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AN AUTONOMOUS NUCLEAR POWER PLANT WITH INTEGRATED NUCLEAR STEAM SUPPLY SYSTEM DESIGNED FOR ELECTRIC POWER AND HEAT SUPPLY IN REMOTE AREAS WITH DIFFICULT ACCESS

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Abstract

The paper contains basic conceptual principles used to develop the technical assignment for an autonomous nuclear power plant with integrated nuclear steam supply system (NSSS) designed to provide heat and electricity for areas *which are remote with difficult access*. The paper also describes technical procedures and equipment, NPP thermal hydraulic flow chart, steam generator design, safety aspects as well as operational and maintenance procedures.

1. *Introduction*

In areas of Russia which are remote with difficult access, for instance in the Extreme North, Far East, or Siberia a possible reasonable alternative to fossil-fuel energy sources, mainly hydrocarbon, is autonomous nuclear power plants (NPP) of relatively low capacity, shipped to the site in large modules and completely withdrawable from the site upon decommissioning. For the areas in question, small setllements and enterprises with low power demand are typical. The complexity of constructing electric transmission lines, gas pipelines, liquid fuel pipelines, and high cost requires to use local self-contained energy sources. Application of NPPs for power and heat supply may be cost efficient and promising from social and ecological point of view.

A necessity arises to develop new approaches to designing these power sources, naturally, taking into account the experience gained in reactor construction based on modern safety level. Such approaches are to be based on:

- use of well proven technology of water-cooled reactors, in particular, those used at transport facilities with adequate optimisation of their characteristics;
- maximum use of equipment which has operational field-checked prototypes;
- use of designs with inherent safety features;
- maximum ecological safety of NPP considering nature specifics in the Extreme North and Far East of Russia extraordinarily sensitive to production activities
- preservation of the natural landscape, flora and fauna due to NPP delivery and removal in large plant-manufactured modules which minimize erection and dismantling jobs at the site;
- minimal capital investments and operating costs to make such NPP competitive with conventional fossil power plants.

The paper briefly describes possible implementation of these approaches using a NPP equipped with the integrated nuclear steam supply system.

