Nuclear power in the USSR

by I.S. Zheludev and L.V. Konstantinov

More than 25 years ago the world's first commercial electricity was produced by the First Atomic Power Station at Obninsk, near Moscow. Its power output was 5 MWe, many times less than that of modern nuclear power plants, but it heralded the beginning of a new era – the era of nuclear power. A general view of the First Atomic Power Station of the USSR is shown in Figure 1. A year later, at the first International Conference on the Peaceful Uses of Atomic Energy, held in Geneva in 1955, Soviet scientists reported on the design features of this power station and on experience in operating it.

The successful construction of the First Atomic Power Station was made possible by the atomic industry which had been built up by that time in the USSR. The scientific leader of the large team of Soviet scientists, designers and engineers who took part in its construction was the eminent scientist and gifted organizer Academician I.V. Kurchatov. Many of his pupils and colleagues are still working successfully on the development of Soviet nuclear power. The First Atomic Power Station remains in operation and is used for research purposes and for training technical staff.

The growth of nuclear power in the USSR has passed through the following stages: four years after the start-up of the First Atomic Power Station the Siberian nuclear power station with a power output of 100 MWe was built. Its capacity was subsequently increased to 600 MWe. Later, commercial electricity was produced by the Beloyarsk, Novo-Voronezh, Kola, Leningrad and Armenia plants, as well as others. Table 1 shows how the capacity of Soviet fossil and nuclear power plants has grown. At present, the total installed nuclear capacity of the USSR is about 12 000 MWe. For comparison, the increase in capacity of all power plants in the USSR since 1921 is also given, that being the year of inception of the first long-term plan for the electrification of the country (GOELRO), prepared on the initiative of the founder of the Soviet State, V.I. Lenin. This plan provided for the construction of 30 power plants with a total capacity of 1740 MWe over a period of 10–12 years; it was completed in 1931.

THE SOVIET TYPE REACTOR

The choice of graphite as moderator for the First Atomic Power Station and of water as its coolant was based on a large body of research and development work. Various types of nuclear reactor were considered, including pressurized-water reactors (PWRs), boiling-water reactors (BWRs), and gas- and sodium-cooled reactors. As the further development of reactor design showed, uranium-graphite channel-type reactors cooled with boiling water are economically competitive not only with other types of power reactor, but also with conventional coal-fired power plants. Such reactors, known as the "Soviet type"

