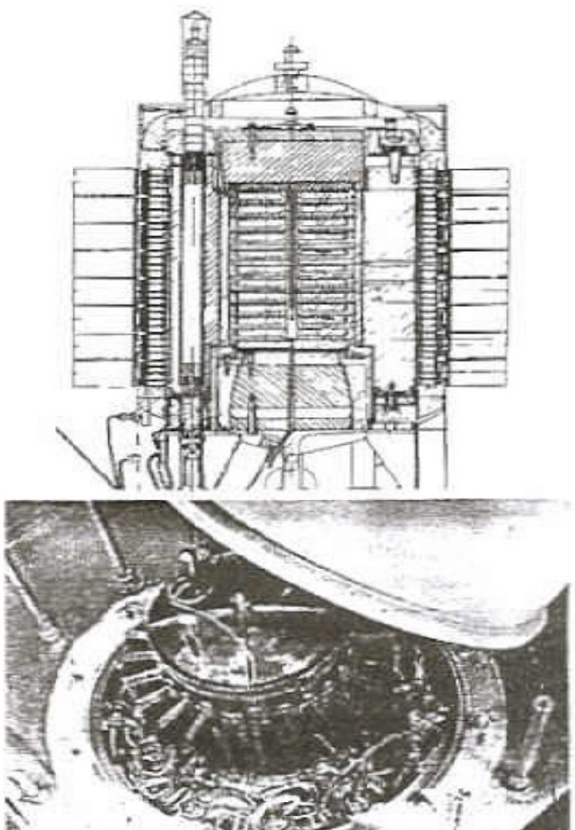
Since many decades Russia devoted considerable resources to develop a light compact propulsion as well as power system for future space ships. The research followed several parallel lines complementing one another.

The converters are devices with direct transformation of thermal energy into electricity without mechanical devices like turbines. Converters are of limited power capacity hardly suitable for propulsion.

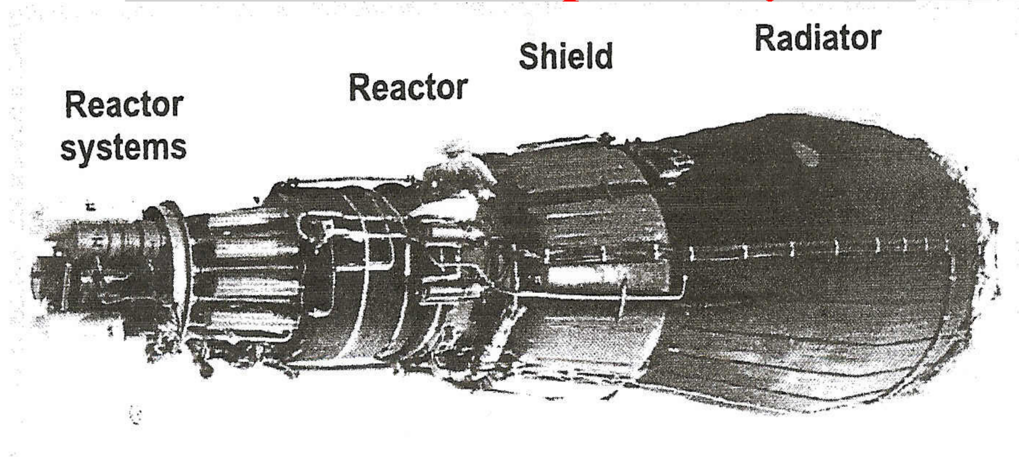
Nuclear thermoelectric and thermionic converters: Direct conversion of thermal nuclear energy into electricity.

In 1968-1988 a number of such systems were successfully used in space: ROMASHKA, BUK, TOPOL, ENISEY, TOPAZ



ROMASHKA system

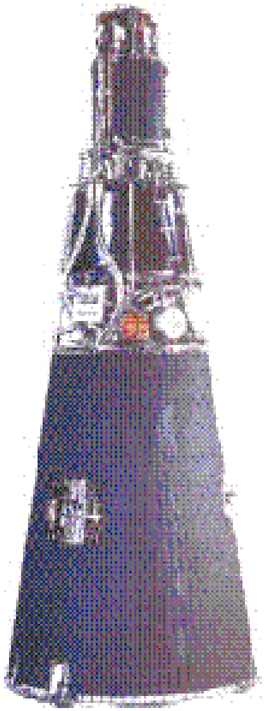
TOPAZ nuclear power system



Cosmos 1818 and *1867* spacecraft

Electric power	5 kW
Thermal power	150 kW
Uranium-235 loading	11.5 kg
Mass	980 kg

In 1991 a joint project (TOPAZ 2) with US has started. Several TOPAZ 2 experimental units were delivered to US in 1992-1994. The successful activities were not completed, they were terminated by US government.

