

NUCLEAR POWER FOR SPACE VEHICLES: A NEW DIMENSION IN THE ENERGY TECHNOLOGY OF THE FUTURE

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This contribution is a review paper presented by the author as a candidate corresponding member of the USSR Academy of Sciences at a session of the OFTPE Academic Council in November, 1990. It deals with various aspects of space-vehicle nuclear power systems as a new dimension in energy technology. It sums up R & D work on a space-vehicle nuclear power system incorporating a TOPAZ nuclear reactor and a thermionic energy converter. The scientific and engineering problems and tasks achieved in the development and operation of the early space-vehicle nuclear power units are discussed and the prospects of space nuclear power engineering as a new field in power-plant building are outlined.

Nuclear power engineering for space applications is among the newest fields in energy technology. In the Soviet Union, the United States and some other countries R & D work on space-vehicle nuclear power systems (NPSs), based on both nuclear reactor and radioisotope sources, has been under way for over 30 years now.

A salient feature in design work on space NPSs is, as a rule, the requirement to keep their weight to a minimum (sometimes even despite a reduction in efficiency), to minimize their size, and to take into account the fact that in outer space excess heat can only be dissipated by radiation. To this, one should add stringent requirements for reliability in unattended operation, durability, nuclear, radiation and meteorite safety, minimal disturbances from an NPS to its spacecraft, and trouble-free operation at high g-loads, in a random attitude, and under zero gravity. These handicaps are further aggravated by the fact that there is no way of carrying out any adjustment, maintenance and repair on board an unmanned space facility. Taken together, these factors add specific features to the layout, choice of operating variables, construction, ground and in-flight tests, and operation of a space-vehicle NPS.

Whatever its type, any space-vehicle NPS consists basically (Fig. 1) of two elements: a nuclear reactor or a radioisotope capsule as a primary (thermal) energy source, 1, and a combination of a thermal-to-electric energy converter and a cooler-radiator, 2, to transfer excess primary energy not utilized in conversion to the surroundings (outer space).

In contrast to radioisotope NPSs where the output electric power is low (from several watts to several hundred kilowatts), reactor-type NPSs offer an opportunity to have on board spacecraft an output power running into tens, hundreds and even thousands of kilowatts, with the more remote promise of tens and hundreds of megawatts. Space-vehicle NPSs in the above output power bracket can be built along the same lines as ground nuclear power plants, with a turbogenerator in a steam or gas circuit in which the working fluid would absorb the heat generated by a nuclear reactor, or along the lines of direct heat-to-electricity conversion (incorporating an MHD-generator or a thermoelectric or thermionic converter). Historically, the course of events has been such that the first to emerge in outer space were NPSs with thermoelectric or thermionic converters, which do not apply any objectionable dynamic loads to spacecraft.

The capacity of nuclear energy sources is many orders of magnitude higher than it is for chemical or solar sources. Moreover, in some cases (such as missions to the distant planets of the Solar system, flights in the Earth's radiation belts, etc.) they would be preferable or, where output power requirements run into many kilowatts, would be the only designs feasible.

R & D work on such space-vehicle NPSs adds an entirely new dimension to energy technology as it involves a synthesis of advances in nuclear science and technology, heat engineering, fluid dynamics, low-temperature plasma physics, electrical engineering, physical metallurgy, and automatic process control. Research in the field of

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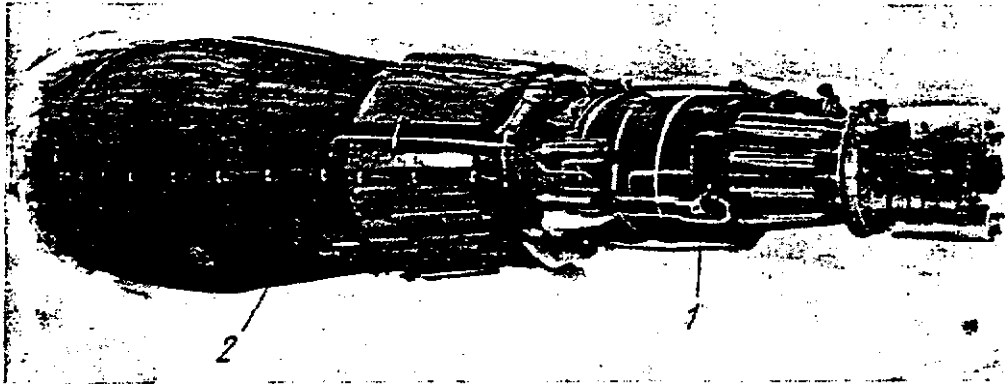


