EXPERIENCE IN THE APPLICATION OF NUCLEAR ENERGY FOR DESALINATION AND INDUSTRIAL USE IN KAZAKHSTAN

XA9848831

E.D. MURALEV
Mangyshlak Atomic Energy Complex (MAEC),
Aktau, Kazakhstan

Abstract

Key design features of the Aktau complex in Kazakhstan with a 1000 MWth fast breeder nuclear reactor are outlined. The experience gained over 20 years of operation and maintenance is briefed. The water costs, the impact on the environment and the water and steam quality have confirmed the efficiency and the reliability of nuclear energy application for seawater desalination and industrial use.

1. INTRODUCTION

Recently the interest in using nuclear energy for non-electrical applications has increased. In line with the ongoing development of nuclear engineering and technology, more reliable and safe reactors are being designed. The public opinion is changing in many countries in favour of development of nuclear energy.

It is the time to evaluate existing experience gained in various countries. Mangyshlak Atomic Energy Complex has been in service since 1973, providing the whole region with electricity, heat and potable water. This paper outlines some representative features of this experience.

2. DESCRIPTION

2.1 Layout

The atomic energy complex is located on the Mangyshlak peninsula, on the East Coast of the Caspian Sea. It is located in an arid zone, with a small amount of rainfall and a limited stock of groundwater which has a salinity of 3.5-5.8 g/litre. The complex was constructed on a platform located 12 km from the city, next to the developed industrial enterprises, and a potable water preparation station was built at a place closer to the town.

Relevant objectives for constructing the complex at the place were:

- To minimize heat losses during the transmission of steam to the industrial enterprises;
- To minimize the water transport costs;

Prevention of the inhabitants exposure to radiation beyond the specified limits for accidents had been also taken into consideration.

The Mangyshlak Atomic Energy Complex consists of:

- A liquid metal fast breeder reactor BN-350;
- A gas-oil fuelled thermal power station;
- A potable water preparation station;
- Ten multi-effect distillation (MED) desalination units, with a production capacity of 8 000 to 14 500 m3/day each;
- A feed water preparation plant for the steam generators.

2.2 Nuclear Reactor

The BN-350 is a loop type fast breeder reactor cooled with liquid sodium. Its main design features and operational history are described in [1]. The reactor has six primary loops located in individual airtight rooms and six secondary loops located in two rooms at opposite ends of the reactor vessel [1]. Each loop has a pump and an intermediate Na-Na heat exchanger. The thermal section of the reactor consists of six steam generators with natural circulation. The reactor core is surrounded by a blanket of depleted uranium. Iron ore concentrate, graphite, steel and concrete are used for the biological shielding. The negative power and temperature coefficients of the core provide self-stability of the reactor. Heat release in the core is stable and the excess reactivity is low. Operation of the reactor is simple. The low pressure of the sodium coolant and the absence of noticeable corrosion ensure the leak tightness of sodium piping and components.

The reactor was designed to produce 1000 MW thermal power, 150 MW of electrical energy and 120 000 ton of water per day but has never been operated at its designed capacity. Operation of the reactor started on 29 November 1972 and since then the reactor has been supplying heat for desalination, industrial use and for electricity production. Tables I and II present the main technical parameters and operating record that were achieved in practice. The maximum output of 750 MWth was achieved in 1984. The restriction of thermal flow in the steam generators was a main obstacle for the operation of the reactor at its rated power. It is possible to increase the power up to 800 MWth. But according to the latest safety requirements, expensive modernization of the safety systems would be necessary for the power increase.

The reactor BN-350 was designed to operate for 20 years. This period ended in May 1993. Thorough inspections led to the authorities to conclude the possibility of continued operation of the reactor with safety and reliability up to 2003.

Table I. MAIN TECHNICAL PARAMETERS OF BN-350

Reactor thermal power	750 MW (th)
Inlet/outlet sodium temperature of the primary loops	288/437^{o}C
Inlet/outlet sodium temperature of the secondary loops	260/420^{o}C
Steam outlet temperature	405^{o}C
Steam pressure	4.5 MPa
Steam flow	1070 t/h
Loop number	5

Table II. PRINCIPAL RESULTS OF THE REACTOR BN-350 OPERATION FROM 1973 TO1995

Power level operation	159 921 hours
Average power	592 MW (th)
Average load factor	0.85
Refueling number	56
Number of unplanned power decrease	62
Fuel burnup	11.8 %