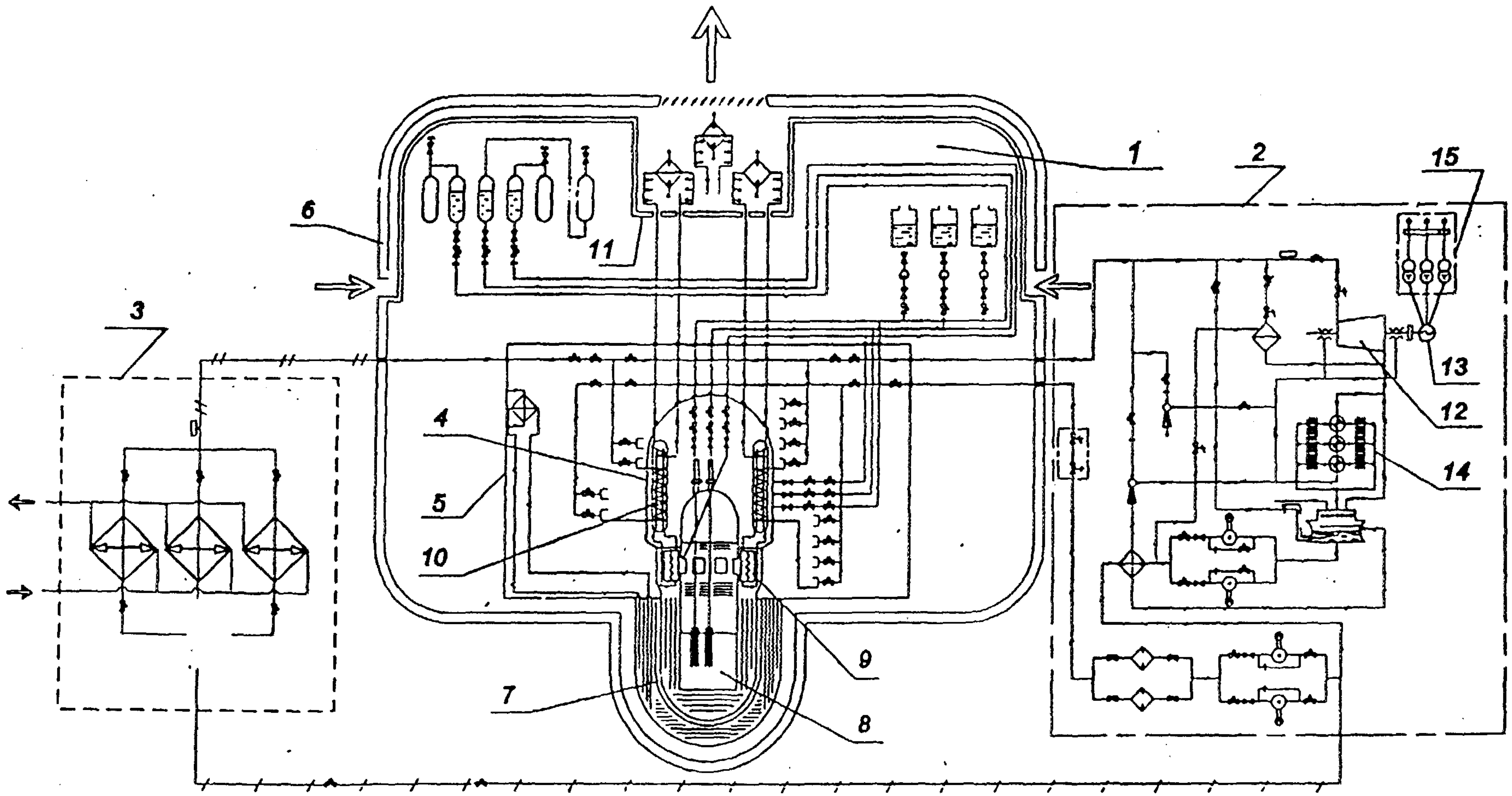

Fig.1. UNITHERM NPP Diagram

1 - Reactor unit; 2 - turbine unit; 3 - heat supply unit; 4 - safeguard housing; 5 - contaiment ; 6 - shock-proof casing; 7 - steam generating unit; 8 - core; 9 - intermediate circuit heat exchanger; 10 - steam generator; 11 - emergency cooling system heat exchanger; 12 - turbine; 13 - generator; 14 - air cooled condenser; 15 - transformer unit

2. *Selection of thermal and technical parameters of a nuclear power plant (NPP). Integrated nuclear steam generating unit design and its main components*

The UNITHERM NPP thermal-hydraulic cycle (Fig.1) includes three interrelated process loops, the last of which accommodates all heat consumers (turbine-generator unit and heat system or process steam boilers).

Selection of coolant parameters for the above-mentioned process loops was based on the proven range of operating pressures and temperatures typical for NPP water-cooled reactor primary circuits, and on the experience with mobile NPP operating with primary coolant natural circulation. Besides, variation limits of the primary coolant parameters without reactivity compensation of nuclear fuel burnup by control rods were taken into account. On the other hand, selection of coolant operating temperatures and pressures for the intermediate and steam-turbine loops was greatly influenced by the conditions which could provide acceptable efficiency and orientation on the development and operating experience with steam turbine units that might be considered as existing prototypes. The analysis of thermal characteristics of steam turbine units of such type enabled selection, taking into account the above reasons, of coolant parameters for the process loop of heat consumers.

Transport of heat from the primary circuit to heat consumers during the phase change in the intermediate loops reduces the required coolant flows and increases pressure in the natural circulation system, while the desire of optimal distribution of the available temperature difference between the coolants of the primary and third circuits determines the intermediate loop coolant parameters. Considering the above reasons, the parameters of the UNITHERM NPP process loop coolants are as in Table 1 below.

