

Practical Application of the RUTA Safe Pool-type Nuclear Reactor to Demonstrate the Advantages of Atomic Energy Use

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ABSTRACT

The concept of the RUTA water-cooled water-moderated pool-type nuclear reactor is presented. The basic results of findings of the RUTA-70 pilot district heating plant in Obninsk science town, Kaluga Region, Russia, and capabilities of using this for nuclear technology research purposes are shown. The basic technical data of the reactor facility are presented and its design is described in brief. Potentials of using low-grade heat in the town's heating networks have been shown. Technical aspects of using the reactor thermal power in a thermal seawater desalination facility have been considered. Issues related to application of the nuclear reactor as a neutron source for implementing modern nuclear technologies have been discussed.

1. INTRODUCTION

The efforts to develop the RUTA pool reactor launched in the late 1980s met the challenge of building an ultimately safe, structurally simple, cheap and easy-to-operate utility reactor to provide Russian cities with heating and hot water supply services. The concept of using a pool reactor as part of a nuclear district heating plant (NDHP) is based on a long-term positive experience in designing and operating pool research reactors: there are 225 research reactors in the power range from several kilowatts to 70 MW operated worldwide, including 23 NIKIET-designed reactors of which 7 are located in Russia. The simple design and low coolant parameters inherent to a pool reactor make it highly reliable with the absence of the potential of severe accidents being the assurance of radiation safety, which makes it possible to deploy facilities in the immediate proximity of consumers.

The conceptual design of the RUTA-20 (reactor facility for heat supply with atmospheric pressure in the reactor) with a thermal power of 20 MW was issued in 1990. This development was given prominence at the ASMM-91 contents of small-size nuclear plant designs held in 1991-1992 under the auspices of the Russian Nuclear Society.

Later on, the RUTA design options with a thermal power from 10 to 55 MW were developed at a conceptual level.

The concept of using the RUTA pool reactor to desalinate seawater was developed in 1997. This included a reactor core consisting of two portions: one of these was the central part similar to that of conventional research reactors while the lateral part was formed by an assembly of modular channels capable to generate high-pressure steam to drive a small-size turbo-generator set. This facility produced up to 65 MW of thermal power and over 3 MW of electric power to operate the desalination plant pumps. When multistage distillation facilities were used, the fresh water output reached 35,000 m³/day (ROMENKOV A.A. et al., 1997). The results of using the RUTA pool reactor thermal power

to produce cold water for air conditioning purposes in hot-climate countries were published the same year (ADAMOV E.O. et al., 1997).

To upgrade the research equipment of Russia's Federal Nuclear Center in Obninsk, Kaluga Region, the proposals were developed in 2001-2004 for the 70 MWt RUTA multipurpose reactor facility. This project combines the functions of a nuclear district heating plant (NDHP) and a research reactor, including potential use of the reactor as a neutron source for medical and technological applications.

A concept of a multipurpose complex based on the RUTA-IT reactor facility of 35 MWt was developed for the Nuclear Technologies Park in the Republic of Kazakhstan. Thus there has been a sustained public interest in the RUTA project since 1980 (during 27 years!). This can be attributed to high safety features of the reactor and its ability to perform a great deal of research and economic functions. So why has not it been built in Russia to date? The major reason is certainly the Chernobyl disaster which virtually led to the suspension in the development of nuclear power worldwide. The second and not the least important reason is that gas used for heating in Russia is relatively cheap. At present time, as the domestic gas price is nearing the international market prices, the project has been facing a renewed interest. And the third reason is that nuclear installations cannot be legally privatized in Russia. The latter is important because the RUTA reactor produces municipal-scale heat and is scarcely attractive to the key private players in large regional power markets.

2. DESIGN OF THE RUTA-70 REACTOR

The RUTA is a pool reactor facility with a water-cooled water-moderated reactor of thermal power of 70 MWt (Figure 1).