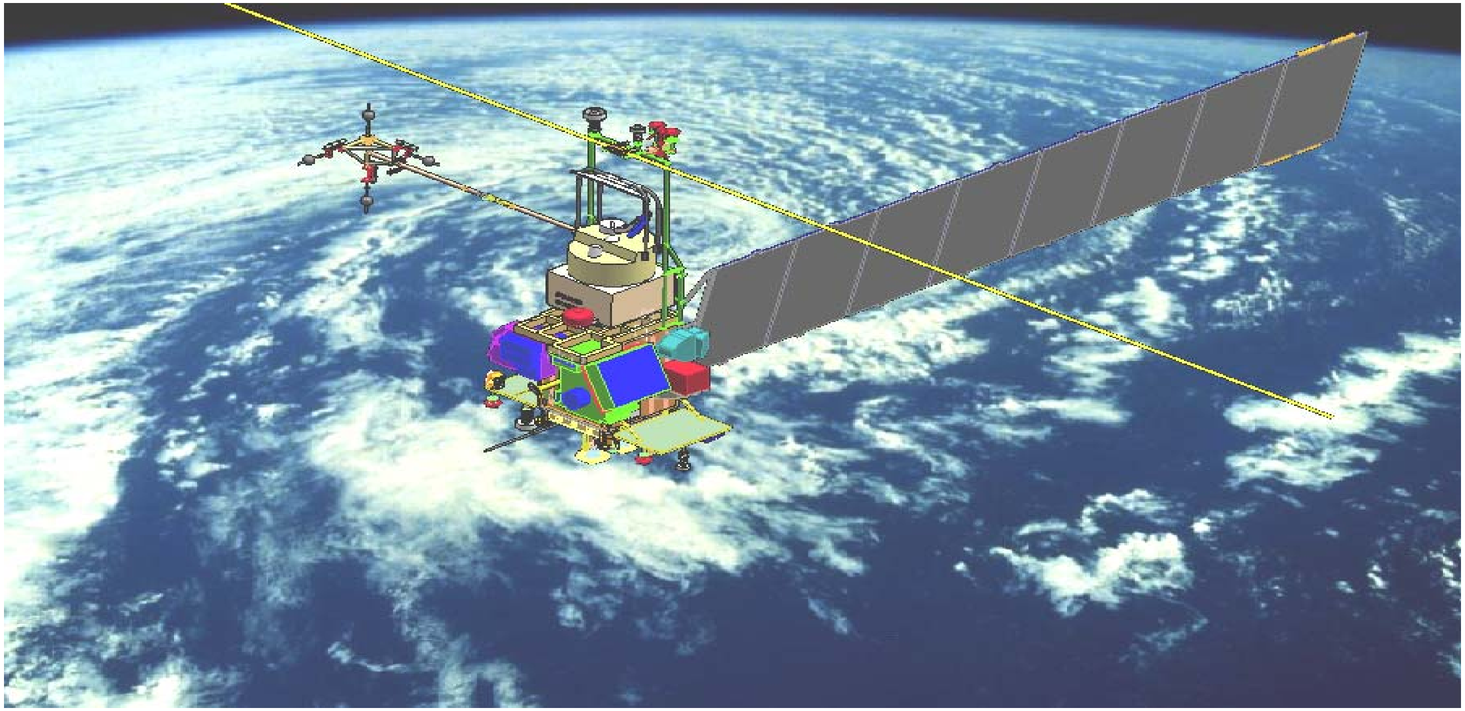


Compact space nuclear power system with thermion converter TOPAZ-2

Active zone height	375 mm
Diameter	260 mm
Uranium	27 kg
Lifetime	> 3 years

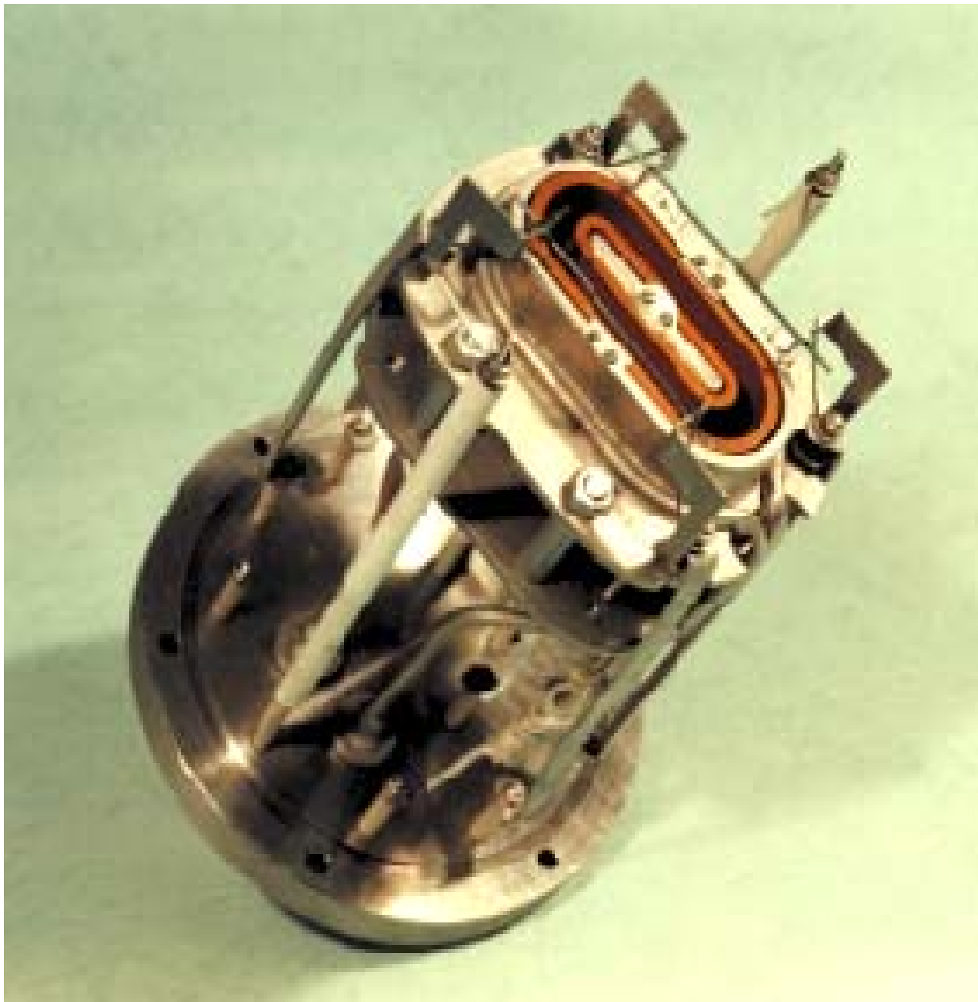
The development of propulsion power source, chemical or nuclear, had to deal with technological challenges like weight, high temperature, safety issues etc.

Stationary and Pulsed Plasma Thrusters for Spacecrafts



Pulsed Plasma Thrusters (PPT) are very advanced electric propulsion devices for Small Spacecrafts being their primary propulsion system. Average value of thrust of PPT is at the level of few mN, mass of PPT propulsion system is up to 10 kg.

Stationary Plasma Thrusters for Spacecrafts



Stationary Plasma Thrusters (SPT) were successfully used at a number of spacecrafts in the structure of plasma propulsion system, as well as plasma generators for the removal of electric charges from the spacecraft surfaces, for astrophysical experiments etc.

SPT parameters

Electric	***0,5 – 25 kW***
Thrust	***2 – 125 g***
Specific	***1000 – 3000 s***
Efficiency	***50 – 70 %***
Life time	***a few thousands hours***

Nuclear Thermal Propulsion

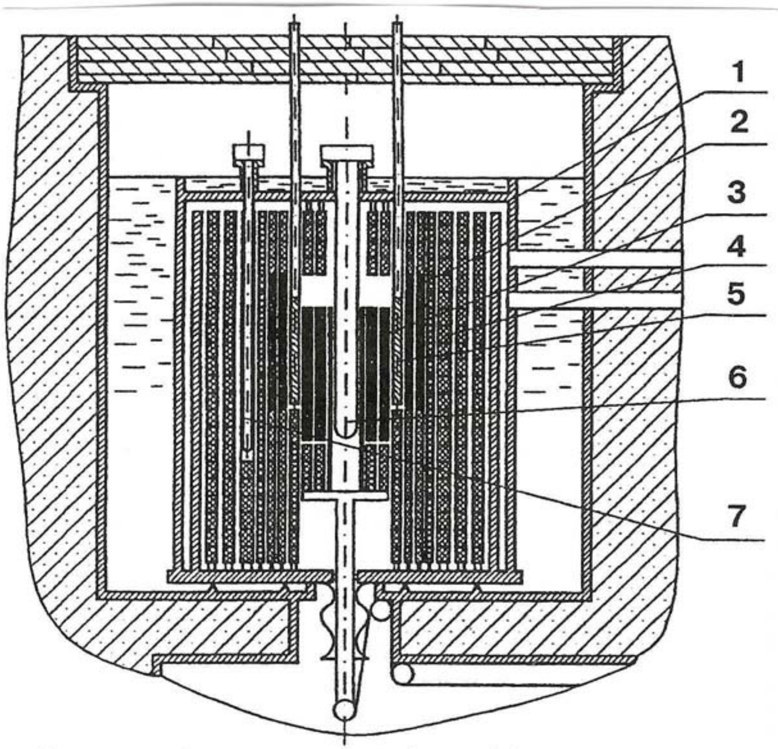
The R&D work in Russia on nuclear thermal propulsion for various applications including submarines, aircrafts and in particular spacecrafts started in 1958.

Extended tests were performed not only with the existing test facilities and research reactors like the high-flow graphite pulse reactor IGR used normally for materials' studies.

Special facilities were built for the purpose, like IVG-1 reactor which was reconstructed to achieve operating parameters to be identical with the space NTP system under design.

A prototype of the NTP flight unit, the IRGIT reactor, was built. The differences from the flight unit consisted of a reactor cooling system and some additional radiation shielding and safety measures.

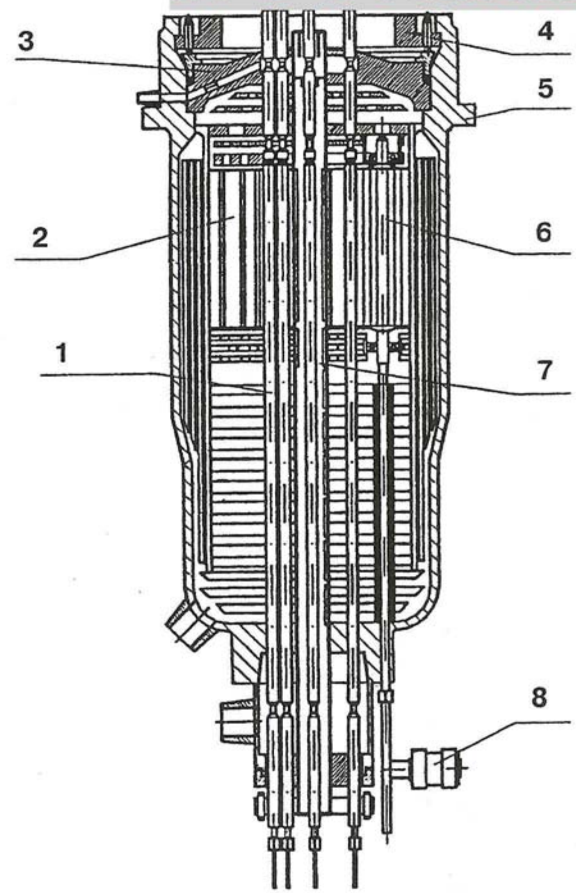
Dynamic reactor tests of assembly fuel elements were made in the IGR pulsed reactor. It has the highest in the world neutron fluence.