Table 1

The UNITHERM NPP process loop coolant parameters

Parameter	Value
Primary coolant parameters (high-purity water of NPP primary coolant quality):	
pressure, MPa	16.0 ... 16.5
core inlet temperature, °C	245 ... 225
core outlet temperature, °C,	325 ... 305
Intermediate loop coolant parameters (water of NPP secondary coolant quality):	
pressure, MPa	3.0
temperature, °C	234
Heat consumer loop coolant parameters (water of NPP secondary coolant quality):	
pressure, MPa	1.0 ... 1.2
steam temperature, °C	207 ... 210
feedwater temperature, °C	45 ... 60

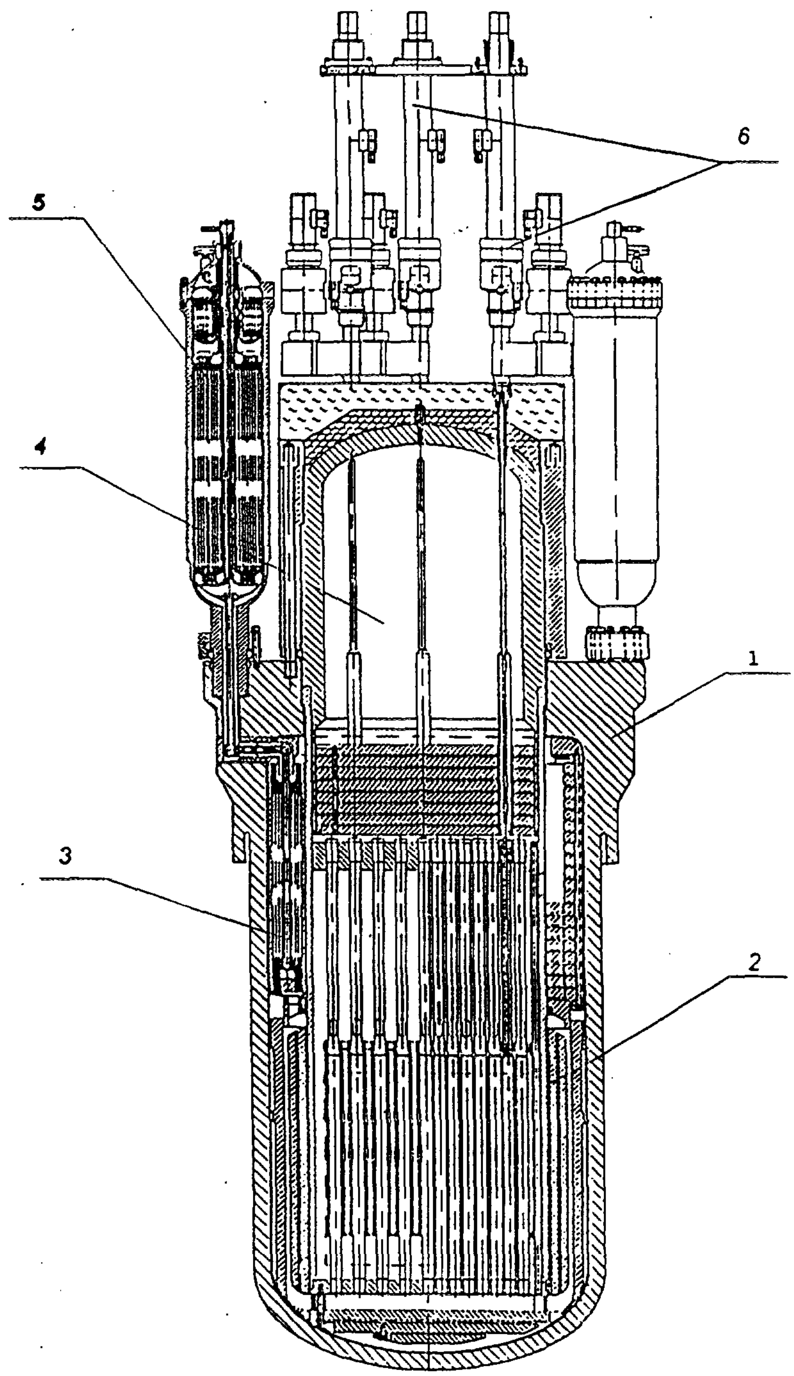

Fig.2. Nuclear Steam Supply System
1 - Vessel; 2 - core; 3 - intermediate circuit heat exchanger;
4 - pressurizer; 5 - steam generator; 6 - control rods drive

The proposed UNITHERM NPP has been designed to employ integrated water-cooled NSSS as a heat source (Fig. 2). NSSS combines in one vessel the main primary circuit components - core, steam generator (SG), pressurizer, control and protection elements. This allows to avoid primary circuit pipework, reach extremely compact location of ionizing radiation sources and potentially dangerous working fluid - primary coolant. The NSSS design ensures core cooling and heat supply to steam generator by convection of primary coolant and thereby allows to eliminate forced circulation. Such approach to the design of the NPP main component - nuclear reactor - is necessary to reach maximum possible reliability and simplicity due to absence of active elements with continuously moving mechanical parts. The group of absorbers with associated drives, which perform the function of emergency protection and compensation for reactivity variation, is a single movable element. The absorbers are displaced once during NPP continuous operation when starting NSSS unit in normal operation. In emergency situations it is possible to drop the absorbers which perform the function of emergency protection.

The integrated NSSS vessel made of 15X2MFA-A steel with corrosion-resistant cladding consists of the shell with welded elliptical bottom and flange.

The central part of the vessel accommodates the removable shield with the core, lattices of absorber rods and devices of additional emergency protection. The thermal shield which also functions as core reflector and radiation and thermal shield, is arranged around the removable shield in the bottom section of the vessel.

Inside the removable shield above the core there is a cavity with pressurizer equipped with a set of flat screens serving as upper radiation shield.