The following design approach has been taken with respect to the reactor's major components and to the selection of the primary circuit flow area geometry:

- in the power range from the lowest level of $\approx 30\%$ N_{nom} and in the cooldown mode (both regular and emergency), the core is cooled and heat is transferred in the primary heat exchangers to the secondary coolant with natural coolant circulation in the reactor;
- for the heat loads from $\approx 30\%$ N_{nom} to 100% N_{nom} the connection of reactor pumps is provided and flow rate is increased in the in-pile circulation circuit.

The forced circulation mode is enabled by axial pumps installed in the natural circulation circuit bypass upstream of the downcomer inlet (Figure 1(a)). Then, the coolant goes to the reactor core (Figure 1(b)) where water is heated. The reactor power is regulated using the CPS drives (Figure 1(c)), which are in the reactor pool water. It should be noted that the CPS absorber cluster rods are flexible and the clusters as such are controlled from the core bottom (Figure 1(d)). The scram rods have an individual two-position hydraulic drive enabling full withdrawal or full insertion of the rods. Heat is removed from the core in plate-type heat exchangers of A-Laval company (Figure 1(e)).

Actually, natural circulation is capable of ensuring the core cooling at power levels up to 50% N_{nom} . At the same time, use of the pumps installed in the reactor circuit and application of forced coolant circulation for operations at power levels of $30\div 100\%$ N_{nom} make it possible to increase the coolant flow rate in the primary circuit and raise the downcomer temperature by reducing water heating in the reactor core.

The reactor core is located at the bottom of the vessel cavity and consists of 91 hexagonal FAs with fuel rods. Under consideration are two fuel element versions, one being of the VVER-440 type and containing uranium dioxide fuel in a zirconium cladding and the other being cermet-based (UO_2 granules in a silicon matrix with the UO_2 volume fraction of 0.6) in a zirconium cladding. The FA structural material is a zirconium alloy. The FAs are arranged in a triangular lattice with a pitch of 147 mm and form a regular and symmetric system. The reactor core height for the first and the second fuel versions is 1400 mm and 1530 mm respectively. The equivalent diameter of the reactor core for both versions is 1420 mm.

The basic technical data of the RUTA-70 reactor facility are presented in Table 1. The spent fuel pool is situated next to the reactor and is connected with the primary water through water via the refuelling channel. Assemblies are reloaded manually beneath the water layer as in research reactors.

2.1 Application of the RUTA reactor for district heating

A general solution as to the district heating technology is combined application of nuclear power sources (base load generation) and conventional fossil fuel power sources (peak load and intermediate load generation).

This combined technology of operation of an nuclear reactor and standby-peaking boiler is suitable in districts which have sufficient outside electric power supply but lack in fuel for heating plants (Figure 2).

Table 1. Basic technical data of the RUTA-70 reactor

Maximum thermal power of the reactor (N_{nom}), MW	70
Coolant circulation in the primary circuit: - up to 30% N_{nom} ; - from 30 to 100% N_{nom} ;	Natural Forced
Core heat removal mode	Two-circuit
Pressure in the air space over the reactor	Atmospheric
Core dimensions (equiv.diameter/height), m	1.42/1.4 (1.53)
Fuel	UO_2 ; cermet (0.6 UO_2 + 0.4 Al alloy)
Uranium-235 enrichment of fuel, %	4.2
Uranium load in the reactor core, kg	4165
Number of FAs	91
Fuel life, eff. days	2332
Cycle length at capacity factor of 0.7, years	3
Fraction of core reloaded each cycle	1/3
Water amount in the reactor tank, m^3	250
Core temperature (inlet/outlet), $^{\circ}C$	75/101