Fig. 1

thermionic and thermoelectric generators intended for use in space NPSs went on at a high pace and has now been resumed after a relative slow-down (for reactor-type NPSs) in the United States. An apt example is offered by radioisotope-thermoelectric SNAP systems specifically designed in the United States for deep-space missions. The SNAP family includes low-power reactor, turbogenerator, thermoelectric and thermionic systems, such as SNAP-8 and SNAP-10A. A later addition is the SP-100 - a new 100-kW system designed recently in thermoelectric and thermionic configurations. Reactor-type NPSs are still in the ground-based component testing stage (except for the SNAP-10A consisting of a compact nuclear reactor and a thermoelectric system, which logged a flight test in space in 1964). Similar work has been in progress in France (the ERATO program) and some other countries.

The basis of thermoelectricity is the Seebeck-Peliter-Thomson effect. The simplest thermoelectric generator is exemplified by an ordinary thermocouple, with the semiconductor-junction type showing a far better performance than the metal-junction type. By interconnecting such thermoelements in various configurations, it is possible to obtain a thermoelectric generator capable of delivering the desired power and voltage. However, thermoelectric NPSs operating at temperatures acceptable for state-of-the-art materials and metalwork as a whole, are still inferior to thermionic NPSs in efficiency, power-to-weight ratio and size.

In the simplest thermionic converter, the thermionic current arises in the gap between a hot electrode (cathode or emitter) and a cold (or, rather, cooled) electrode (anode or collector). For better efficiency the gap is filled with cesium vapor and the thermionic current increases in proportion to the emitter temperature. By cascading such thermionic (or thermal) elements into what are known as electricity-generating channels (EGCs) in Russian usage, with their emitters heated directly by a uranium-containing core and with their collectors cooled via an insulation by a suitable coolant, we obtain (given a sufficient number of properly interconnected EGCs so as to ensure both the critical uranium mass in the reactor and the required electrical parameters for the thermionic reactor-converter which operates in the temperature range between $T_1 = 1800-2000$ K and $T_2 = 800-1000$ K, where T_1 and T_2 are the upper and lower temperature levels of the thermodynamic cycle. Thermionic converters have the highest T_2 of all the heat-to-electricity converters (except MHD generators) used in space-vehicle NPSs where excess heat is dissipated by radiation and proportional to T_2^4 , thus ensuring small size and, as a consequence, small weight for thermionic power units.

In the field of such systems the USSR has always been ahead of other countries, beginning with the development of the world's first TOPAZ nuclear reactor-converter system and ending with thermionic NPSs for space applications. Put in radiation-safe orbits, the Cosmos series of space vehicles carrying thermionic NPSs demonstrated for two years in 1987-1988 the validity of all scientific and engineering principles that lie at the basis of thermionic power generation for spacecraft.

As we believe, the success in the development of thermionic reactors and the related NPS has been due to the judicious choice of a viable conceptual design for the reactor-converter (RC) and the NPS, in which proper consideration is given to the entire set of factors involved: exposure of the RC throughout its long service life to elevated temperatures and to the hostile working media, such as cesium, potassium and sodium; the need to preserve the integrity of electrical insulation and the EGCs at these temperatures; prevention of local heat build-up and a near-boiling condition for the heat-transfer agent; maintenance of stable properties by the zirconium hydride moderator; confinement of hydrogen within the active zone of the reactor; proper operation of rotating