In the annular space between vessel and removable shield the steam generator tube system banks are located. Intermediate circuit heat exchanger is heat exchanger with coil-type heat transfer surface, where primary coolant moves in the tubes while the intermediate circuit fluid moves in the intertube space. The heat transfer surface is made up by 24 banks of the same type, the shells of which are designed to withstand the primary circuit pressure. The banks are pairwise combined into 12 assemblies which are connected to 12 sections of the intermediate circuit heat exchanger.

Steam collecting headers and water distribution chambers of intermediate circuit heat exchanger sections are located in the vessel flange area.The chambers are also connection points of SG sections to the NSSS vessel. The shell of each SG section is a cylindrical vessel with welded spherical bottom with a coil-type tube system inside cooled by the coolant from the heat consumer circuit. In each section of the SG above the tube system the coil-type system of independent cooldown circuit is arranged. From the top the shell is closed with a spherical head.

In the choice of characteristics and structure of the core and its control elements the following priority concepts have been adopted:

- maximum possible reduction of operative reactivity margin, in particular, the fraction of total efficiency of shim elements, per group of absorber rods with individual drive;
- optimal power, coolant temperature and fuel feedback factors;
- specific power density (about 15 kW/l) which guarantees specified long-term operation without fuel element clad leaking, and minimum specific levels of residual heat release for reliable heat removal in severe accidents;
- increased reliability of emergency core chain reaction suppression system by using in the control system of additional passive emergency protection channels with operation mechanism differing from that of main functional components.

To reduce core overall reactivity the adopted design philosophy excludes withdrawal of control elements from the core in power generation mode during continuous NPP operation. In this period, the core operates in self-control mode due to variation of coolant average temperature and absorber burnup.

The additional emergency protection actuator is a structure with leaktight vessel, which by its lower part enters the core instead of one fuel assembly, while the upper part is flange connected to the NSSS vessel head. Inside the actuator vessel, actuating element consisting of the accumulator with absorber and interconnected receiving chamber made of two elastic membranes. The space between the vessel and the actuating element is filled with nitrogen, control fluid. Gas (He-3 or boron trifluoride) is used as absorber.