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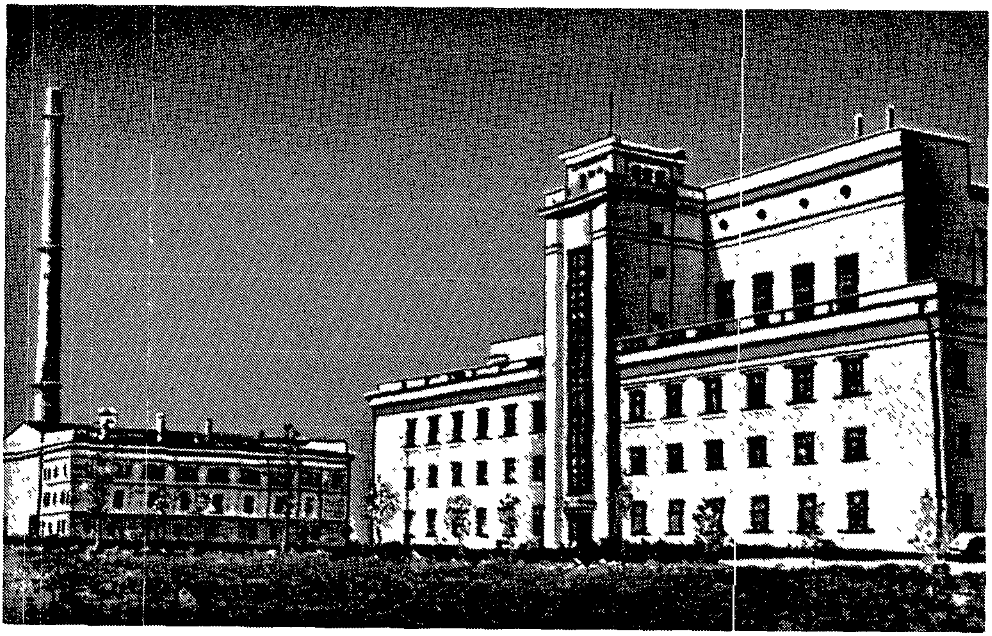
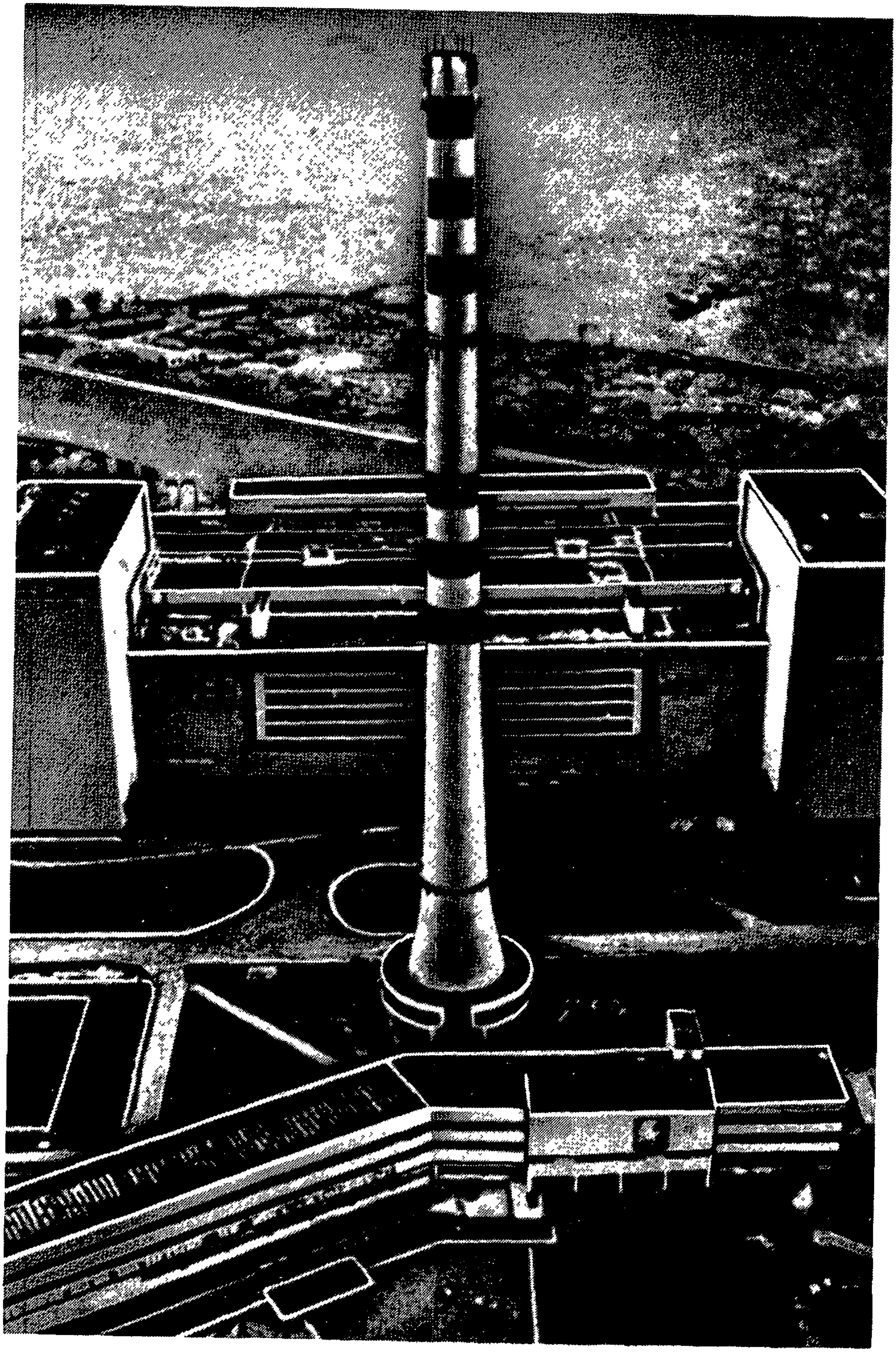


Figure 1. The First Atomic Power Station at Obninsk.