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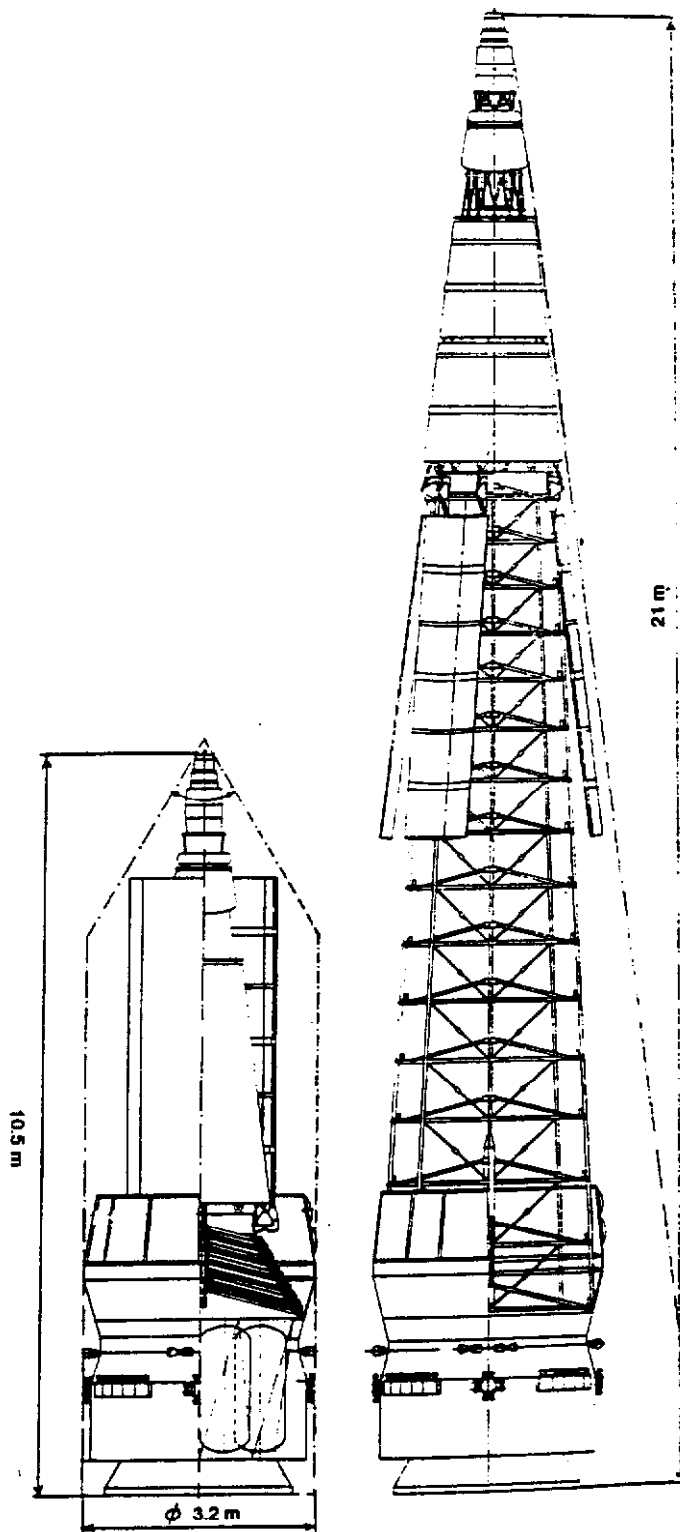


Fig. 2

controls and drives; and complete tightness of all (cesium, coolant, moderator and control) reactor spaces at 500-600°C. In view of the requirements for safe behavior in coming up to full power, reliability and service life, special measures have been taken to provide thermal isolation between the various modules of the RC and of the NPS as a whole.

The maintenance of the thermal parameters for all modules and subunits of thermionic space-vehicle NPSs

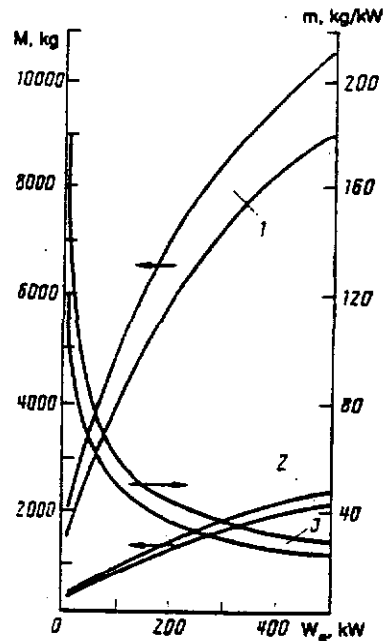


Fig. 3

within the specified limits under any operating conditions is a factor which has a vital bearing on their serviceability over the entire service life. However, different subunits must meet widely different requirements for their thermal state. This calls for an appropriate layout and arrangement of the subunits within an NPS and the use of certain control algorithms, thermal regulation, and heat shielding. Restrictions of one kind or another have to be satisfied on at least 70 thermal variables of some 25 subunits.