When there is no emergency signal, the membranes of the receiving chamber are under control fluid pressure and the absorber is displaced into the accumulator. The emergency signal activates the electromagnetic switch and control fluid is discharged to the NPP containment volume. By its pressure in the accumulator the absorber is displaced to the receiving chamber spacing the membranes apart. To return additional emergency protection to initial position, the control fluid from the tank outside NSSS vessel is fed to the actuator which compresses the membranes and displaces the absorber to the accumulator.

3. *Design Safety Aspects*

In accordance with modern NPP safety approaches, radiation exposure on personnel, population and environment in normal operation and design-basis accidents should not lead to excess dose rates for people, and in beyond design-basis accidents, this effect should reasonably limited. To this end, technical and organisational measures are taken to ensure safety with any initiating event envisaged by the design with superposition of one failure independent of the initiating event of any of the following safety system element: active or passive element with mechanical movable parts or one personnel error independent of the initiating event. Besides one failure independent of the initiating event, it is necessary to take into account the nondetectable failure of elements affecting safe operation, which are uncontrolled in operation, and influencing accident propagation.

Safety of the UNITHERM NPP is achieved by a complex of technical solutions among which the following are worth mentioning.

The NPP employs water-moderated, water-cooled reactor with inherent safety features which reflect its capability of keeping safety on the basis of internal feedbacks, natural physical processes applying passive residual heat removal systems and automatic protection devices which ensure chain fission reaction suppresion without intervention of operator. The UNITHERM NPP is also capable of self-controlling chain fission reaction due to negative temperature, power and void coefficients of reactivity. The core physical characteristics are so selected that the above coefficients are negative in the entire range of temperatures during the core life both in normal and emergency operation modes. This eliminates spontaneous core power excursion in normal startup and heatup and stabilizes operation in steady-state and transient conditions when heat consumer circuit modes of operation change.

After NSSS is started up and brought to a preset load, moving of shim groups upwards is mechanically blocked thereby eliminating possibility of unauthorized introduction of additional positive reactivity.

The NSSS design is such that all potential leak initiation locations are in the top part of the vessel with limiting equivalent leak diameter sufficiently small and not exceeding DN 20. The integral layout of NSSS unit with rather efficient iron-water radiation shield between the core and wall of NSSS vessel excludes vessel brittle fracture because of metal neutron irradiation. All this allowed to exclude accidents associated with large and medium leaks, and prevent dangerous propagation of accidents due to core dryout. To this end, the containment (Fig. 3) is used designed for localization of primary leaks within the inner volume. The use of three-section liquid