Table 1. Increase in Electricity Production in the USSR

Year	Installed capacity of power plants (10^6 kW)		Generation per year	
	Fossil and nuclear	Nuclear	10^9 kW-hour	Power production *kW-hour/capita*
1921	1.2	–	0.5	4
1927	1.7	–	4.2	25
1940	11.2	–	48.3	256
1945	11.1	–	43.2	250
1950	19.6	–	91.2	480
1960	66.7	0.605	292	1365
1970	167.5	1.0	740	3060
1975	220.5	4.7	1038	4100
1980	290 (planned)	~18.0 (planned)	1340–1380 (planned)	5200



(after their design), with power ratings of 1000 MWe and more will comprise about half the total nuclear capacity in the USSR during the next 10—15 years. Another reactor type on which the nuclear power programmes of the Soviet Union and of other CMEA member countries will be based is the water-moderated water-cooled power reactor (designated WWER), analogous to the familiar PWR. In view of this similarity we shall not dwell on the design of the WWER, but rather limit ourselves to describing some of the special characteristics of the uranium-graphite channel-type reactors.

One such reactor is the RBMK-1000 with a power output of 1000 MWe. The first of a series of nuclear power plants with such reactors was put into operation in 1973 near Leningrad. At present, seven such units are in operation and a further seven are under construction. It has been demonstrated that the power output of these reactors can be stepped up by a factor of 1.5 without substantial changes in design and without altering the reactor dimensions. This higher output is obtained by increasing the power density in the fuel significantly and intensifying heat exchange in the core. A power station using RBMK-1500 reactors, with an output of 1500 MWe per unit, is now being built, and the construction of further power stations with RBMK-1500 reactors is planned for the future.

Figure 2 shows a general view of Stage 1 of the V.I. Lenin nuclear power station at Leningrad; figures 3 and 4 are a cross-section of one unit in the 1000 MWe series, and a simplified heat flow diagram, respectively. The main characteristics of the RBMK-1000 and RBMK-1500 reactors are given in Table 2. The fuel elements in the vertical zirconium channels are cooled by boiling water. Steam is separated from the water in four drums and transferred to two saturated-steam turbines each with a power rating of 500 MWe; the water is returned to the reactor channels by eight circulation pumps. Thus, there are no heat exchangers in the reactor's cooling circuit, and its operating cycle is analogous to that of a BWR.

An important advantage of the uranium-graphite channel-type reactors is that they can be built in normal non-specialized machine works, since the high-pressure vessel and heat exchangers needed in PWRs are absent. Refuelling can be carried out without reduction in power ("on-load" refuelling); this provides an opportunity of removing any defective fuel elements while maintaining the minimum reactivity reserve required. In the final analysis, all this makes it possible to build these power plants quite quickly and to ensure a high load factor. A disadvantage of such reactors is the extensive piping network in the cooling circuit, which entails greater capital investment than in WWERs. However, as we shall see below, building nuclear power stations with RBMK-1000 and RBMK-1500 as well as WWER-440 and WWER-1000 reactors in the European part of the Soviet Union is entirely justified economically at the present time.

A further stage in the development of uranium-graphite channel-type reactors is the RBMKP-2400 project with a power output of 2400 MWe per unit. The distinctive design features of this reactor are that it is manufactured in sections and that is has nuclear steam super-heating. Structurally, the rectangular core consists of 12 sections, including 4 sections for steam super-heating. These sections will be manufactured serially at the factory, delivered by rail and assembled at the construction site. Depending on the number of

Figure 2. Stage 1 of the V.I. Lenin nuclear power plant at Leningrad.