The first TOPAZ facility with an output power of 5-7 kW was tested in 1970 when it blazed a trail to space for nuclear reactor-thermionic converter power systems and to their newer generation on which R & D work is still going on.

It seems worth dwelling on some scientific and engineering problems and tasks that we have tackled in our work on the design of a nuclear reactor-thermionic converter power system.

1. Mathematical models were developed for a thermionic converter and the associated nuclear reactor, using the data pooled from laboratory studies and tests of thermionic converters. On this foundation, engineering procedures were derived for the design of a thermionic converter built into the active core of a reactor.

For these purposes, a dedicated electronic model was developed and built. With it, various layouts and configurations for the interconnection of thermionic emf-generating elements and channels were tried so as to optimize their parameters and to get insight into the effect produced by the nonuniform heat field in the reactor, the consequences of open- and short-circuits in the EGCs, variations in output characteristics (electric power and efficiency) of the RC, and the thermal state of the EGC emitters.

2. As an outcome of research into the effect of axial variations in the reactor heat field on the electrical characteristics of the thermionic elements and channels, it was found advantageous to configure the geometric profile of the TOPAZ system so that its length (and, as a consequence, its thermionic emission surface area) increased from center toward ends. In this way, the effect of axial variations in heat release on the electrical characteristics of the RC was materially reduced.

3. An issue in its own right, directly bearing on the RC design, was the problem of electric breakdown in the cesium vapor. It imposes rigorous constraints on the placement of the EGCs in the active core and sets the limit to the minimum spacing of fuel elements in the reactor. An optimum interconnection scheme for the EGCs in the RC, the configuration and geometry of sealed lead-outs, electrical insulators, interconnecting jumpers and current leads in the EGCs were all analyzed and chosen, taking into account the Paschen law according to which the breakdown voltage is a function of only the product of the gas or vapor pressure by the distance between two plane-parallel electrodes. Since this relationship in our particular case was not known, we had to determine the investigate it for different temperatures, electrode materials, and impurity gases produced in operation (xenon, krypton, and