1. reactor vessel
2. core
3. movable part of the core
4. reflector
5. control element
6. central experimental channel
7. side experimental channel

IGR reactor

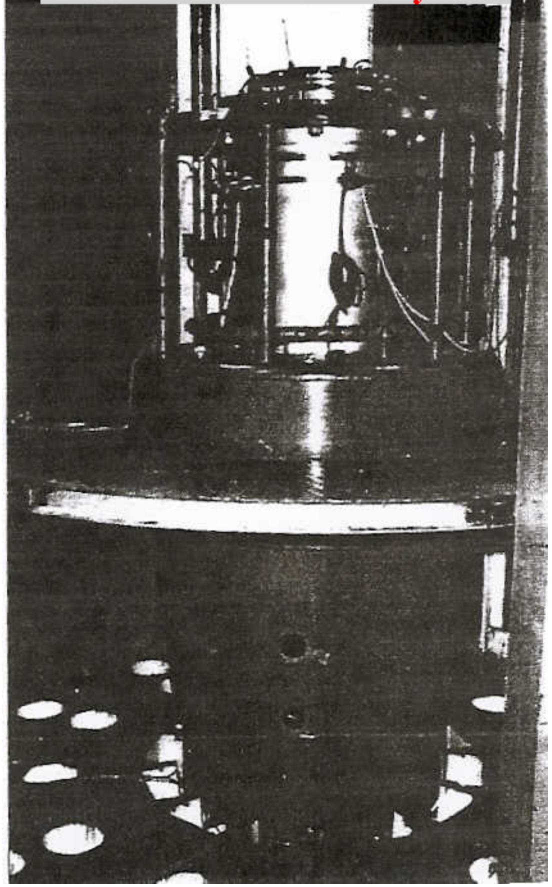
IVG-1 reactor



1. FA (fuel assembly)
2. reflector
3. lid
4. lock
5. vessel
6. control element
7. loop channel
8. drive

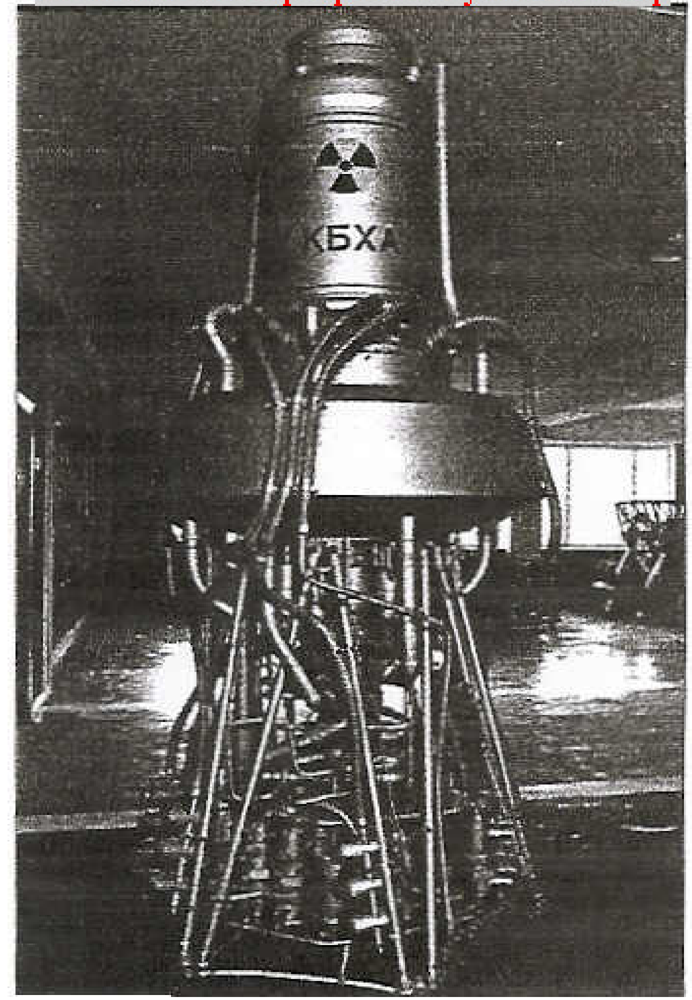
Lifetime tests of fuel assembly at different power levels were performed at the IVG-1 reactor.

IRGIT reactor at test facility berth

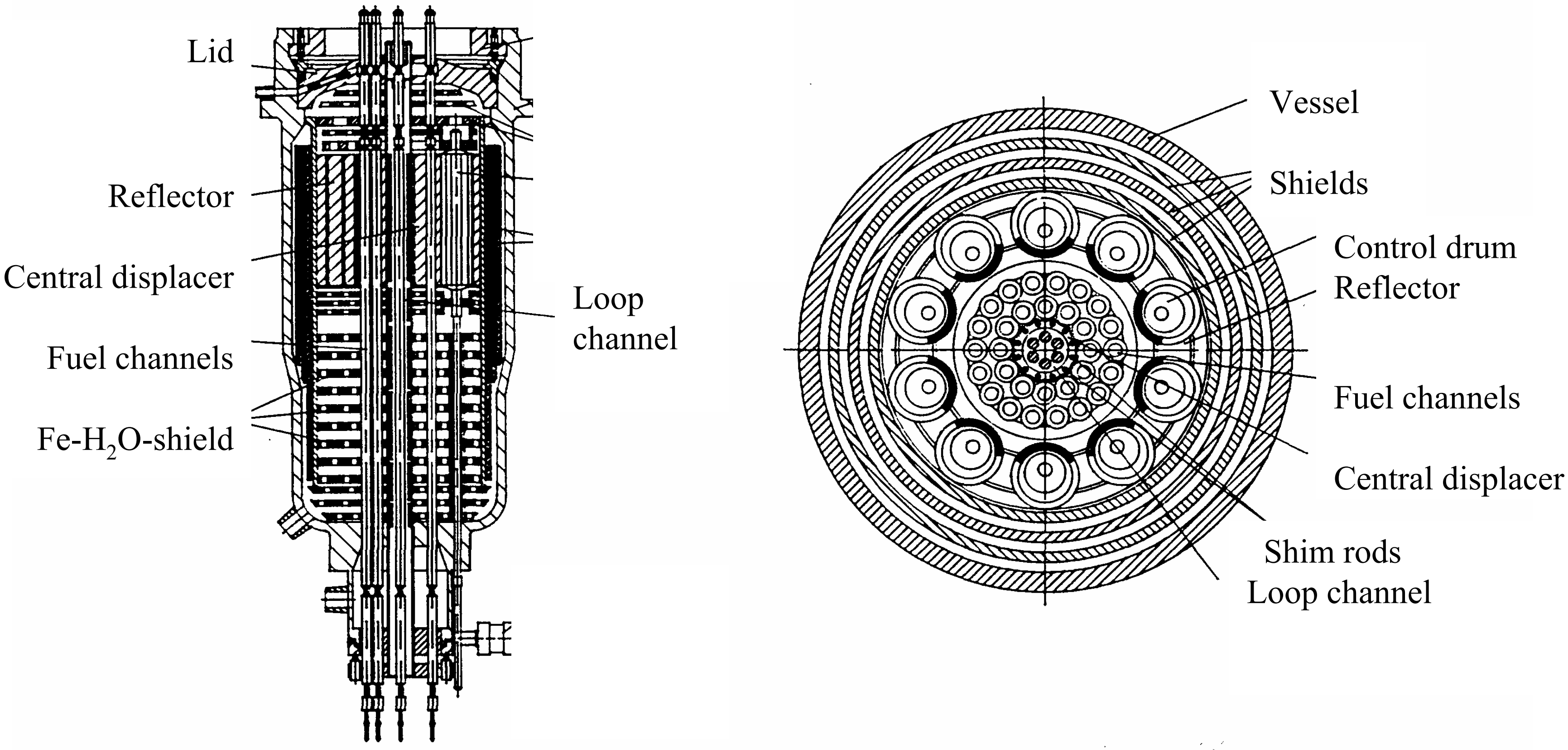


The IGRT, prototype of the space flight reactor, was built to test all the components and materials except cooling system.

Nuclear thermal propulsion system mockup



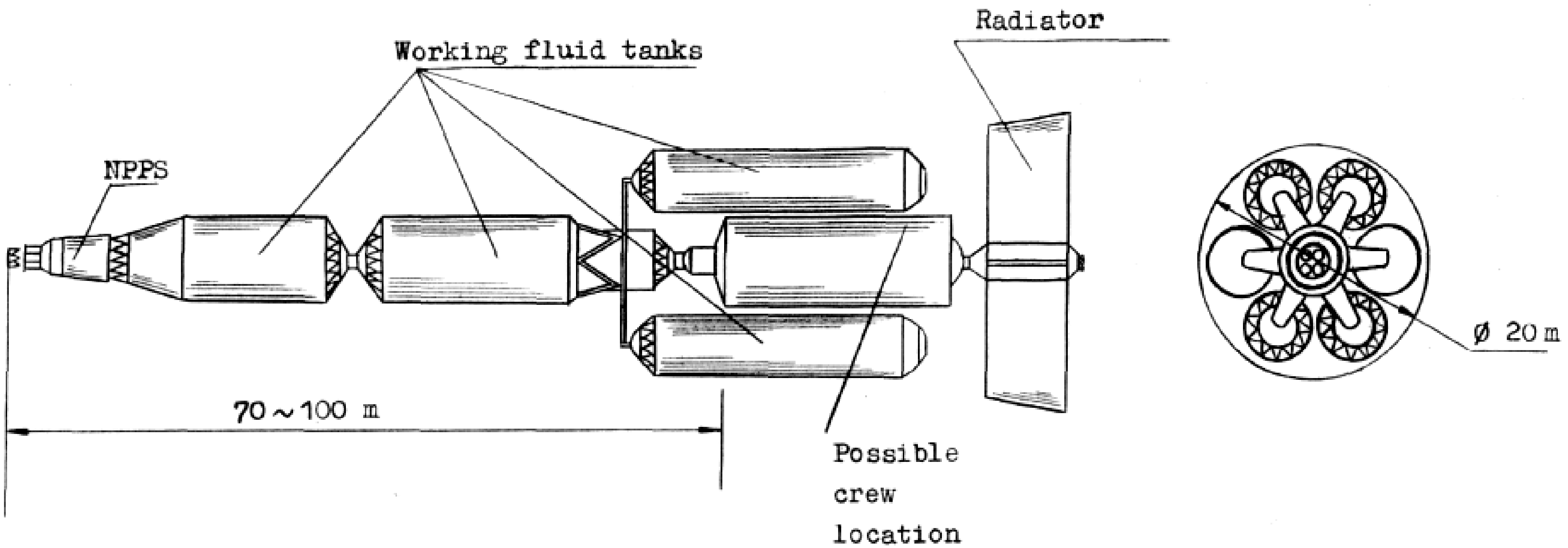
The closing stage of the space fuel assembly development involved tests on all three reactors.