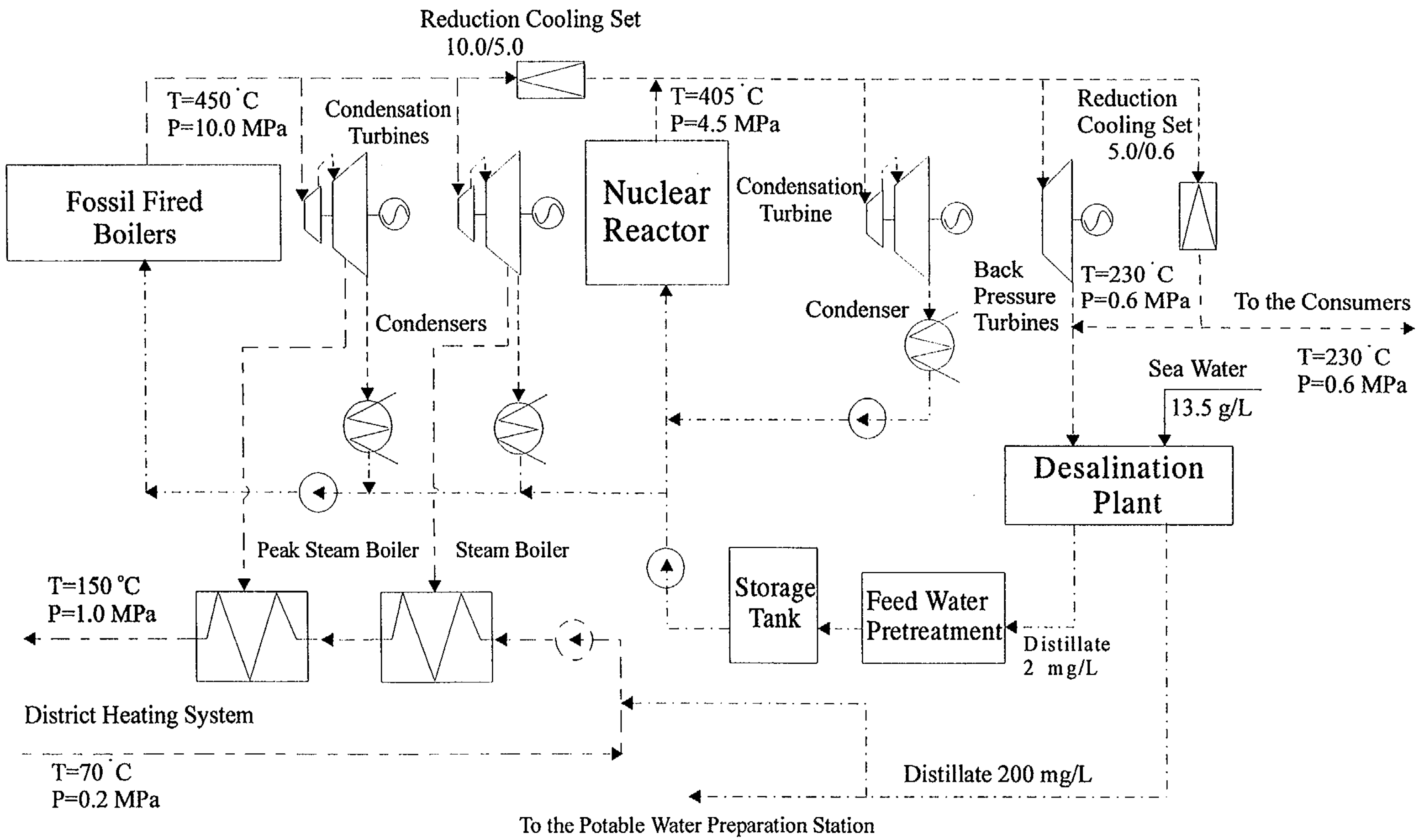

Fig.1. Principle Flow Diagram of Mangyshlak Atomic Energy Complex

2.3 Heat Application Scheme

The complex includes a thermal power station, a nuclear reactor, a condenser and three back pressure turbogenerators (Fig. 1). The exhaust steam (0.6 MPa) from the back pressure turbines is used as the heat source in the heating chambers of the first stage evaporators of the desalination plant. If more steam from the reactor is available than required for the desalination, it is used to supply heat energy to the industrial enterprises and settlements located within 7 km from the complex.

There are also some steam boilers for district heating and for hot water supply. The boilers are usually heated by extraction steam from the turbogenerators of the thermal power station. A transit pipeline exists between the thermal power station and the nuclear power station, which allows to use the 0.6 MPa steam from the back pressure turbines of the reactor for supplying heat to the district heating system.

Part of the distillates from the desalination plant is fed to the district heating system to keep the normal pressure, since hot water in the district heating system is partially consumed by inhabitants.

Pressure reducing and cooling devices are installed in order to provide redundant high grade steam of the reactor to the desalination units during the periods of low electrical power demand, or in case of turbine failures. Another set of devices can provide steam to the desalination plant from the fossil fired boilers of the thermal power station when the reactor is shut down or when steam from the nuclear reactor is not sufficient for required water production. To meet daily peak demands of water, reservoir tanks are installed for the distillates and for the feedwater of the steam generators and boilers.