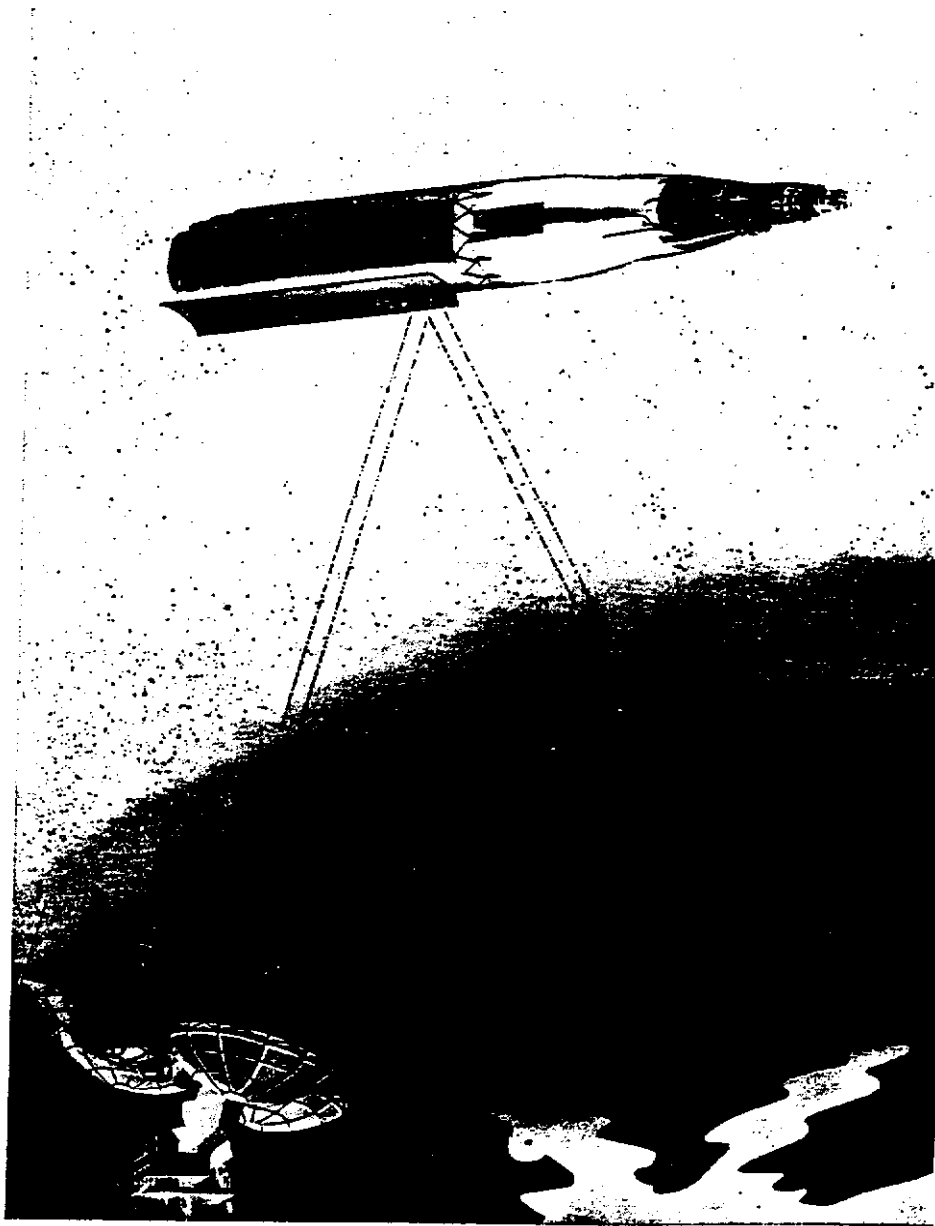


Fig. 4

hydrogen).

Final tests which had as their objective to determine the limits of safe operation from the view-point of an electrical breakdown were made at the operating currents and voltages on a full-sized RC model, with the EGCs simulated by suitable electric analogs.

4. Analytical and experimental studies were undertaken with a view to determining the dynamic behavior of the RC during the transients related to the cesium vapor filling the electrode gaps in the EGCs, electrical load switching, and variations in thermal power.

5. These studies yielded a wealth of data and allowed us to proceed with full-scale tests of the TOPAZ reactor. In these tests, the reactor was started up with its RC short-circuited so as to avoid an electrical breakdown during transients (that is, when the reactor is brought up to its full output power and cesium vapor is admitted inside and when favorable conditions present themselves for a breakdown to occur because the cesium vapor pressure runs through all values from zero to its maximum). This suggested a way to avoid an electrical breakdown at start-up.

