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SAFETY CONCEPT AND OPERATION CONTROL APPROACH IN THE DESIGN OF SMALL NUCLEAR REACTORS

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Abstract

Operating experience and manifold feasibility studies reveal promising market potential for Small Reactors (SR) in remote areas of Russia. A number of SR designs ranged from few MWth to several dozens MWth are proposed by designers for power or heat production and cogeneration. Some of them are at the detailed design stage and ready for practical implementation.
Safety concept and operation control approach of SRs are discussed in the paper using Floating Nuclear Power Plant VOLNOLOM-3 design as a typical example.

1. Small Reactor Design Activities

Long term operating experience of Bilibino Nuclear Power Plant /1/ (four water-graphite reactors EGP-6 of 48 MWth each) at Chukotka peninsula (North Siberia), as well as results of manifold site specific feasibility studies revealed that Small Reactors (SR) have promising market potential in remote isolated regions of Russia and can be considered as a viable alternative to fossil fuel energy sources. About 90 sites in the fuel deficient regions in the North and North - East of Russia were found prospective for detailed assessment of technical and economic aspects of Small Nuclear Power Plants construction.

Taking into account this favourable conditions for small reactor application, a number of SR designs ranged from several MWth to several dozens MWth were proposed by designers for power or heat production and cogeneration. These designs are based on the experience gained in construction and operation of existing small and large power reactors, as well as ship propulsion, space, and research reactors.

Most of the proposed SRs are at the preliminary design stage. But there are several SR designs advanced to a practical implementation. Detailed design has been completed for Floating NPP (FNPP) VOLNOLOM-3 equipped with two ABV /2/ reactors of 38 MWth and for water-graphite reactor ATU-2 /3/ of 125 MWth for second stage of Bilibino NPP. Conceptual design of pool-type heating reactor RUTA /2/ of 20 MWth has been completed. Technical and economic assessments of construction of Nuclear Heating Plant using four RUTA reactors of 55 MWth are in progress now. The design activities for Floating NPP with two ice breaker reactors KLT- 40 /2/ of 160 MWth were started this year and scheduled to finish the basic design in 1997.

The experience gained in SRs operation and design showed that the objectives of a better operability and enhanced safety of SR can be easier achieved in the design providing minimal operators actions under normal conditions and minimal prompt operators intervention in case of an accident. Exclusion of requirements for any operators actions under normal operating conditions and inherent provisions for long grace period (up to few days and even more) for all credible accidents are considered as a desirable objectives in SR design approach.

The FNPP VOLNOLOM-3 design is considered in more details to clarify the design approach aimed at development the SRs capability for minimal operators actions in a reactor control process.

2. Reactor Safety Concept

Detailed design of the Floating Nuclear Power Plant (FNPP) VOLNOLOM-3 using two integral pressurized water reactors ABV was completed in 1994 and licensing process has started. The ABV reactor characteristics are presented in Table 1.

Table 1. ABV reactor design characteristics

Parameter	Value
Rated reactor capacity	38 MWth
Electric output	6 MWe
Heat production capacity	12 Gkal/h
Refuelling (batch) period	4 - 5 yr.
Primary circuit	
pressure	15.4 MPa
temperature (inlet/outlet)	245/327 ^{0}C
water flow rate	85.4 kg/s
water inventory	7.6 m^3
Secondary circuit	
steam pressure	3.17 MPa
steam temperature	290 ^{0}C
steam flow rate	14.7 kg/s

The principal design solutions which define high level of reactor safety and reliability are:

- integral arrangement of the primary circuit and natural primary coolant circulation,
- self-protection and self-control properties as well as inherent safety characteristics,
- usage of engineered safety features including passive ones,
- usage of primary coolant pressure and temperature driven devices for direct safety systems actuation,
- simplified reactor and safety systems design.