The turbogenerators are in the turbine hall of the thermal power station, separate from the reactor building. Maintenance is performed by the thermal power station personnel.

There is an independent source of electric power and water which can start up the complex, even when the complex is disconnected from the regional electric grid.

3. OPERATION AND MAINTENANCE

3.1. Reliability of the operation

The reactor has been in operation since 1973, with a cumulative operating time of more than 150 000 hours. During this period, there were no significant sodium leaks in the primary and secondary loops. Abnormal operation of the sodium pumps was not observed. Cavitation damage in the driving wheels of the pumps was insignificant. In the first period of reactor operation, depressurization of the heat exchanger tubes of the steam generators was repeatedly experienced due to manufacturing defects of the tubes. When the steam generators and the water preparation system were reconstructed, one loop of the thermal section was disconnected and another loop is maintained as a reserve. Because of this reserve loop, failure of the heat exchanger tubes no longer result in a decrease in the operating power of the reactor. After a modification of the feedwater preparing system, operation of this section has become more stable (Table III). Since the nuclear reactor came into service there have been no serious problems with the reactor equipment.

Twice a year the nuclear reactor is shut down for twenty days for refuelling and scheduled maintenance. During the periods the heat for the desalination plant is supplied by the thermal power station. Such switching between heat sources for the desalination plant has been carried out regularly for more than 24 years, and no problems have arisen.

Table III. FEEDWATER CHARACTERISTICS

Conductivity, (μS/cm)	< 40.0
pH	9.1 ± 0.2
Iron, (μg/l)	< 10.0
Copper, (μg/l)	< 5.0
Total Hardness, (μg/l)	< 33.2

3.2. Safety Aspects

The anticipated events of the abnormal operation of the fast breeder reactor BN-350 include 40 initiating events. In some of them, one loop of the thermal section should be disconnected. It calls for the decreasing of the reactor power by approximately 10-12%. Sixty four such events have been experienced during the 24 years of reactor operation.

When necessary, the high-speed reactor shut down system is activated. Since 1973 there were 77 such cases when the emergency response system functioned. During the last six years, such events were not observed.

Water and steam leaks in the steam generator result in sodium-water reactions, generating hydrogen and emitting energy. But even a complete destruction of heat exchanger tubes does not cause a pressure pulsation of above 0.5 MPa. When it happens, the pressure of the water circuit is decreased quickly, and the defective loop is disconnected from the steam and water collectors. The ingress of the reaction products to the thermal section steam is avoided. These products are completely contained in the second contour and transferred to a separate tank.

There are four variants of probable failures considered for BN-350.

- Sodium leaks in the primary loop;
- Gas system tightness failure;
- Loss of sodium circulation in one of the core subassemblies;
- Damage of the core subassembly during refuelling.

None of these failures would lead to the contamination of the steam delivered to the consumers. This is supported by relevant features of the fast breeder reactor with liquid metal cooling:

- Low pressure in the reactor vessel
- Three circuits system of reactor cooling, where the first one has the lowest pressure, and the last one the highest

Owing to FBR features fast destruction of the core can be avoided. Even for such heavy failures the steam circuit of the reactor is not exposed to radioactive contamination.

Three independent water sources are connected to the deaerated water circuit and to the emergency feed water tanks: Storage of feed water for the reactor steam generators; water tanks on the thermal power station, and storage of distillate of the desalination plant. They can provide the necessary heat sink to the reactor during emergency cooling. It provides high reliability and safety of the emergency cooling of the reactor.

3.3. Emergency response systems

The emergency protection systems of the nuclear desalination plant are the same as those established for other reactors and thermal power stations. The activation of local protection systems does not have much influence on operation of the nuclear desalination plant. However the situation changes if the high-speed reactor shut down system is activated. In this case only one steam generator remains in the operating mode for reactor cooling. Steam production decreases from 700 t/h to zero within a few minutes, therefore it is necessary to increase the steam supply from the fossil fired boilers in order to keep the desalination system in service. Since it is impossible to offset such a deficit in a short time, some heat and electric power consumers have to be temporarily disconnected.

3.4. Product water quality

There are two distillate lines from the Desalination Plant: for drinking water quality for potable water production (TDS up to 200 mg/L) and for high quality water (TDS= 2 to 10 mg/L) for preparing feedwater and technological need of industrial use. The characteristics of the product water are given in Tables IV. The quality of the product water meets the WHO requirements, and does not depend on the heat source used, i.e. nuclear or conventional. The amount of radioactive substances in the product potable water is determined by the contents in the mineral water which is added to the distillate to obtain the drinking water quality. The analysis of tritium in the nuclear desalination plant streams has shown that it is at the background level, close to that of the sea or the ground water. The tritium concentration in the steam and water of the thermal sections does not exceed 1.6×10^{-10} Ci/kg, though the allowable level for the drinking water is 0.81×10^{-6} Ci/kg.