a/ longitudinal section b/ cross-section

Reactor IWG1 design

Martian manned spaceship arrangement



Flight duration 500-900 days
Launch vehicle mass 300-700 tns
Propellant mass ~ 400 tns

MHD generators need strong magnetic field and superconducting magnets offer a natural and very economic in terms of weight and power as well as compact, solution.

Over the years Russia has developed a number of different types of MHD generators. Some were intended for ground use and thus were not limited by weight.

Those intended for spacecraft and aircraft applications were equipped with superconducting magnets also developed for the purpose.

About 40 years ago the world-first superconducting magnet for space has been designed and put to a near-Earth orbit. O.P. Anashkin et al, “Testings of the 20 kOe Superconducting Magnet during the Earth Satellite Flight”, *Cosmic Researches*, vol. 7, № 5, 1969 (In Russian).

In the eighties the Kurchatov Institute in collaboration with *Energia* corporation developed and successfully launched a superconducting magnet for a sub orbital test flight to prove that it was possible to shield plasma with magnetic field and in this way maintain radio communication when spacecraft has being going trough the dense layers of the atmosphere.

The use of MHD generators to provide power for spacecraft with both chemical and nuclear heat sources have been investigated, and the latter was the preferred choice for applications such as supplying electric propulsion power for deep-space probes.

Extended design and practical studies of various MHD systems was performed in Russia over many years.

The result was a number of completed designs as well as real MHD power installations.

The design studies also included nuclear thermal propulsion systems in combination with MHD power generation intended both for aircraft and space applications.

Space NPS with MHD generator

Reactor NERVA

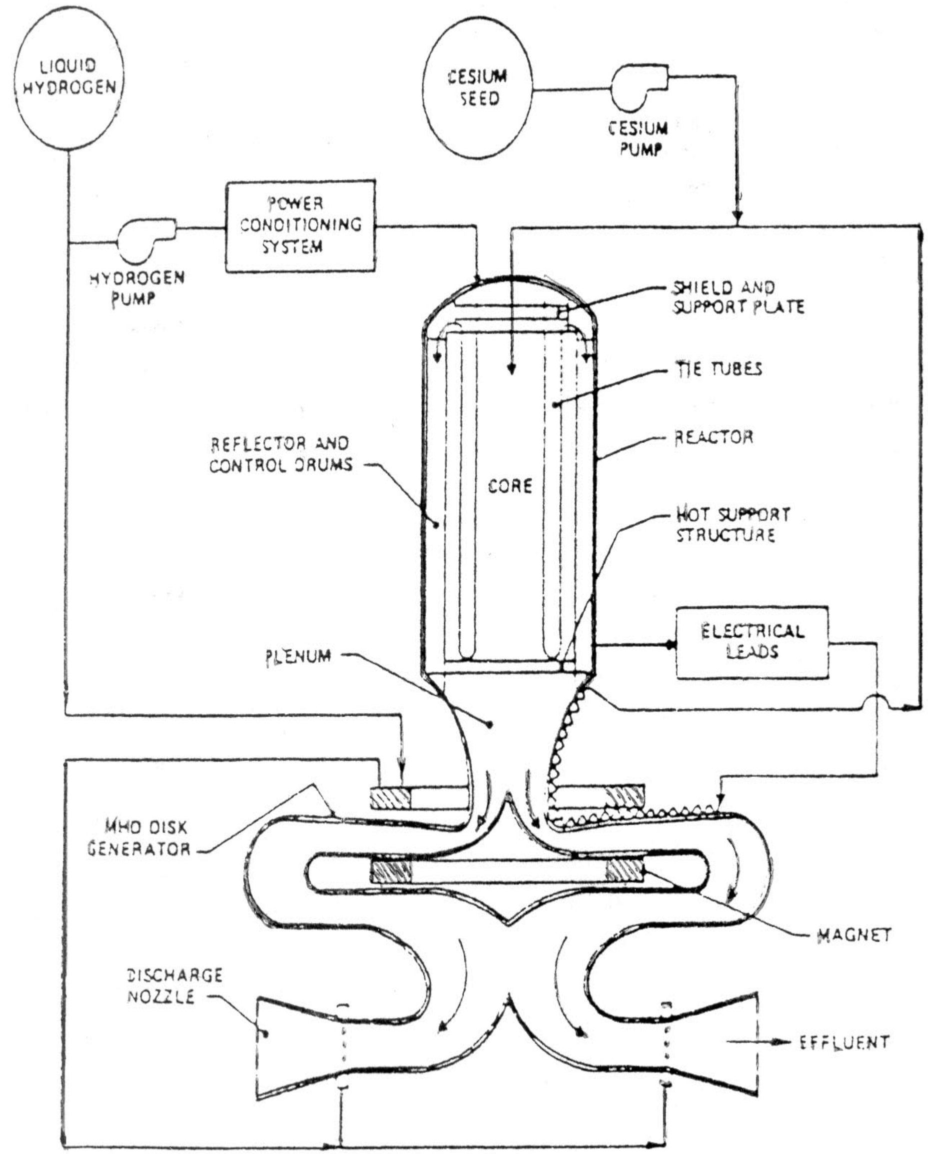
Nuclear fuel	U_2C–ZrC -C
Thermal power	245 MW
Mass/volume	2.2 tons/m^3

MHD channel

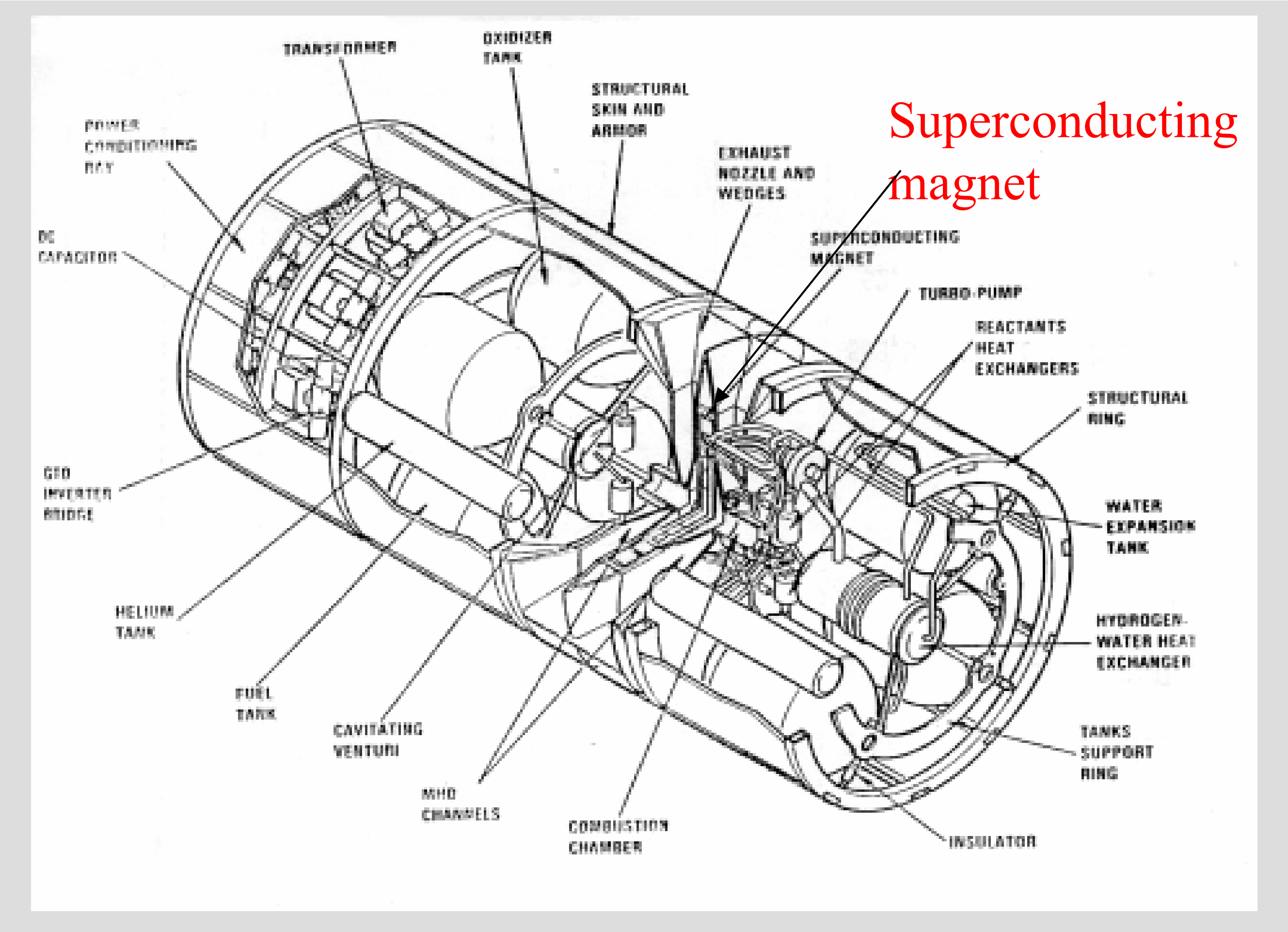
Electrical power	107 MW
Voltage	40.6 kv
Radius (in/out)m	0.18/0.7
Height (in/out)m	0.07/0.17
Energy conversion	44%