6. Radiation safety. As is the case with ground-based nuclear power plants, research reactors, and marine

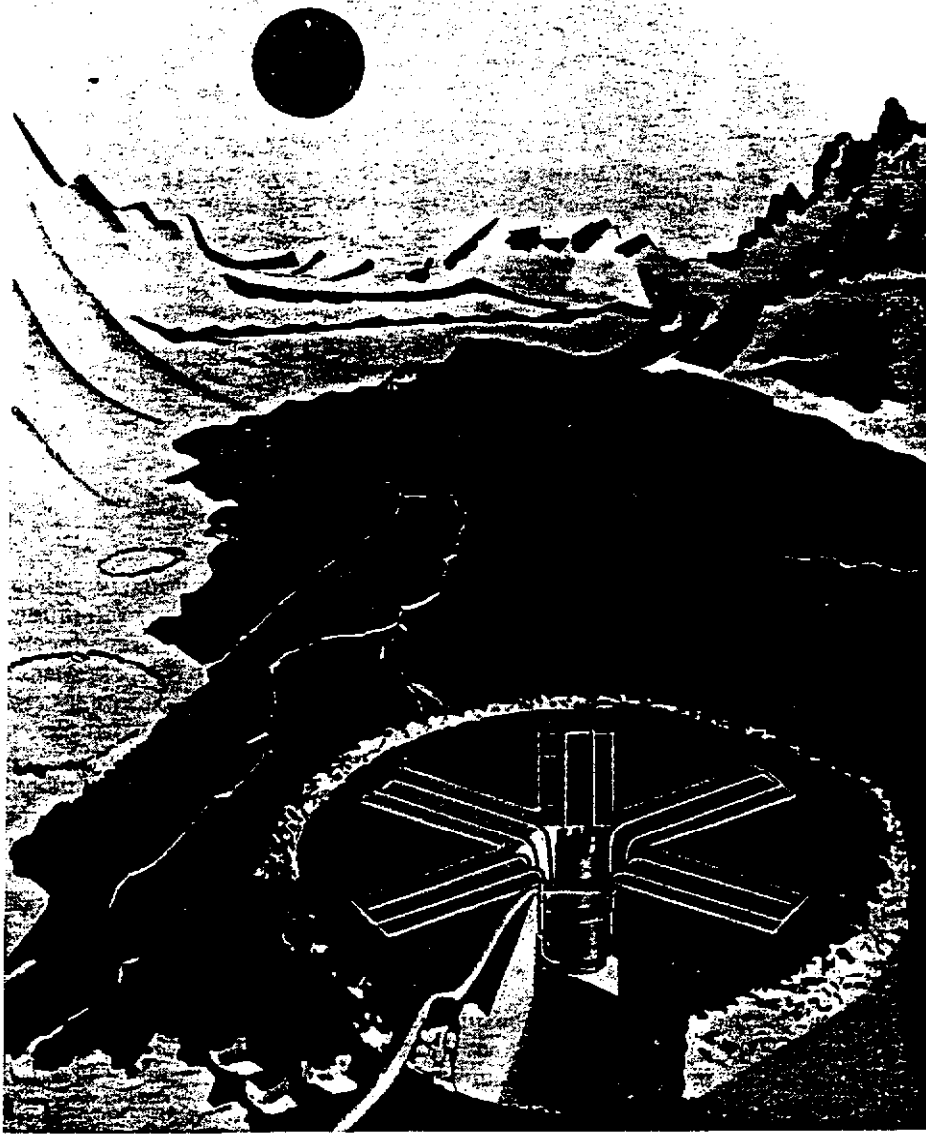


Fig. 5

nuclear propulsion units, there is a need in the case of space-vehicle NPSs to envisage features in their design and operation that would ensure safety to man and to the environment against ionizing radiation and likely radioactive pollutants under both normal and emergency conditions.

The safety of space-vehicle NPSs can hardly be cause for doubt or anxiety as long as these systems are brought up to full power and operated in high orbits (800-800 km) and with a time to re-entry into the dense atmosphere sufficiently long for radioactive products to decay to a safe level.

Where nuclear-reactor power systems are intended for use in low orbits, the required safety can be ensured by transferring them to a long-term orbit (in an orbit at an altitude of 800 km, an NPS would exist for 400 years), thus effecting a "sanitary burial" of radioactive wastes after a satellite has completed its mission.

Further radiation safety measures have been developed by our team and embodied in production spacecraft. They are brought into effect by a back-up radiation safety system which causes the reactive material to be dispersed after the active core detaches itself from the reactor upon aerodynamic heating in the terrestrial atmosphere. This operation is carried on to an extent such that, should the dispersed material reach the ground, the dosage would not exceed the safe limit (0.5 rem over a year), as recommended by applicable international

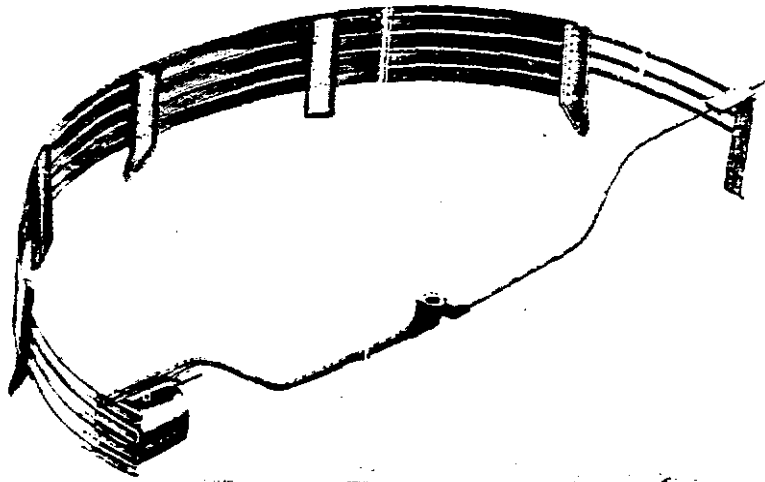


Fig. 6

regulations. Here we run into a paradox: a space-vehicle NPS must be both durable in service and readily destroyable at the end.