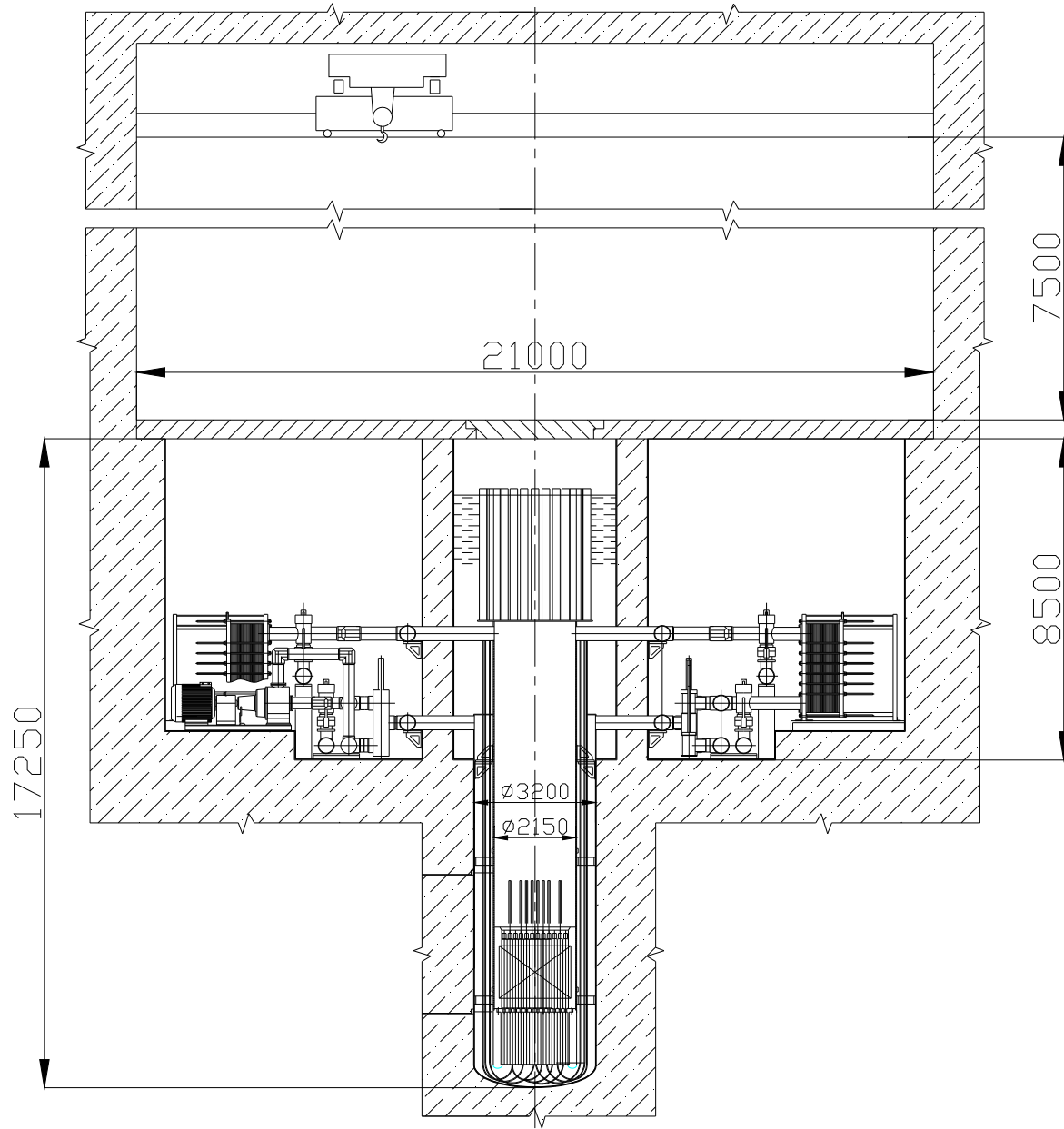


Figure 1: Sectional view of the reactor department

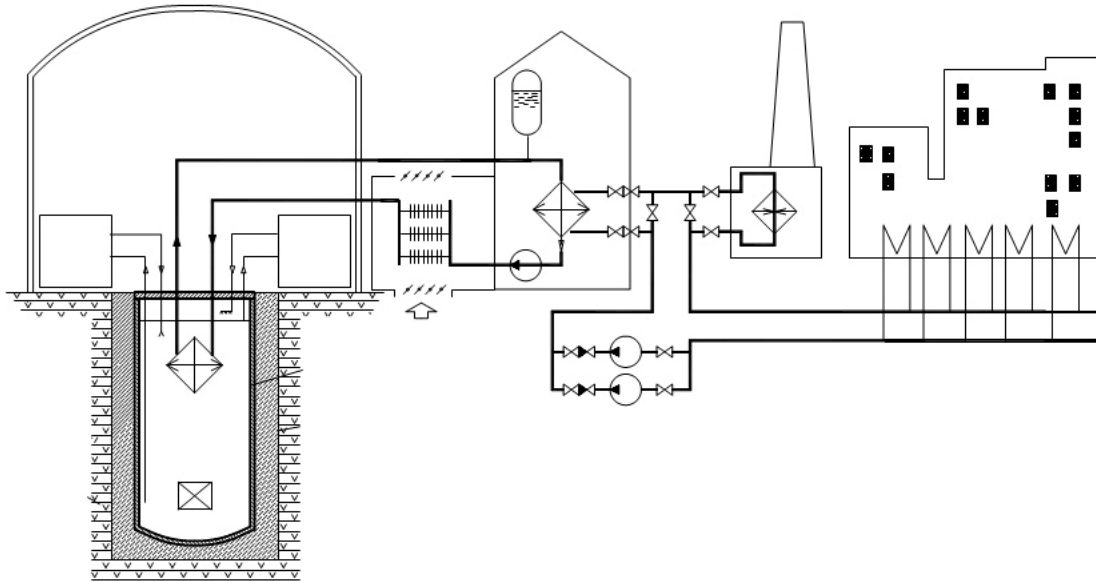


Figure 2: Schematic of the nuclear heat source connection to the district heating network

Studies to optimize the components of water heating plants in heat supply systems prove the expediency of ensuring redundancy and thus attaining the required reliability through the use of fire-powered or electric water heaters (Figure 2 (d)).

The RUTA reactor facility has a two-circuit layout. The primary circuit (Figure 2 (a)) is an in-pile reactor core cooling circuit and the secondary circuit (Figure 2 (b)) is an intermediate one that removes heat from the reactor and transfers it to the third circuit (Figure 2 (c)), which is the consumer circuit, i.e. to the heating network. Heat is transferred from the primary circuit to the secondary circuit and from the secondary circuit to the third circuit through the leak-tight heat-exchange surfaces which are used to avoid the spread of radioactive products from the reactor circuit to the consumer.

The smallest staffing of the operating shift is 4 persons. These are NDHP Shift Supervisor, Chief Reactor Control Engineer, a fitter-walker for normal operation systems and a duty electrician for attendance of electrical devices and systems, instrumentation and the control. Respective services are responsible for radiation monitoring during operation and repair. A supervising physician and a refueling operator from a specialized organization are added to the regular shift staff for the core fueling, first criticality attaining, power startup and refueling periods. Inspection and repair of the NDHP systems and components are done by hired personnel.