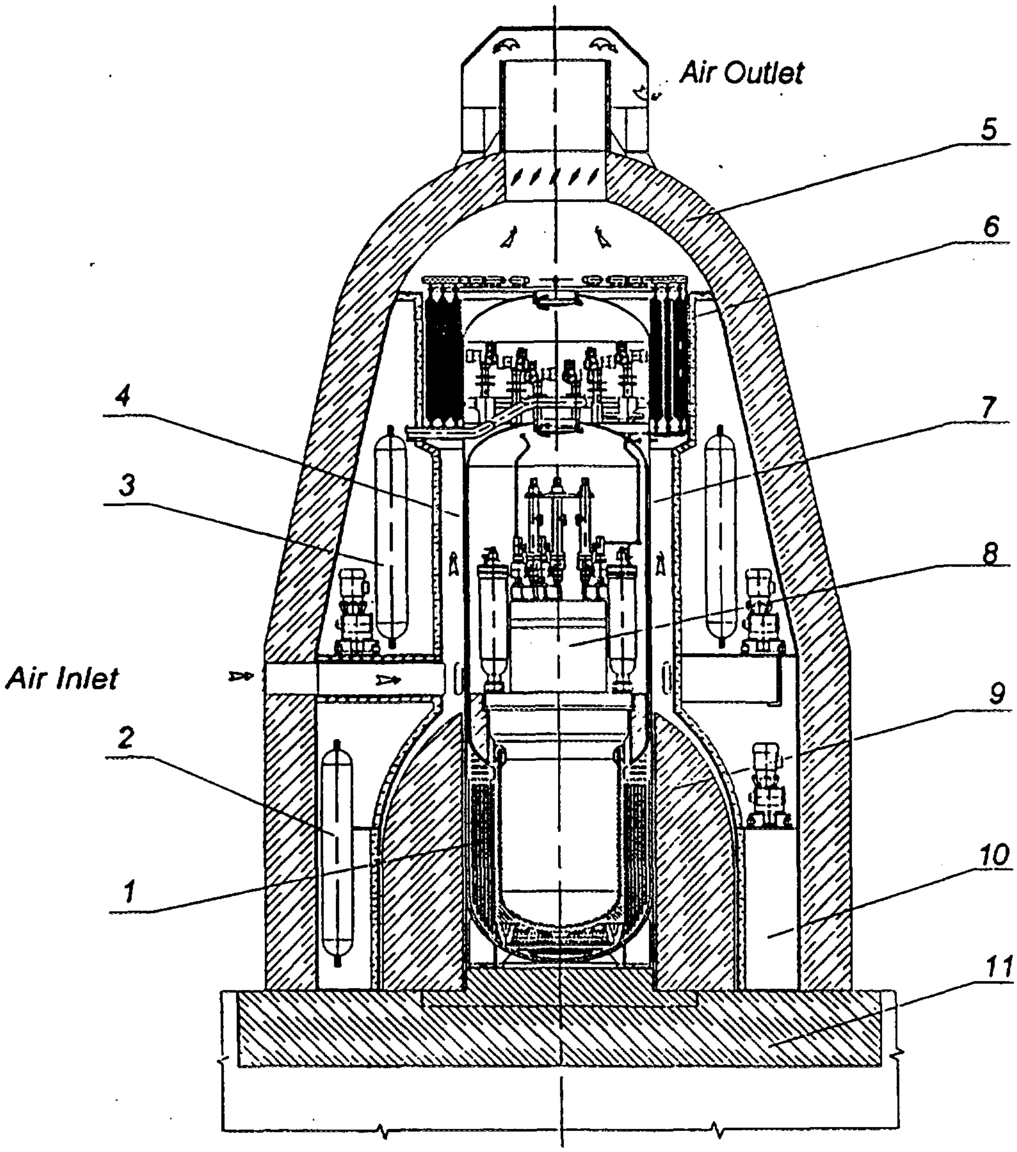

Fig.3. Reactor Plant
1 - Iron-water shielding tank; 2 - radioactive gases storage cylinders; 3 - liquid absorber supply system; 4 - containment; 5 - shock-proof casing; 6 - cooldown system heat exchanger; 7 - safeguard housing; 8 - steam generating unit; 9 - biological shielding blocks; 10 - liquid and solid wastes storage tanks; 11 - basement

absorber feed system ensures flooding this part of the containment in the emergency situation under consideration with liquid medium up to the level above potential primary circuit depressurization points which completely eliminates core drying in any design initiating events or accident scenarios. Thus, as a maximum design-basis accident it is possible to consider the primary circuit leak of conventional equivalent size of DN 20 max. The estimates showed that propagation of such an accident follows the scenario typical for the small leaks in containment without deterioration of its leaktightness and core damage. This is contributed by reasonable emergency cooling core system (ECCS) redundancy and its passive principle of operation using no forced circulation means.

Incorporation into the UNITHERM NPP of additional localizing safety barrier - safeguard housing - enables even in the case of beyond design-basis accidents due to containment depressurization practicale to eliminate radioactivity release to the environment and risk of core drying. Beyond design-basis accident due to containment depressurization and postulated damage of 10 % of fuel elements and primary coolant and radionuclides discharge to the safeguard housing does not lead to significant radiation damage for population and individual exposure will not exceed 0.11 rem/y.