Cryogenic magnet

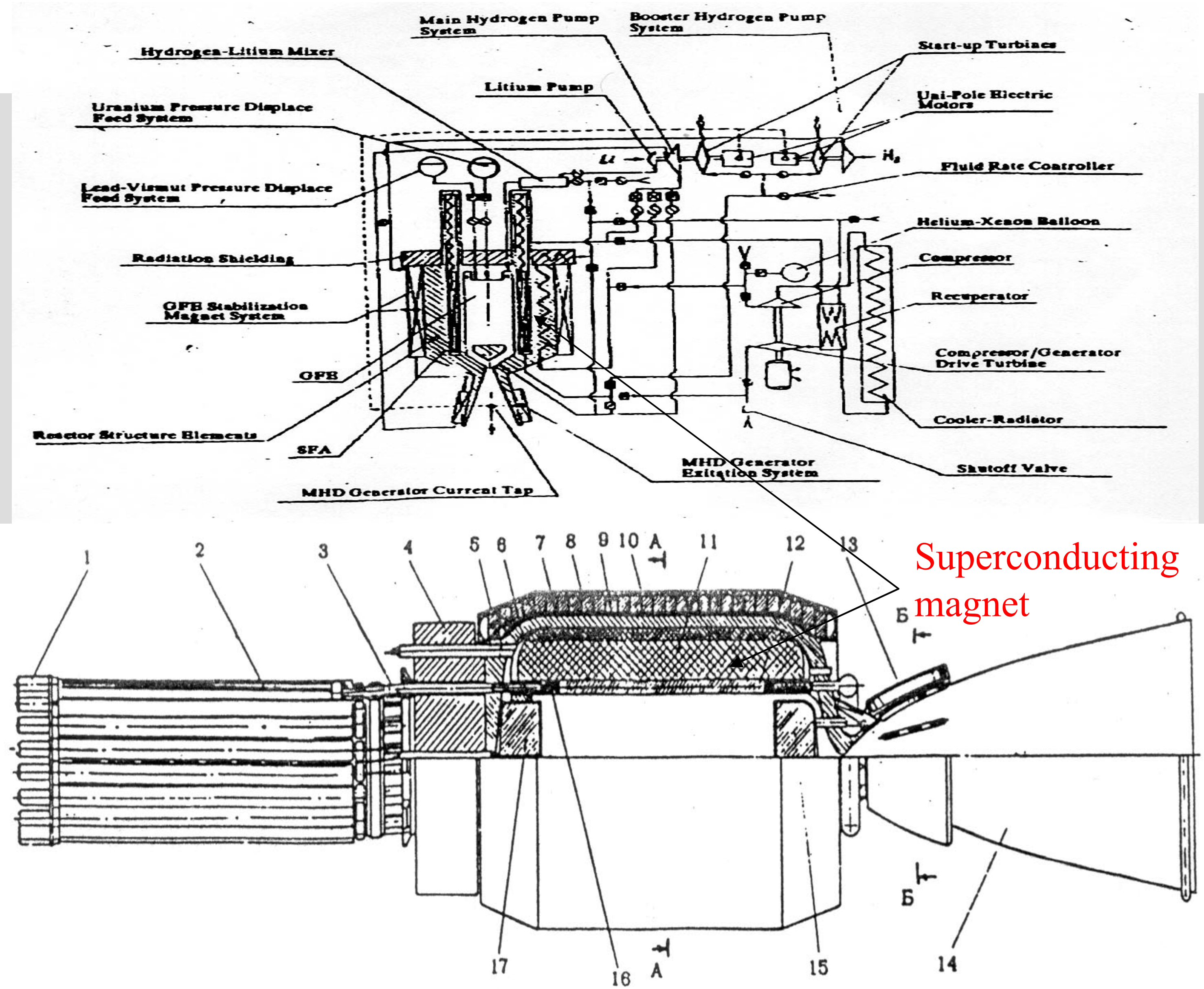
Type	Cryogenic
Coil	Al
Radius	0.8m
B	4 tesla
Mass	1.5 t



Conceptual design of a 10 MW space power system with disk MHD generator and liquid fuel