With managers, engineers and technicians working in one shift (chemical engineer, engineer for electrical devices and systems, engineer for instrumentation and the CAPCS) and the administrative staff taken into account, the total personnel number is about 40 persons.

2.2 Application of the RUTA reactor as a neutron source

Given the diversity of tasks and concerns faced by research and production organizations of Obninsk, an important consideration that favors the construction of the RUTA facility in this city is that it can be used in multipurpose applications:

- production of a broad range of medical and commercial radionuclides;
- neutron-transmutation doping of silicon monocrystals for modern microelectronics; generation of neutron beams for ray and neutron-capture therapies;
- irradiation of thin polymer films for subsequent production of track membranes;
- neutron-activation analysis of ores, minerals, etc.
- For these applications, it is possible to fit the reactor with the following irradiation devices:
 - irradiation channels in the reflector blocks;
 - not less than 8 radioisotope production channels;
 - a channel for neutron-transmutation doping of silicon ingots;
 - 2 rabbit channels (pneumatic post) for neutron-activation analysis;
 - external irradiation devices with neutron beams;
 - 1 fast-neutron therapy (FNT) channel;
 - 1 neutron-capture therapy (NCT) channel;

- 1 channel for irradiation of polymer film used to produce track membranes.
- The channels of irradiation devices are situated above the reactor core in special tube structures which are lowered into the core. The horizontal neutron beam channels are used to produce track membranes and for medical purpose.