Table 2. Characteristics of the RBMK-Type Reactors

PARAMETERS	RBMK-1000	RBMK-1500	RBMKP-2400
Thermal power (MW)	3 200	4 800	6 500
Electric power (MWe)	1 000	1 500	2 400
Number of turbines x turbo-generator power (MWe)	2 X 500	2 X 750	2 X 1200
Efficiency (%)	30.4	31.3	37.0
Core dimensions:			
Height (m)	7.0	7.0	7.0
Diameter or (width X length)	11.8	11.8	(7.5 X 27)
Number of fuel assemblies:			
a) for steam production	1 693	1 661	1 920
b) for steam superheating	–	–	960
Initial core loading of uranium (tons)	192	189	293
Fuel	UO_2	UO_2	UO_2
Enrichment (%)	1.8	1.8	1.8 & 2.3
Average burn-up (MWd/ton uranium)	18 100	18 100	19 000
Fuel can material	Zirconium alloy	Zirconium alloy	Zirconium alloy Stainless steel
Water flow through the reactor (tons/hour)	37 500	29 000	39 300
Steam flow to turbine (tons/hour)	5 400	8 200	8 580
Turbine operating parameters:			
Steam inlet pressure (bars)	65	65	65
Steam inlet temperature (°C)	280	280	450

sections, the power output of the reactor can be increased or reduced as required by the customer. (The main characteristics of the RBMKP-2400 are given in Table 2.) Construction of power stations with these reactors is to begin after 1985. The RBMKP-2400 design is based on experience accumulated in the Soviet Union with nuclear steam superheating. It can be noted here that the Beloyarsk nuclear power station in the Urals has been successfully operating for approximately 15 years with two units of 100 and 200 MWe respectively, with steam temperatures at the reactor outlet of 520–540°C and at a pressure of about 100 bars.

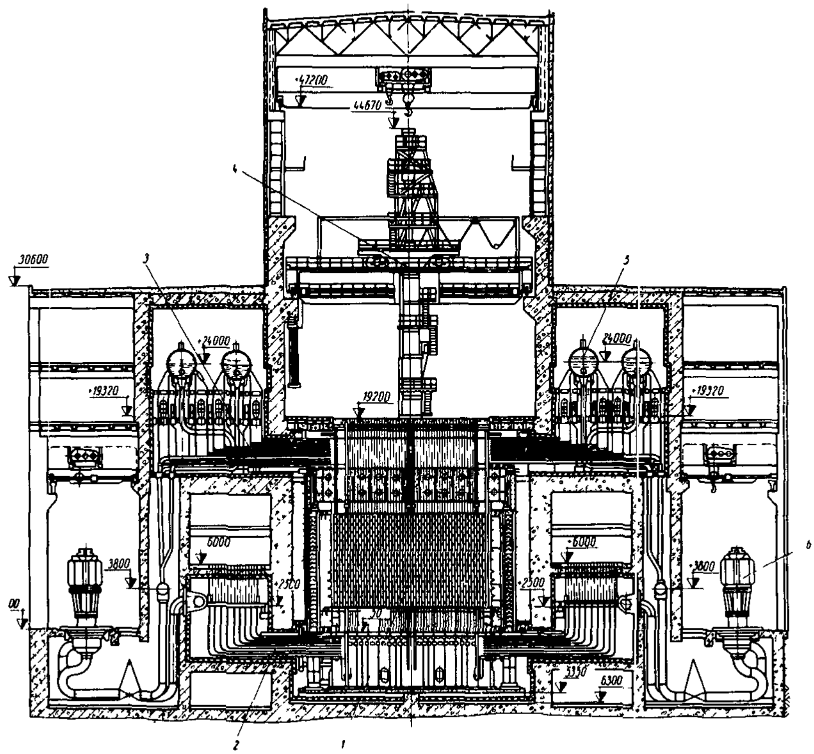
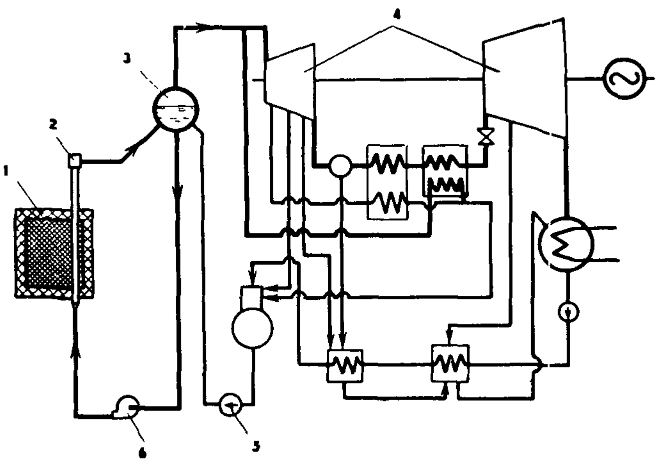