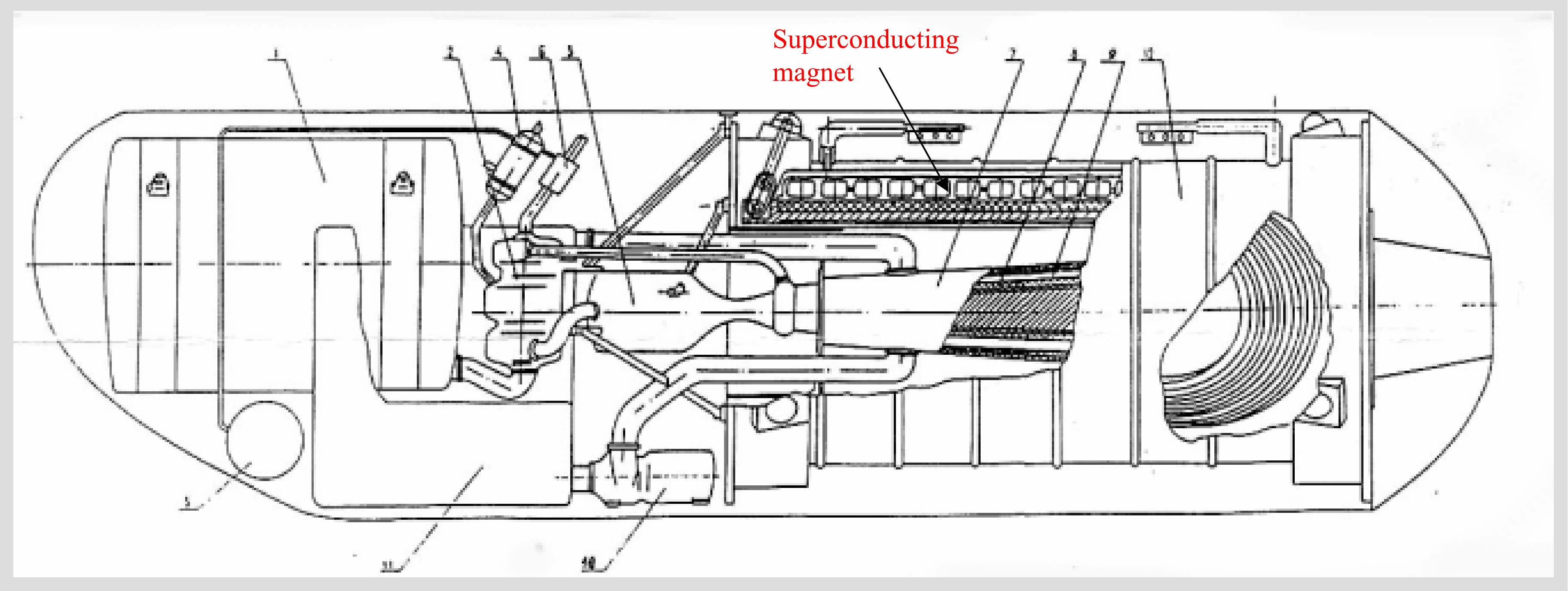


Space 25 MW MHD Nuclear Power Propulsion System



Conceptual design of a space-born MHD unit of 25 MW

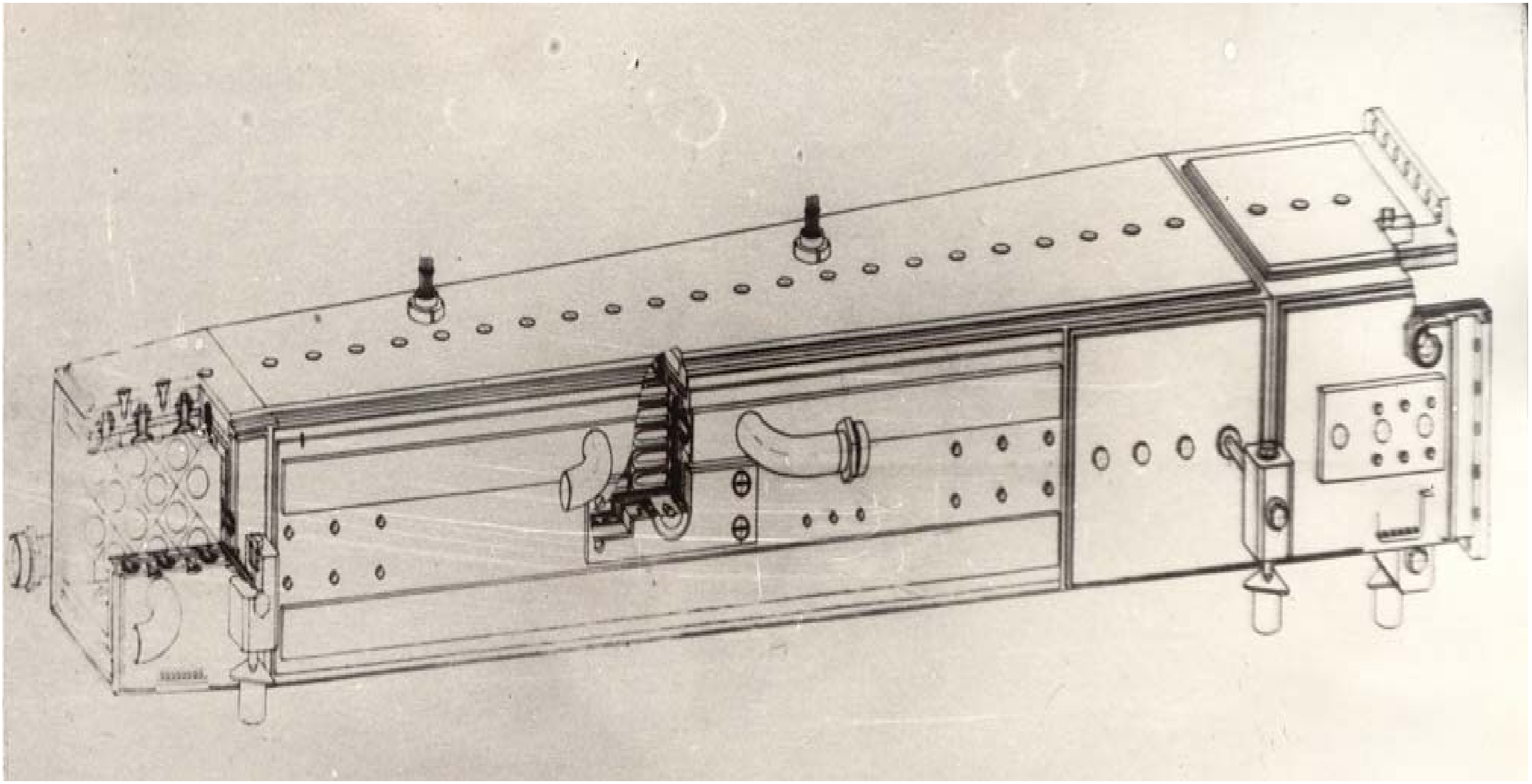
(chemical fuel)