Still measures are taken to reduce the tritium concentration in the distillate for preparing potable water. The distillate streams for preparing potable water are isolated from the high quality water line where condensates of the steam from the reactor steam generators and fuel fired boilers.

Table IV. WATER PRODUCT CHARACTERISTICS

Characteristics	WHO guideline values	Distillate «G»	Distillate «A»
Total dissolved solids (mg/L)	<1000	1.96	198.6
Temperature (^{o}C)	NG	45	28
Color (TCU)	15	-	-
Turbidity (FTU)	5	-	-
Conductivity (μS/cm)	NG	4.05	326.7
pH	6.5-8.5	8.46	8.07
Total Hardness (mg/L) ($CaCO_3$)	500	0.78	66.0
Chloride (mg/L)	250	0.48	55.6
Sulfate (mg/L)	400	0.31	33.2
Calcium (mg/L)	N.G.	0.08	7.6
Magnesium (mg/L)	N.G.	0.09	8.2
Sodium (mg/L)	200	0.18	48.5
Aluminum (mg/L)	0.3	-	-
Copper (mg/L)	1.0	0.013	0.06
Iron (mg/L)	0.3	0.033	0.09
Zinc (mg/L)	5.0	-	-
Fluoride (mg/L)	1.5	-	-
Nitrate (mg/L)	10.0	-	0.27
α-activity (Bq/L)	0.1	-	-
β-activity (Bq/L)	1.0	-	-

NG - no guideline value set

The feedwater for the steam generators is partly taken from the distillate, too. The distillate is already of high quality and requires only some minor final processing for that purpose. As compared with conventional technologies, the costs of feedwater preparation for the distillate are several times lower. Regeneration of the ion exchange filters is done twice a year.

3.5. Materials and corrosion

The operating behaviour of reactor equipment made of special steel has been generally satisfactory. Cu-Ni and stainless steel tubes were used for the tube bundles of the steam generators. Repeated damage of Cu-Ni steam generator tubes have been caused by their poor durability at elevated temperatures.

Because of the high quality of the feedwater, scale depositions were not observed in the heat exchanger tubes of the reactor's steam generators or in the fossil-fired boilers.

4. EVALUATION OF PRODUCTION COSTS

The costs of water, electric power and heat depend on the cost of fuel. As the prices of gas and reactor fuel rose between 1994 and 1996, the production costs have risen accordingly. Analysis of the average data has shown that these costs increased by 10-15% when the reactor was shut down for refuelling or repair works (Table V).

TABLE V. COMPARISON OF PRODUCTION COSTS

	Reactor operation (Normal)	Gas/oil plant operation (Reactor shutdown)
Distillate (US$/t)	0.956	1.08
Electric power (US$/kW(e)*h)	0.016	0.018
Thermal Energy (US$/GJ)	1.09	1.22

5. RADIOLOGICAL IMPACTS ON THE ENVIRONMENT

A big advantage of BN-350 is its minimum radiological impact on the environment. The average emission of radioactive gases is, including argon, xenon and krypton, 0-15 Ci/d (as compared with the allowable level of 500 Ci/d. These gaseous effluents have a short period of half-lives and are not harmful to the inhabitants. Operational experience and analysis of the design basis and beyond design basis accidents of the reactor have shown that the radiological consequences at all normal and abnormal operating conditions do not have any effect on the quality of the product water and steam.

The chemical contents of the brine and the cooling water discharged into the sea are also within the allowable limits. Overall emission of the radioactive substances to the sea does not exceed 1 Ci per year, that is below 3% of the allowable level. For many years, the artificial shallow lake, in which the disposal water is aerated and cleaned, has served as a place for the wintering birds and fishing.

6. CONCLUSION

The scheme applied at MAEC in Aktau has shown high reliability and flexibility of control owing to the combined use of a nuclear reactor and fossil fuel fired boilers.

No adverse effect on the environment and no contamination of the steam and water was experienced. The radiological characteristics of the product water is not different from those of the water obtained from the traditional desalination plants, and meet the WHO standards.

Over 20 years experience of safe and successful operation of MAEC in Aktau has confirmed the high reliability and efficiency of application of nuclear energy for desalination and industrial heat.

REFERENCES

[1] NIKOLSKIY, E., LEBEDEV, P., Experience with Nuclear Desalination in Kazakhstan, Options Identification Programme for Demonstration of Nuclear Desalination, IAEA-TECDOC-898, IAEA, Vienna (1996), 111-120.

[2] BARANOV, J. S., KABLUCHKO, N. A. et al., Operating Experience of Desalination Units in Shevchenko, (Work Papers of First World Congress on Desalination and Water Re-use, IDA, Florence, Italy, 1983), Vol.2, 167-175.