All matters related to the use of nuclear power sources in space have been discussed in the United Nations' scientific, technical and legal subcommittees and committee for peaceful uses of outer space. These bodies have ruled that nuclear power sources may be used in space applications subject to safety measures.

Apart from the radiation safety measures mentioned above, this goal can be achieved by operating NPSs in radiation-safe orbits. This approach opens up broad prospects for the use of nuclear power by what are classed as applications satellites. Figure 2 shows a sketch of a universal orbiting platform carrying an NPS. It is intended to supply electric power for a wide range of satellites, such as used for global communications (telephone and telegraphy), navigation of ships and aircraft, various forms of monitoring and surveys, materials manufacturing and processing, etc. Furthermore, the platform could be used to transfer payloads from a low parking orbit to a higher (including geostationary) orbit by electric thrusters. The platform could be operated in radiation-safe orbits from around 800 km upwards.

The universal orbiting platform is envisaged to carry a nuclear reactor-thermionic converter system, a radiation shadow shield, a heat-tube radiator-cooler, an automatic control system, and an auxiliary propulsion unit. The latter will include electric thrusters for transfer from a parking to a high orbit and attitude control, an independent power and control system, and a facility to effect docking with a spacecraft. The net electric power at the platform's terminals is expected to be 25-30 kW, available for seven years.

As can be seen from Fig. 3, thermionic NPSs compare favorably with their thermoelectric counterparts in size and weight. In constructing the graphs of Fig. 3 it has been assumed that NPSs with a power output (W) of less than 100 kW(e) would use thermal-neutron reactors and those with over 100 kW(e), fast-neutron reactors and those with over 100 kW(e), fast-neutron reactors, whereas the coolant would be a eutectic sodium-potassium alloy at powers up to 200 kW, and lithium above that figure. The power expended to put an NPS in orbit and to support its "house-keeping" needs is expected to be up to 30% of what would be available at the reactor terminals. Figure 3 relates electric power W_e in kW and mass M in kg for an NPS incorporating an RC along with the support and heat-withdrawal systems (curve 1), and for an automatic control system along with an energy-quality control system and circuits coupling the NPS to the instrumentation module of the space vehicle (curve 2); curve 3 gives the weight-to-power ratio, or specific mass, m_w (in kg/kW).

Our studies and estimates show that NPSs in the 3-100 kW(e) range can be used to advantage in near-Earth orbits to supply power for navigation systems and information-handling satellites (Fig. 4); those rated at over 100 kW(e) are well suited for a lunar base (Fig. 5); and those in the megawatt class for a Martian mission - a scientific and engineering project currently topical with the space-minded community in the USSR and the United States. Special mention is to be made as regards the reliability of space-vehicle NPSs - an issue of particular significance which calls for novel design features, notably the use of heat pipe in the cooler-radiator.

This technology can be used in a wide temperature range extending from the temperature of liquid nitrogen (used as the heat-transfer agent) to 1500°C (with lithium used as the heat-transfer agent). Developed and reduced to practice by our team, heat-withdrawal systems based on heat pipes have a service life of 5 years and

more, as evidenced by their operation on Cosmos satellites (Fig. 6).

From the experience gained in the design of NPSs for which the key criteria are self-contained and unattended operation, our team has been able to develop units suitable for ground-based civil applications. One apt example is the ATEAS-3000/100, an unattended thermoelectric nuclear power plant with a net electrical power of 100 kW, a net thermal power of 3000 kW, and a design service life of up to 30 years. This is an assemblage of modules not over 20 metric tonnes in weight each, which can be carried to the desired site individually. The plant uses a multilayer protective shell, natural convection, and direct conversion to electricity, with all of these features ensuring a high level of radiation safety. Furthermore, the self-regulation principle used in the reactor provides an improved reliability. The plant has been designed in two modifications, one for underwater service as a source of power for offshore oil platforms in the northern seas, and the other for underground service to supply heat and power for residential and production facilities (including those on oil and gas fields) in hard-to-reach and remote localities, especially with a high level of earthquake hazard.

CONCLUSIONS

The regular use of nuclear-type NPSs on Cosmos satellites is now well into its second decade, and a new division of energy technology, space-vehicle nuclear power, has come into being in this country - for the first time in world practice.

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