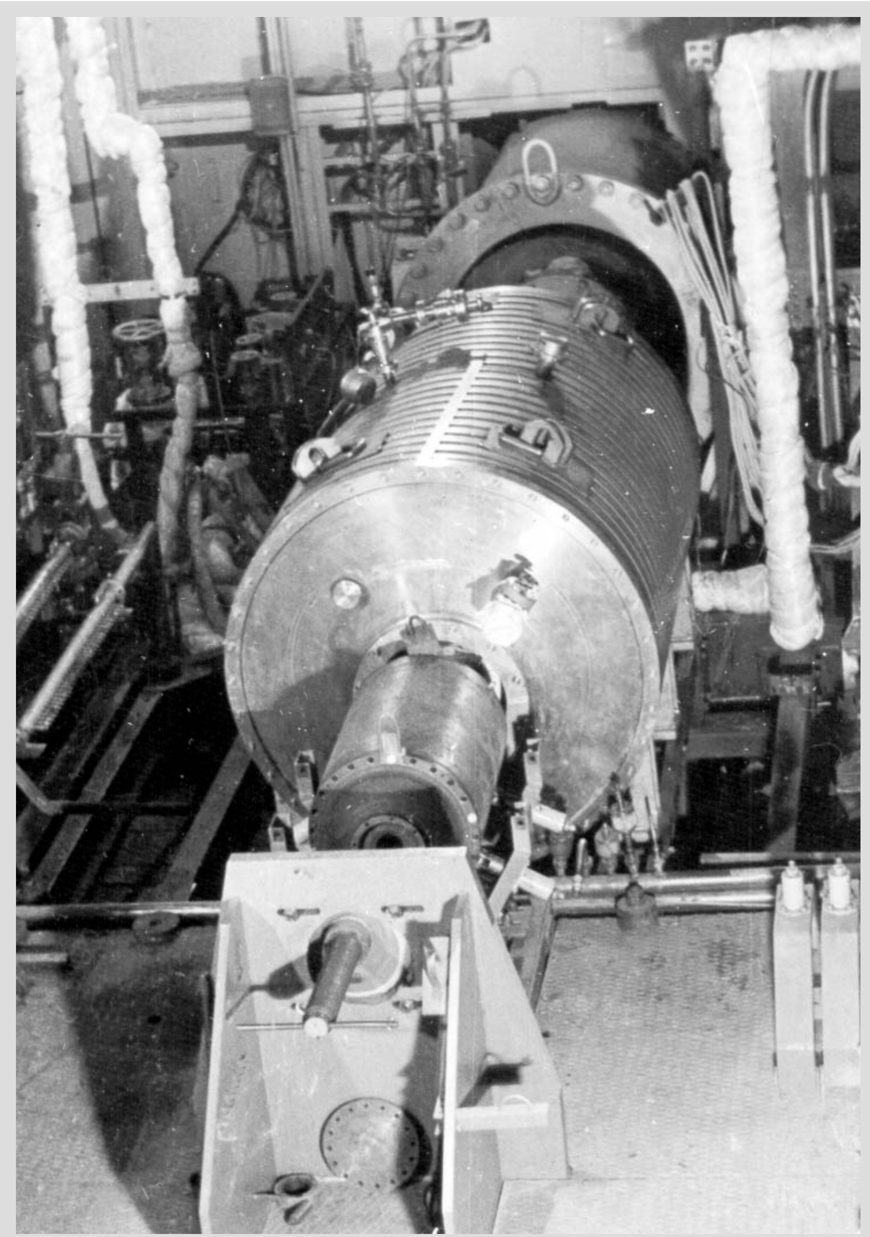


A few examples of working MHD generators

Some of them were working as electrical power installations

Compact prototype MHD Channel With Hydrogen-Oxygen Fuel

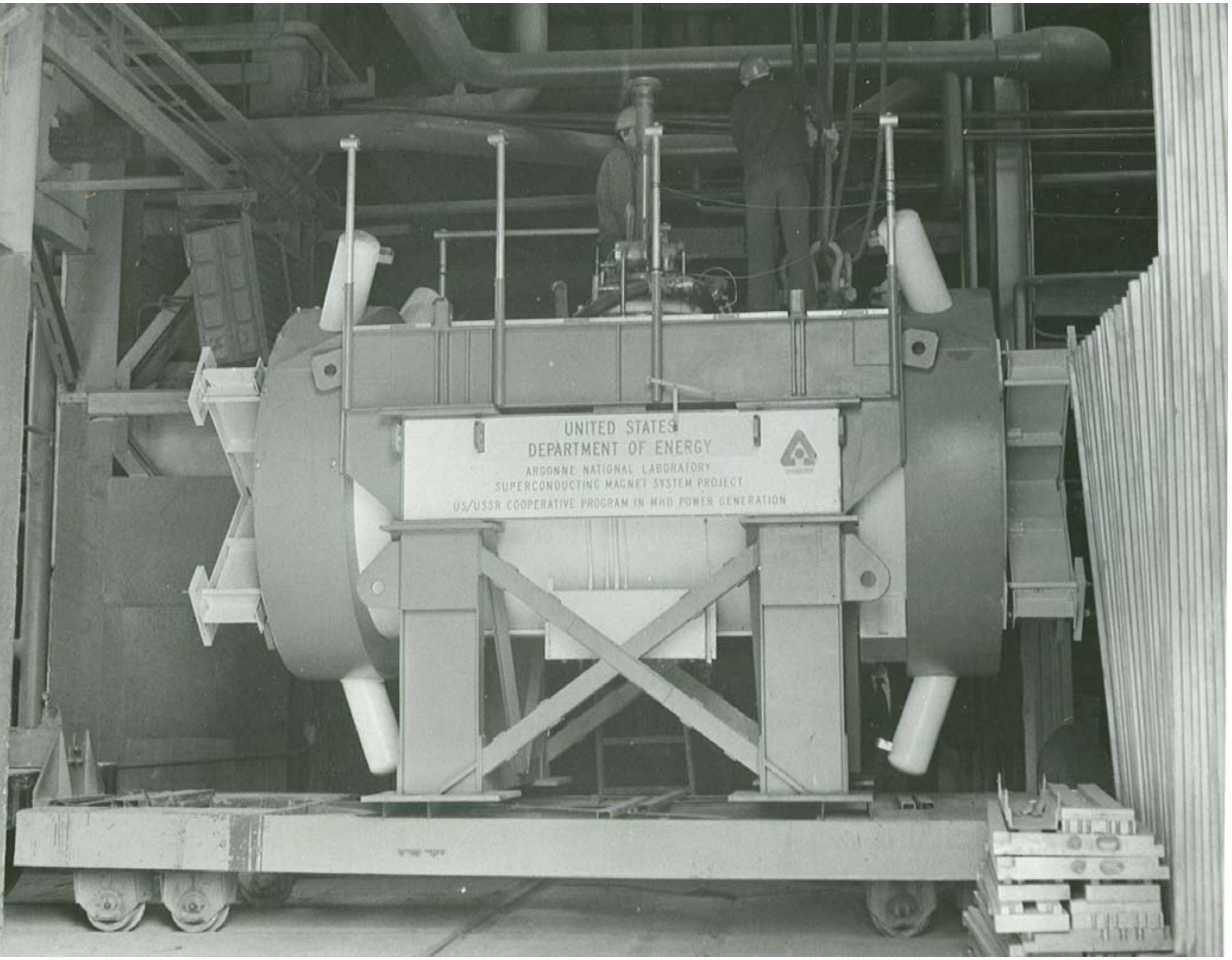




10 MW MHD generator SEVER-M with Superconducting magnet

Joint US-Russia effort:

Open-Cycle MHD Electrical Power Generation



REPORT DOE-TR-119, 1979

MHD generator with superconducting magnet.

Field at center 5T.

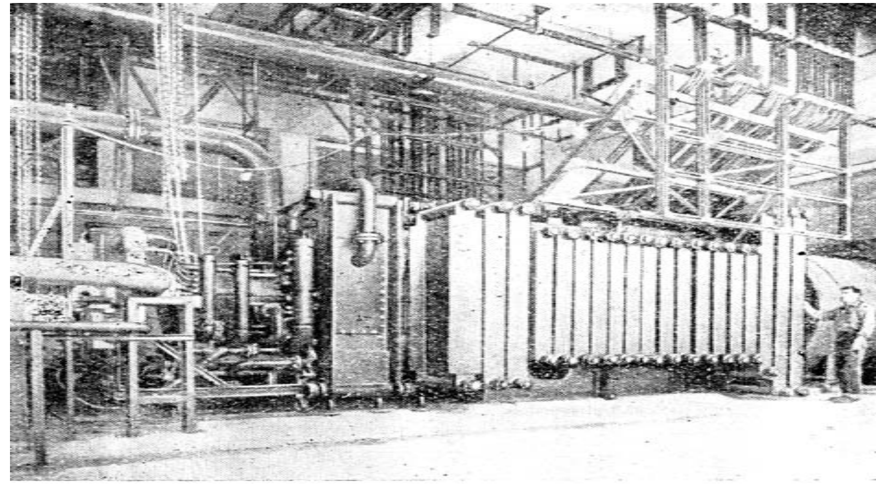
Stored energy 34 MJ.

Input bore 40 cm

Output bore 60 cm

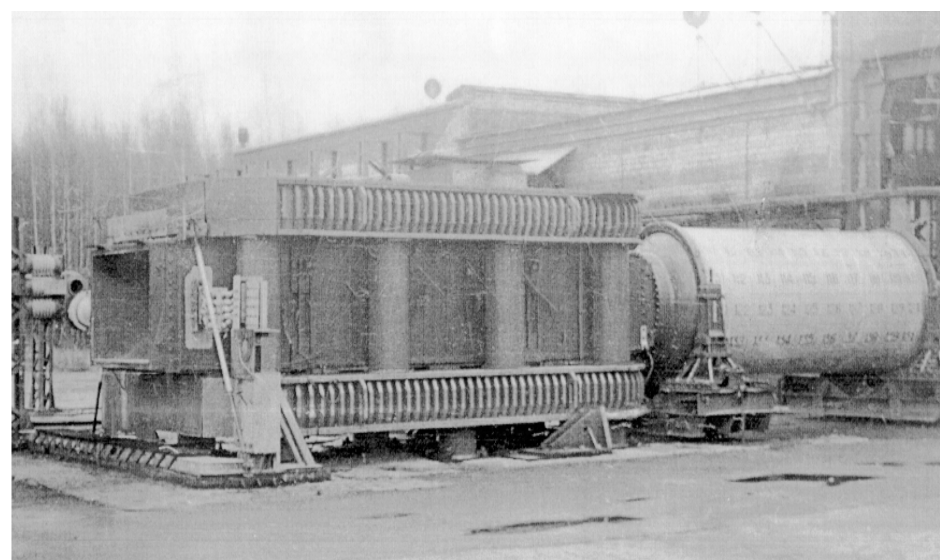
20 large -scale experimental MHD facilities have been constructed including the unit “Khibiny” of 120 MW and “Sakhalin” of 600 MW

Pulsed MHD generator MARK-V

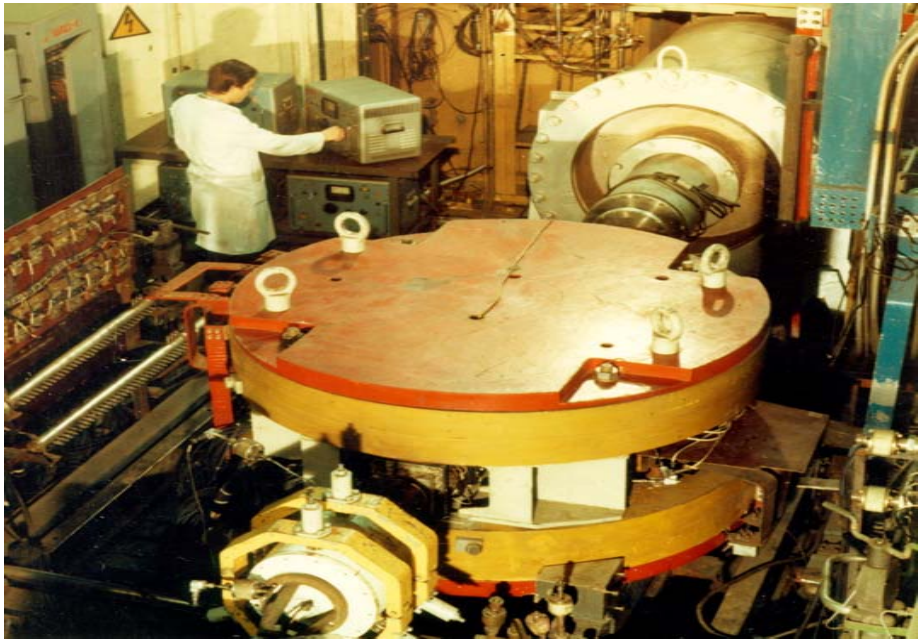


MHD generator KHIBINY

500 MW MHD generator SAKHALIN



Pulsed MHD generator PAMIR at test bench in Troitsk near Moscow



MHD unit PAMIR at the test facility in Garm (near Pamir mountains)