Table 2 presents characteristics of fluxes for neutron groups, which are conditionally designated as fast (f), epithermal (et) and thermal (t), in the core center and at locations of special channels and devices as of the beginning (b) and the end (e) of the operating cycle. For cells of the reflector row 1, it shows the spread of the neutron flux values depending on the location of the cells and fuel burnup.

The adopted design approaches provide for such in-pile arrangement of special-purpose channels and devices that ensures as small effects on the neutronic and fuel characteristics of the core as possible while meeting the specific requirements to parameters of the neutron fluxes in the irradiation channels and devices.

2.3 Nuclear desalination of seawater using the RUTA reactor

Application of the RUTA reactor as a heat source for distillation plants is considered (Figure 3). Seawater is desalinated in distillation desalination plants (DDP) with horizontal-tube film units. A relatively low temperature of the heat generated by the reactor has required special designs to provide for as high distillate output of the nuclear desalination complex (NDC) as possible. The layout combining a reactor facility and a desalination plant includes steam generating equipment. The steam generation circuit is designed as the third circuit loop of the reactor facility. The number of such loops connected in parallel to the common header depends on the number of desalination modules in the NDC. Each multistage desalination module is equipped with a preliminary multistage self-evaporator which partially evaporates the third circuit water to heat the first DDP stages. Distillate is used to make up for the third water losses.

Structurally, the self-evaporator is a part of the desalination module and is installed immediately next to the cascade of the evaporation stages. Such layout with the preset reactor heat parameters makes it possible to achieve the maximum boiling temperature of ~80 °C. The daily output of the NDC comprising one reactor and four desalination modules is around 35 000 m³/day.

3. SAFETY ASSURANCE

Pool reactors are fairly widespread worldwide and used largely for research purposes. They are rather commonly deployed within urban residential areas. High safety level of pool reactors is achieved through their design features which make it possible to resolve some of the major safety issues thanks to employing naturally inherent properties of the reactor. In a general case, the advantages offered by this reactor type are:

- no excessive pressure in the reactor tank (pool) which makes it possible to avoid accident with an instantaneous reactor tank rupture and loss of heat removal from the reactor core because of its uncovering;
- a large amount and, therefore, high accumulating capacity of the reactor pool water which ensures slow change of the coolant parameters during transients and emergencies and reliable heat removal from the fuel elements even if there is no controlled heat removal from the reactor core.

Apart from these features inherent in this reactor type, the design approaches used in the RUTA project give the reactor the following essential safety properties:

- Stabilizing reactivity feedbacks determined by negative fuel and coolant temperature reactivity coefficients and by the positive density reactivity coefficient. This means that heat-up of the core structural components, including fuel, or water boiling in the core results in spontaneous reduction or self-limitation of the reactor nuclear power at any initial position of the control rods, including the scram rods;
- In the range of operating modes at power levels from the minimum controlled power level to 30 % N_{nom} heat is removed from the core thanks to natural coolant circulation in the reactor thus ensuring reliable cooling of the fuel and passive cooldown of the reactor when it is shut down;
- Natural circulation in the secondary circuit provides for residual heat removal from the shut down reactor and passive cooldown of the reactor facility in blackout emergencies;
- The loop arrangement of the primary circuit components with the secondary circuit pressure exceeding the pool water pressure makes sure that the reactor coolant is localized within the reactor tank.

In development, the RUTA pool reactor had its safety enhanced considerably thanks to implementing the defense-in-depth concept. This provides for several levels of devices, systems and operations to ensure the performance of the basic safety functions such as:

- o control of the reactor power;
- o heat removal from the core;
- o confinement of radioactive product release.