Figure 3. Cross-section of one unit in the RBMK series. (1. Reactor core. 2. Piping for coolant inlet. 3. Piping for outlet steam-water mixture. 4. Refuelling machine. 5. Drum-type steam separators. 6. Circulation pump.)

Figure 4. Simplified heat flow diagram of an RBMK-1000 power plant. (1. Reactor. 2. Channel with fuel elements. 3. Drum-type steam separator. 4. Turbogenerator. 5. Feed-water pump. 6. Circulation pump.)



BREEDER REACTORS IN THE USSR

It is well known that thermal reactors use only 1–2% of the energy contained in natural uranium, because the isotope uranium-235 is used as fuel, whereas the uranium-238, which is about 140 times as abundant in natural uranium, is scarcely used at all. For this reason it is important to determine to what extent the scope of nuclear power based on thermal reactors may be limited by the available nuclear fuel resources, so that the construction of breeder reactors can be started in good time. Such fast breeder reactors will have to supply fuel not only for new generations of breeders but also for older thermal reactors. The world uranium reserves available at extraction costs of up to US $100/kg (at 1973 prices) are currently estimated at 5–10 million tonnes. However, if only thermal reactors are built, the known uranium reserves (excluding those in seawater) that are economically workable from our present point of view do not very much exceed the existing reserves of oil and gas in energy content.

Research aimed at proving and subsequently introducing fast reactors has been under way in the Soviet Union since 1949. After experience gained on the first experimental and demonstration fast reactors BR-2, BR-5 and BOR-60, a power plant using the BN-350 fast reactor was put into commercial operation at Shevchenko, on the Caspian Sea, in 1973. In addition to 150 MWe of electricity, the BN-350 supplies desalinated water at a rate of 120 000 tonnes/day. This reactor has a "loop-type" equipment layout, in contrast to the BN-600 reactor with an electric power output of 600 MWe which was recently put into operation in the Urals near Sverdlovsk. The BN-600 reactor has a "pool-type" or integrated layout, with the core and the entire primary circuit immersed in a tank of molten sodium. A cross-section of the BN-600 is shown in Figure 5. Operating experience with the BN-350 and BN-600 reactors will show what advantages and disadvantages both layouts may have.

Power stations are now being planned with fast reactors designated BN-800 and BN-1600 with outputs of 800 MWe and 1600 MWe respectively. This work will draw on experience acquired in operating BOR-60, BN-350 and BN-600. The basic parameters of the Soviet fast reactors are given in Table 3.

Nuclear power plants accounted for 20% of the entire electricity generating capacity installed in the USSR during the period of the tenth five-year plan (1976–80). This corresponds to an increase by a factor of about three in the capacity of operating nuclear power plants during this period. By the end of 1980 nuclear power plants are to be producing about 10% of the total electricity consumed in the European part of the USSR, or 5.8% of the country's total output, as against 1.9% in 1975. The advance of nuclear power plant construction in the European part of the USSR is to continue in the future. In the next 10–12 years the country's nuclear power plant capacity will increase to about 90 000 MWe. After 1990 an increasingly large part of the nuclear power stations will be equipped with the BN-1600 breeder reactor which will have been developed by then.

The general trend in the future development of Soviet nuclear power is towards the construction of fast reactors. Nevertheless, for the present time and until the end of the century, the basis of nuclear power in the USSR will be thermal reactors of the RBMK and WWER types. From 1990 onwards there will be large-scale construction of serial breeder reactors, which should then be able to make a considerable contribution to the country's power resources at the beginning of the next century.