The UNITHERM NPP three-loop thermal-hydraulic design when consumers even with two consecutive interloop leaks can be reliably protected by reasonably redundant shut-off and cut-off localizing valves against radionuclides discharge to heat consumer circuit, and against harmful effect of ionizing radiation on personnel.Thanks to this, NPP personnel is beyond the area of ionizing radiation and the ionizing radiation rate on the NPP protection surfaces does not exceed the background values in normal operation. The dose rate of ionizing radiation in maximum design-basis accident 100 m away from NSSS is only by 10% above the background level.

Special attention has been paid to NPP UNITHERM emergency core cooling system (ECCS) which plays the important role in safety assurance. This was mostly due to the fact that because of inapplicability of traditional technical solutions we had to search for new ones taking into account not only general approach to NPP design, but climatic conditions of the NPP site as well.

The ECCS is designed as independent process loop associated with the intermediate loop. In emergency situations, the heat removed from the core via steam generators arranged within the NSSS vessel is fed to the intermediate loop,and further, through heat exchangers of the loop, is removed, via independent ECCS, to its heat exchange surfaces cooled by atmospheric air. The low winter temperature level in UNITHERM NPP application areas demands the selection of low-boiling coolant of the aforementioned independent loop of ECCS. To this end ammonia may be used.

Specific features of ECCS is that it does not have isolating and cut-off devices, i.e., the system is in continuous operation. Therefore, marked seasonal ambient air temperature fluctuations may greatly influence the amount of heat discharged through the system to atmosphere. So, in summer the capacity of heat removed through the system is 3-4 % of the nominal NPP heat capacity, the respective figures in winter may increase as high as 1.5-2 times. To reduce heat losses, the system of shudder-type gate valves is envisaged in the air duct. Switching of the gate valves from summer to winter operation is made during NPP preventive maintenance. Apart from its main functions, ECCS provides the possibility to keep NPP in hot stanby, i.e., at minimum possible core power level when power take-off is stopped.

Another improvement in reliability and safety of the UNITHERM NPP is the passive nature of core protection system. During NPP operation under load variations, core power is self-controlled, whereas variation of reactivity during continuous operation practically compensated for by burnable absorber and temperature effect, and only once a year reactivity is adjusted by remote relocation of absorber rods.

Emergency scram of NSSS and the core subcriticality is achieved by insertion of absorber rods in the core by motor-operated drives or by gravity and compressed spring energy in case of de-energizing of drives. Shutdown of NSSS with malfunction of the above absorber rods is ensured by using additional emergency protection based on alternative design philosophy. To prevent unauthorized withdrawal of control and protection system elements in commissioning the electromagnetic "arrestors" are provided in the drives limiting movement of absorber rods.

For quantitative evaluation of the UNITHERM NPP safety the following possible scenarios of severe accidents have been considered (unauthorized introduction of positive reactivity in the core, loss of preferred power, and primary circuit depressurization)and probabilities of final states of the following categories have been determined:

- the first category – accident localized without violation of safety limits;
- the second category – accident localized with partial deviations from safety limits and without core damage;
- the third category – accident localized with significant deviations from safety limits and accompanied by transition to core steam cooling which in the case of long-term accident can lead to partial core damage.

Predictions showed that core damage probability in any of the above-mentioned accident situations will not exceed 10^{-5} 1/y. In this case, probability of core damage with primary circuit depressurization is $6.7 \cdot 10^{-12}$, and with blackout is $5.4 \cdot 10^{-8}$ 1/y.