Neutron energy in the group	Central FA		Reflector row 1 (radioisotope production channels)		Silicon doping channel		FNT channel, bottom (Al)		NCT channel, bottom (Al)		Graphite TM column (layer in the region of the water downcomer)	
	b	e	b	e	b	e	b	e	b	e	b	e
ϕ_f (0.1-10 MeV)	12.1	7.6	1.0÷2.6	1.4÷2.1	0.13	0.16	1.3	1.5	0.83	1,0	$7.71 \cdot 10^{11}$	$7.86 \cdot 10^{11}$
ϕ_{et} (1 eV-100 keV)	5.8	3.7	1.1÷2.4	1.3÷1.9	0.11	0.13	1.2	1.4	0.76	0.89	-	-
ϕ_t (<1 eV)	3.8	2.6	7.0÷9.6	6.0÷6.5	1.8	2.3	4.6	5.4	2.8	2.9	$1.28 \cdot 10^{13}$	$1.36 \cdot 10^{13}$

Table 2: Neutron fluxes in the reactor core center and at locations of irradiation channels and devices as of the beginning and the end of the life, $10^{13}/(cm^2 \cdot s)$

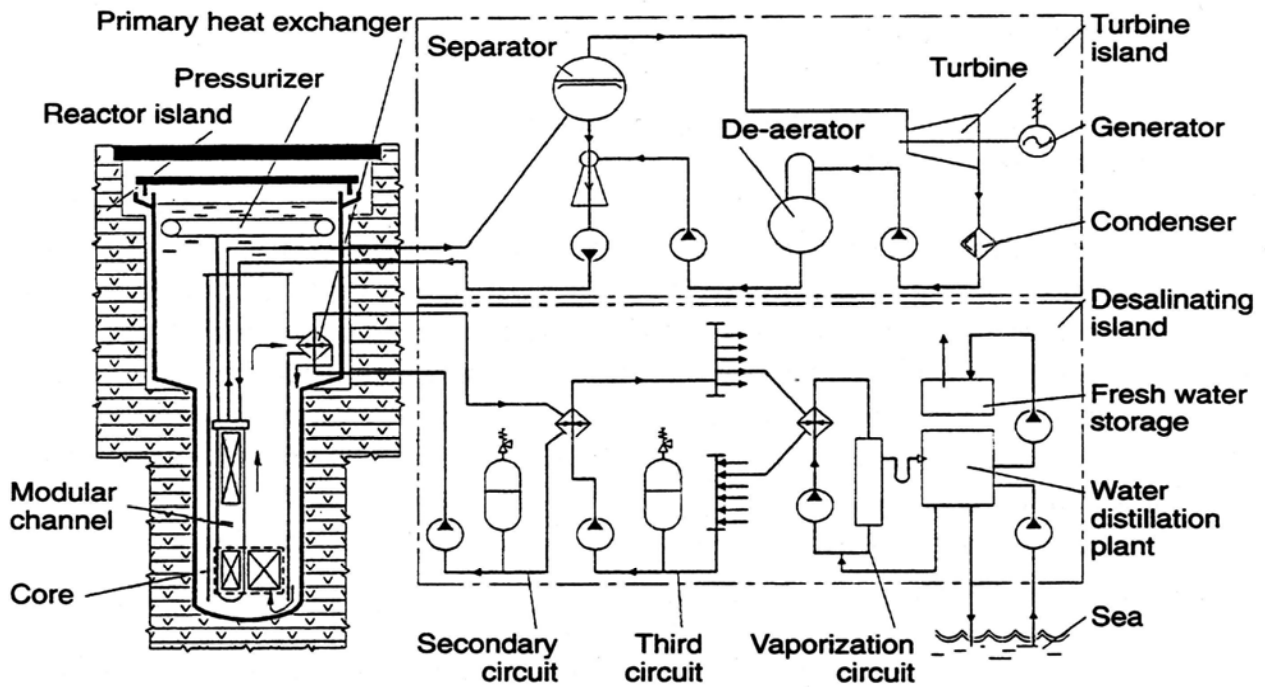


Figure 3: Seawater desalination using the RUTA reactor with modular channels for electricity production

To enable the reactor power control function, two independent reactor shutdown systems are provided. One of these performs the scram functions and the other, when actuated, ensures guaranteed subcriticality for an unlimited time and with regard for any reactivity change effects, including emergency ones. Each of the systems performs its functions when at least one most effective control rod fails. When the CPS is de-energized, all CPS rods are inserted into the core by gravity.