Table 3. Characteristics of Fast Reactors

PARAMETERS	BN-350 in operation	BN-600 in operation	BN-1600 at design stage
Thermal power (MW)	1000	1470	~4000
Electric power (MWe)	350 or 150 MWe + 120 000 tons desalinated water per day	600	1600
Efficiency (%)	35	42	~40
Diameter/height of core (cm)	150/100	205/75	330/100
Maximum fast neutron flux $(cm^2 \times sec)^{-1}$	8.10^{15}	10^{16}	10^{16}
Initial core loading of U^{235} or Pu^{239} (tons)	(UO_2-PuO_2)	(UO_2-PuO_2)	(PuO_2)
Average fuel burnup	5 %	10 %	10 %
Maximum power rate in core (kW/l)	780	840	710
Reactor coolant	Sodium	Sodium	Sodium
Outlet sodium temperature (°C)	500	500	530–550
Successive coolant circuits	Sodium/ sodium/water & steam	Sodium/ sodium/water & steam	Sodium/ sodium/water & steam
Steam temperature (°C)	435	500	490–510
Steam pressure (bars)	50	130	~140
Term between refuellings (effective days)	55	150	120
Site for nuclear power plant	Schevchenko (on shore of Caspian Sea)	Beloyarsk (near Sverdlovsk)	Not yet chosen

It should be borne in mind that the operational lifetime foreseen for nuclear power stations using thermal reactors is not less than 30 years. Thus, both breeders and thermal power reactors will be operating simultaneously and complementing each other by the end of this century. The breeder reactors are to operate mainly on base load to provide larger amounts of fuel for new breeders as well as for thermal reactors. The latter will be used to compensate day-to-night and seasonal fluctuations in electricity consumption.

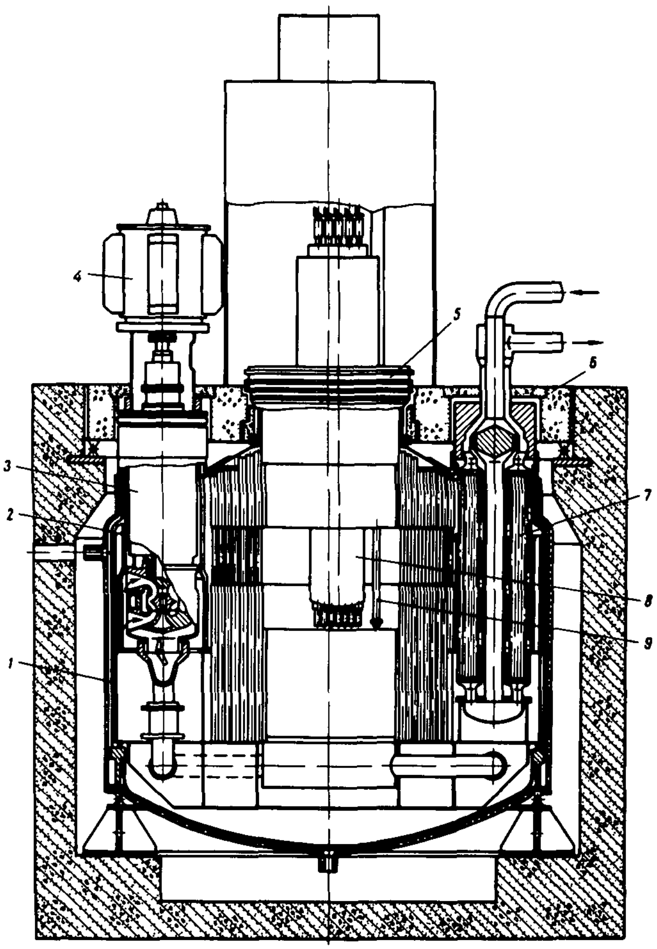


Figure 5. Cross-section of the BN-600 reactor. (1. Load-carrying ring. 2. Sodium tank. 3. Pump. 4. Pump motor. 5. Rotating reactor cover. 6. Upper shield. 7. Heat exchanger (sodium-sodium). 8. Central channels for control rods. 9. Fuel loading mechanism.)