4. *Operation and maintenance*

The UNITHERM NNP design allows complete shop manufacture, assembly and adjustment with further shipment of 10-15 blocks of 100-175 t to the site where a small-scale erection and commissioning is required. The blocks may be shiped by barges or other vessels, and when unloaded - further transported by trucks and trailers. Upon life expiration, NPP is completely removed from the site to specialized enterprises for disassembling and utilization. The waste nuclear fuel may be either reprocessed or buried. Also buried are the reactor monoblock vessel and lower steel-water shielding components together with the containment lower fragment. Remaining metal may be reused after adequite treatment.

The erection works for the UNITHERM NPP will be carried out at the beforehand prepared site in minimum scope because transportable shop-fabricated blocks can be directly installed on the foundations designed according to future local plant operation conditions. Upon installation and fastening of the blocks on the foundations works are carried out to locate connecting pipes and cable, consumers are connected to district heating system and electrical networks, process loops are filled with working fluids and commissioning tests of the systems and components are made. The planned duration of the UNITHERM NPP erection works is 4-5 months since NPP blocks shipment to the site.

Location of the UNITHERM NPP on the site envisages combination of the entire complex into the following free-standing blocks:

- reactor plant;
- turbine-generator;
- air-cooled condenser unit;
- main control room and communication station;
- transformer substation, if necessary;
- auxiliary eqipment and plant systems rooms;
- NPP emergency auxiliary power supply room.

NPP is planned to operate continuously during 1-year periods. At that time the service personnel performs constant surveilance making no maintenance operations. The NPP staff is beyond the irradiation area both in normal operation and in the case of ultimate design-basis accident. Two persons work in each shift. The total number of persons required for current supervision over the UNITHERM NPP operation is 12-15 men for 5 shifts one of which is reserve to substitute operator on vocations, desease, etc. The staff qualification rerquirements depend on functional duties which in the process of operation are reduced to sufficiently simple operation of the equipment control and keeping constant communication with regional service center. All repair and preventive maintenance works are made by qualified specialists of part-time service team of 5-10 men, once a year during 1-2 weeks.

Analysis of the performed calculations for steady and dynamic NPP operation modes shows that accepted flow chart and design solutions for implementation of conceptual issues are right in principal. Parameters of circuit coolants are within permissible limits for the entire range of NPP load and outer conditions variation. Transition from one operation mode to another, including transition from full load shedding and restoration, are carried out due to reactor self-control and do not require personnel or reactor plant automatic equipment intervention.

5. Conclusion

Table 2 presents some consumer characteristics of the UNITHERM NPP designed for power supply of settlements and industrial enterprises. In case of necessity, heat may be extracted for district heating connecting the consumers to the mains,interconnected to the NPP intermediate loop. When the UNITHERM NPP is used for combined electricity and heat generation, the most optimal heat removal is within 20-30 % of the nominal thermal capacity of the NPP.

The estimates of required demand for power plants of the suggested design showed the figure of some tens in Russian Federation. This fact allows to plan a centralized regional service of such NPPs to ensure transport, erection and commissioning, preventive on-site maintenance and repair, and withdrawal from the site upon life expiration.

Thus, designing and evaluation activities carried out at RDIPE make it possible to suggest the concept of self-contained transportable NPP of small capacity to supply power to areas of Extreme North and Far East of Russia. Modifications of UNITHERM NPP are possible to suit operating conditions in other areas of the world. We expect that not only developed but also developing countries may become interested in such power plants.

Table 2

Basic UNITHERM NPP consumer characteristics

Characteristic	Value
Thermal capacity, MWt	from 7 up to 30
Electric capacity, MWe	from 1,5 up to 6.5
Number of integrated steam supply system	1 ... 2
Refueling-free life, y	up to 20
Safety assurance	In accordance with the Russian Federation normative documentation
Number of protection barriers against radioactivity releases	5
Type of cooling of condensers of the turbine-generator unit and safety systems	Air. No local water sources are required
Seismic resistance	8 points against MSK-64 scale. Protection against radioactivity releases to the environments is ensured at 9 points
Service of NPP in operation	Supervision during continuous operation.Preventive maintenance by a mission team once per year. Personnel is beyond area of ionizing radiation (category B)

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