Mobile MHD unit PRIKASPY

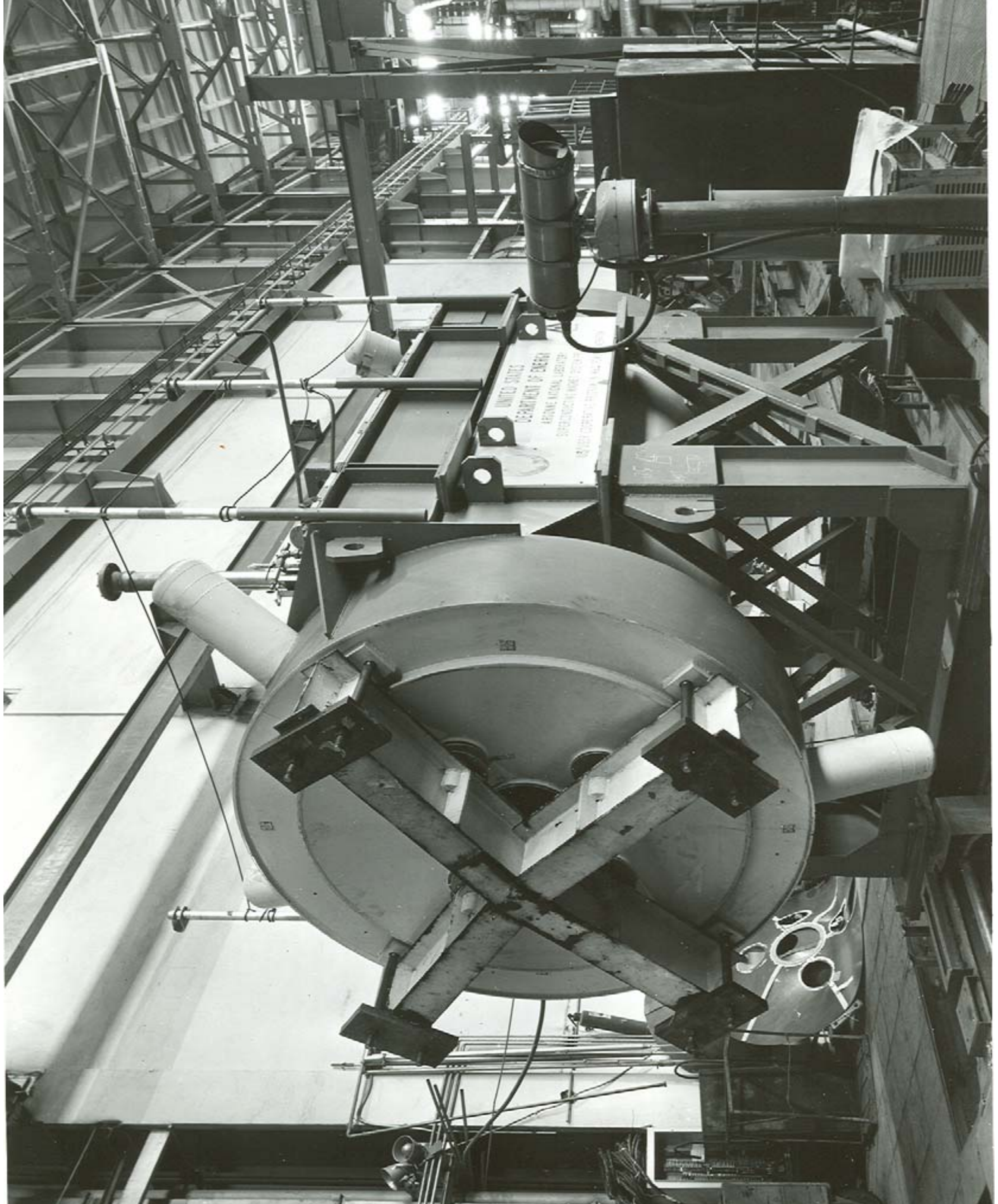
Night startup of the PRIKASPY unit

PULSED MHD POWER SYSTEMS FUELED BY SOLID PROPELLANTS

MHD power system	Pamir	Pricaspiy	Khybiny	Soyuz	Sakhalin
Maximal electrical power of MHD channel, MW	20	20	120	32	500
Working medium mass flow rate, kg/s	≈50	≈50	≈200	≈40	≈800
Number of MHD channels	2	2	2	1	1
MHD channel length, m	1	1	1.17	1.8	4.5
Mass of MHD generator, ton	8	12	34	25	50
Overall dimensions, m	4 x 1.5 x 2	4 x 1.5 x 2	8 x 7 x 1.5	7 x 2 x 2	13.5 x 3.7 x 2.7
Operation duration, s	3-7	3-7	7-10	10	8

Present status of the power systems with MHD generators

	Pulsed <1 min	Short <1hour	>1h
Chemical fuel	Production 1000 MW	Production 50 MW	Production 20 MW
Nuclear fuel	Concept	Concept 100 MW	Design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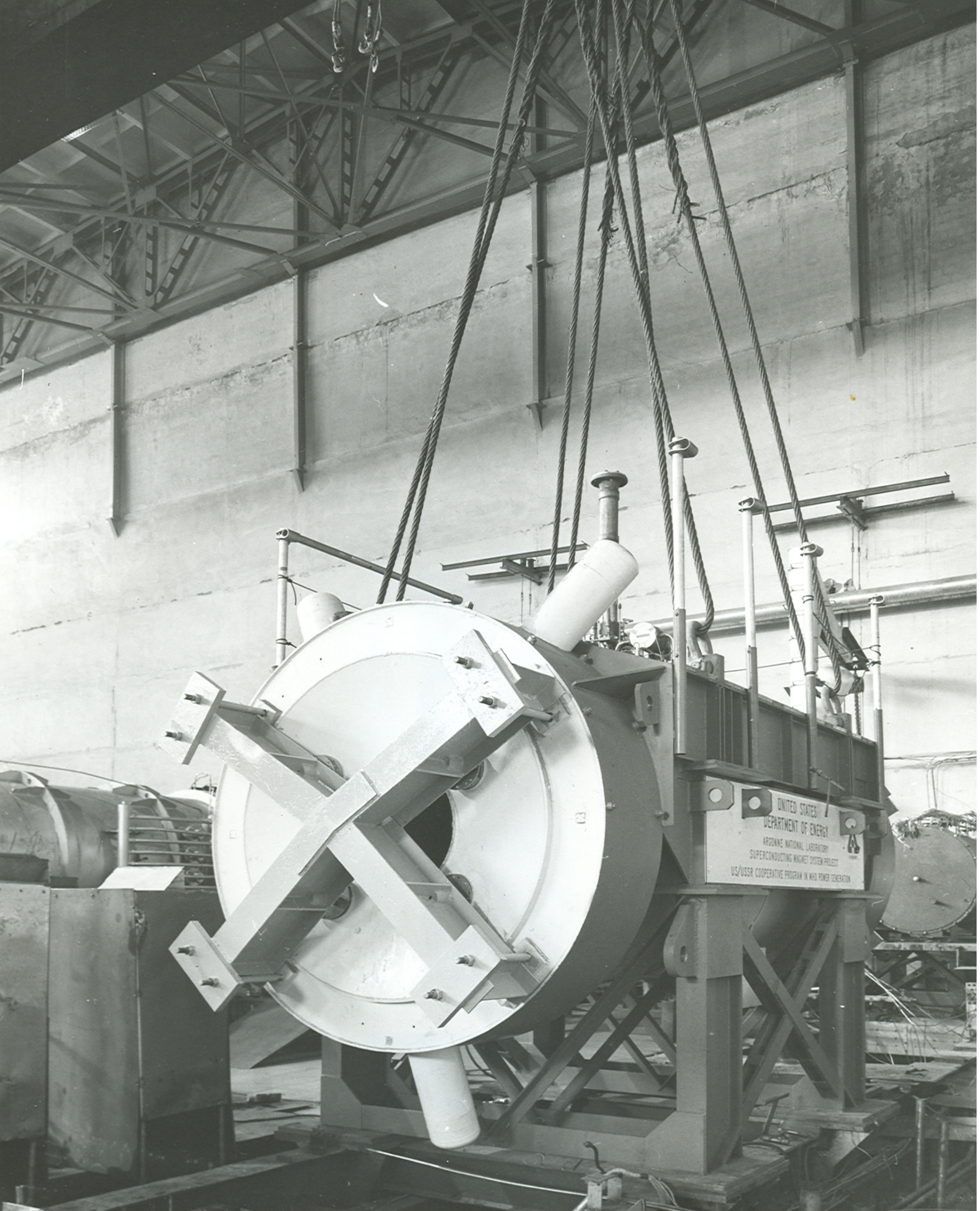
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SUPERCONDUCTING MAGNET SYSTEM PROJECT
US/USSR COOPERATIVE PROGRAM IN MHD POWER GENERATION