NUCLEAR AND OTHER ENERGY SOURCES

The Soviet Union is one of the few industrially developed countries that possess large energy resources. Experts estimate that the territory of the USSR holds up to 30% of the world's oil reserves, up to 40% of its gas and up to 50% of its coal. However, 90% of these reserves, as well as 80% of the hydroelectric reserves, lie outside the European part of the USSR while approximately 75% of the population live in the European part and account for about 80% of the total energy consumption. It is thus necessary to transport fuel over distances of 800—900 kilometres on average and to transmit electricity over many thousands of kilometres. The fact that fuel already represents about 40% of the country's entire freight traffic speaks for itself. In order to meet the growing energy demand of the European part of the USSR, therefore, energy must be supplied in more concentrated forms than conventional fuel, and nuclear fuel meets that requirement.

It is thus economics that dictate the scale and growth rate of nuclear power and its role in the country's energy supply. Although the specific capital investment for the construction of a nuclear power plant is greater than for conventional power plants, building nuclear power plants in the European part of the USSR is already economical now and would be even if their capital costs increased by a factor of 1.5. Economic calculations concerning the question of whether to build a nuclear or a conventional power plant take into account both the need for larger supplies of the fuel chosen and the cost of fuel transport.

A further very important problem associated with energy supply is that of protecting the population and reducing environmental pollution. At present, oxygen consumption through the burning of fuel is several times greater in many industrialized countries than oxygen production by photosynthesis, and in such countries, this situation can continue only by virtue of an inflow of oxygen from equatorial regions where oxygen production is considerably greater than its consumption. On a global scale, today's power plants release annually 200—250 million tonnes of ash and about 60 million tonnes of sulphur dioxide into the atmosphere. By the year 2000 these releases may increase five- or six-fold and become hazardous. Nuclear power plants, on the other hand, are the cleanest existing industrial sources of energy. The foregoing applies fully to the European part of the Soviet Union, where the necessary conditions for large scale development of nuclear power already exist.

The development of nuclear power has also given man a new responsibility: that of preventing the contamination of the environment with radioactive products from the fusion of uranium and plutonium nuclei. In the Soviet Union, much attention is being paid to ensuring the safety of nuclear power plants. Scientifically sound standards and rules for nuclear and radiation safety in the planning, construction and operation of nuclear power plants have been formulated, and special supervisory bodies for nuclear power plant safety have been established. It may be said with confidence that by taking the proper technical and organizational precautions now we can guarantee the safe development of nuclear power on a large scale. Particular attention must be devoted to the safety of nuclear district heating plants, the construction of which is economic near large cities.

NUCLEAR POWER IN CMEA COUNTRIES

The Soviet Union provides considerable and varied assistance to the socialist countries within the Council for Mutual Economic Assistance (CMEA), including the construction of nuclear power plants in those countries. In the German Democratic Republic the Rheinsberg and Bruno Leuschner nuclear power plants have been put into operation. The former went into service in 1966. In the latter, three units with 440 MWe WWER reactors were installed between 1973 and 1977; the remaining generating units are still under construction. In Czechoslovakia, a nuclear power plant with several 440 MWe units is being built at Jaslovske Bohunice; the first two units went into service in 1978 and 1980, respectively. In Bulgaria the Kozloduj nuclear power plant with two 440 MWe units is in operation and further units are under construction. Nuclear power plants are also under construction in Hungary (at Paks) and Poland, and another is being planned in Cuba. In addition, a plant with two 440 MWe WWER Soviet reactors is operating in Finland.