Heat is removed from the reactor core via two independent channels. Each of these has three circuits with consecutive pressure increase from the primary circuit via the secondary (intermediate) circuit to the third (network) circuit, which precludes ingress of radioactive products to the network coolant.

During anticipated operational occurrences and in emergencies, residual heat is removed thanks to natural coolant circulation in the reactor tank and in the secondary circuit in case of loss of power. When this happens, heat is removed from the secondary circuit through the emergency cooldown air system convectors with circulation of the air in the convector rooms.

The basic approach to assurance of the RUTA facility safety is consistent implementation of the defense-in-depth concept based on using a system of physical barriers to prevent release of ionizing radiation and radioactive substances into the environment and a multilevel system of engineered and organizational features to protect the barriers and keep them efficient. The system of physical barriers includes:

- the fuel matrix;
- the fuel cladding;
- a steel-lined reinforced-concrete reactor vessel (pool) with a leak-tight lid;
- a leak-tight heat-exchange surface of the primary heat exchangers;
- leak-tight enclosures of the central hall rooms and the systems connected to the primary circuit;
- leak-tight components and pipelines of the secondary circuit and leak-tight heat-exchange surfaces of the secondary and third circuit (network) heat exchangers.

Ingress of radioactive substances from the reactor to the network water is avoided through the following additional design approaches:

- the choking ratio of pressures in the heat exchangers of the reactor facility's primary and secondary circuits (the design-required top position of the secondary circuit relative to the reactor pool ensures that the secondary coolant pressure exceeds the reactor coolant pressure even when the secondary circuit loses the design-specified excessive pressure in the event of depressurization);
- the choking ratios of pressures in the secondary and third circuit heat exchangers.

The pressure reduction from the network circuit side in the heat exchanger may be caused by disconnection of the heating network or by depressurization of the heat supply line. Interim loss of heat removal from the secondary circuit in such situation does not require prompt shutdown of the reactor and the reactor response

to the excitation caused by the decreased heat removal will be rather slow. The danger of the network circuit contamination, even if there are leaks in the network heat exchanger is excluded thanks to absence of radioactive products in the secondary coolant.

4. CONCLUSIONS

Thanks to the reactor design approaches and low coolant parameters, the RUTA facility features high reliability, ultimate safety and environmental friendliness, which makes it possible to deploy NDHPs with the RUTA reactor in the immediate vicinity of the heat consumers. The simple reactor design and reactor facility's major systems ensures good economic indicators with relatively low capital costs contributing to the low cost of produced heat.

Studies show that the construction of the first-of-the-kind unit with the RUTA reactor in Obninsk, Russia, will pay back the investments through the heat supplies to consumers. At the same time a wide range of scientific development and application of modern nuclear technologies in production of new materials and advancement of medicine is carried out.

Development of innovative nuclear technologies based on the RUTA facilities appear to be promising also for other RUTA deployment places. The most attractive sites are cities involved in nuclear industry both in Russia and abroad, as well as research centers.

The construction of a multipurpose RUTA complex will provide the countries being at the initial stage of developing their own nuclear programs with a capability to create and commercialize advanced and cost-effective nuclear power technologies. This primarily includes arrangement of production facilities and services based on nuclear and radiation technologies, creation and expansion of the applied scientific research framework, training of research and operating personnel for nuclear power plants as well as nuclear heat supplies to consumers.

5. ABBREVIATIONS

- CPS:** Control and Protection System
FA: Fuel Assembly
NDHP: Nuclear District Heating Plant

6. REFERENCES

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- [2] ADAMOV E.O. et al. (1997), Inherently safe pool reactor as a generator of low-grade heat for district heating, air conditioning and salt water desalination, *Nuclear Engineering and Design*, 173, pp. 167-174.