Table 4. Nuclear Capacities in the CMEA Countries

	STATUS AND CAPACITY		Projected to be in operation by 1990 MWe
	In operation MWe gross (number of units)	Under construction MWe gross (number of units)	
USSR	12 000 (32)	13 760 (15)	~90 000
Bulgaria	880 (2)	880 (2)	
Czechoslovakia	880 (2)	2 640 (6)	
Cuba	–	440 (1)	
German Democratic Republic	1 830 (5)	1 760 (4)	37 000
Hungary	–	880 (2)	
Poland	–	880 (2)	
Romania	–	–	
	15 590 (41)	21 240 (32)	~120 000
TOTAL:	36 830 (73)		

The importance of nuclear power for the socialist countries increases year by year. In accordance with the long-term programme of co-operation in the fields of energy, fuel and raw material which was approved in 1978 at the thirty-second meeting of the CMEA Session, nuclear power plants with a total capacity of 37 000 MWe are to be built in CMEA member countries (excluding the USSR) by 1990. Thus, the total nuclear power capacity of the CMEA countries including the Soviet Union will reach about 120 000 MWe by 1990. This will save the equivalent of about 240 million tonnes of reference fuel per year. Dozens of specialized enterprises in the socialist countries are taking part in the manufacture of equipment for these power plants, thus assuring the development of nuclear power at an accelerated rate. It is expected that by the end of the century nuclear plants will provide up to 40–45% of the electric power in the CMEA member countries.

SOME COMMENTS ON THE FUTURE

Although atomic energy was used mainly to generate electricity in the early stages, it is now clear that its range of applications will broaden in the future. Of the total energy consumption in the Soviet Union, electricity now accounts for about 25%, while 75% (mainly oil, gas and coal) is used in the production of industrial and domestic heat and for transport, as well as in the form of heat and chemical components for metallurgical and chemical processes. In the USSR, up to 35–40% of the total energy is consumed in the production of medium- and low-grade heat (up to 200–300°C) for industrial and municipal or domestic purposes. Centralized heat supply throughout the country exceeds 50% of total heating requirements as a result of the combined production of heat and electricity. Clearly, therefore, the necessary conditions for using atomic energy in this field of the national economy are already fulfilled now; and its use will significantly reduce the consumption of oil and gas, which are valuable raw materials for the chemical industry. The development of nuclear installations for heat supply purposes is being accelerated in the USSR in view of their economic usefulness. For example, work is under way on building reactors of 500 MW thermal each for district heating in the cities of Gorky and Novo-Voronezh.

In the future, nuclear reactors will also be able to supply industry with the high grade heat needed for technological processes, at temperatures of the order of 1000°C. A considerable proportion of the transport that now relies on the internal combustion engine may eventually be fuelled with hydrogen obtained with the help of atomic energy; to the extent that this is accomplished, the transport sector would then no longer pollute the atmosphere with combustion products as is does at present.

In the USSR, as in other countries, the usefulness of building not just individual nuclear power plants spread over the country's territory, but power complexes or parks with capacities of several tens of thousands of megawatts is under consideration. These would include not only nuclear power plants but also fuel cycle facilities and radioactive waste disposal sites. Such combined installations would considerably reduce or even eliminate the transport of radioactive materials beyond their boundaries. They would do no great harm to the environment if they were built in sparsely populated areas with soil unsuitable for agriculture or forestry. In this question, too, economics and environmental protection remain the decisive factors.

We have spoken of a long-term programme for the large-scale development of nuclear power both in the USSR and in the CMEA countries. Inevitably the question arises, What other energy sources may exist and what might their importance be for the energy economy of CMEA Member States. Why should it be nuclear power in particular that compensates for the growing shortage of conventional fuel? Surely it must be possible to use the energy of the sun, the tides, the wind and the heat of the earth's interior on a large scale. However, a thorough analysis performed by experts shows that all these energy paths are useful only for the solution of special energy supply problems in comparatively small areas with the appropriate favourable conditions, and cannot form the basis for the power supply of a whole country. These sources can meet at most 1—2% of our energy needs. Of course, this does not in any way mean that they can be neglected. For the satisfaction of local energy requirements, renewable sources of energy will be highly useful.

Undoubtedly, the ultimate solution to the energy problem will be the harnessing of thermonuclear fusion. Work on this topic started in the Soviet Union in 1950. Since then, considerable progress has been made in producing high-temperature plasmas and in understanding their behaviour, and it has been possible to start preparations for a demonstration fusion reactor. But that is the subject of another lecture.

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