Design and neutronic characteristics of the reactor core ensure negative power, temperature, and void reactivity coefficients. As a result, self-limitation of the reactor power at the reactivity accidents and transients without scram takes place. Reactor self-control properties enable to change reactor power in the range of 20 - 100% of rated power (No) at a rate up to 0.5%No/s without control rods displacement and just for automatic control of feed water flow rate.

Increased primary coolant inventory, natural primary coolant circulation and negative reactivity feedback slow down accident progression and ensures rather long grace period for engineered safety systems actuation.

The ABV reactor is equipped with the following engineered safety systems:

Reactor shut - down is carried out by means of deenergizanion of control rod drives and subsequent gravity driven control rods insertion to the reactor core.

Emergency heat removal system has 5 independent trains. Two of them supplying cooling water to the steam generators from pressurized tanks are passive gas pressure driven ones.

Emergency water injection system for reactor flooding under LOCAs is designed as active one because of certain size limitations in the FNPP. It includes 3 high pressure and 2 low pressure pumps. Water recirculation system for long term decay heat removal is also provided. It is essential that even in case of all emergency heat removal and water injection systems failure under LOCA the reactor core uncovery starts only after 3 hours of the accident initiation.

The ABV reactor is equipped with the low pressure boron injection system and reactor cavity flooding system. Both are non-automatic and non-safety graded systems and designed for severe accident management.

Two ABV reactors in the FNPP VOLNOLOM-3 are located in separate steel containments withstanding internal pressure up to 0.6 MPa.

3. Safety Analysis and Control Concept

The results of safety analysis taking into account single. failure criteria demonstrated that for all design basis accidents (DBA) the ABV reactor safety was ensured without reliance on any operators actions. Practically no on - site and off - site consequences take place at the DBA.

The relevant general results of the beyond design basis accident (BDBA) analysis are presented in Table 2. They show that for most of the realistic BDBA scenarios it is possible to cope with the accidents without reliance on the operator actions for a very long (several days) period. Only for a few low probable (commutative frequency $< 10^{-6}$ per year) scenarios operator actions are required in 5-12 hours. But even in that case operator actions are rather simple and unambiguous. This actions can be carried out from control room or from local equipment control terminals located at the FNPP in such a way to guarantee operating staff exposure, in accident conditions, well below the permissible level.

The most important task of the operators for severe accident prevention is restoration of at least one heat removal train. The simplest but not a single way to do this is reactor cavity flooding to provide better conditions for heat transfer to radiation shielding tank water. Usage of this heat sink ensures decay heat removal for a practically infinite period of time. Only two valves should be open remotely from control room to actuate corresponding passive gravity driven system.

Consideration of the ABV reactor operability and safety actually revealed a good potential for operating staff minimization. But final decisions for this has to be made taking also into account required high level of reactor and NPP reliability and availability. It is extremely important for the FNPP VOLNOLOM-3 designed for siting in remotely isolated regions where it can be and probably will be the one and the only long term power and heat source. In such conditions the NPP staff has to be ready to carry on required maintenance and contingent repair procedures without reliance on local manpower and industrial capabilities. These reasons force designers to be very careful approaching to FNPPs staffing minimization.

The FNPP VOLNOLOM-3 operating shift staff schedule as it is in the design documentation is presented in Table 3. A part from that, provision is made for day-time staff consist of 2 engineers, 2 technicians, and 4 workers. These figures demonstrate how real staffing formation practice looks like for current FNPP design.

Detailed assessment of operating and maintenance procedures shows there is a certain design margin in staffing formation for VOLNOLOM-3. But very strong and clear arguments are required to overcome existing conservatism based on feedback from current NPPs operating experience.

Table 2. General Results of the ABV Reactor Beyond Design Basis Accidents Analysis

Initial Event Considered	Additional Safety Systems Failures	Required Prompt Operator Actions to Cope with the Accident	Grace Period
2 control rod clusters (CRC) withdrawal at reactor start-up	Scram failure	NN[1]	VL[2]
All (6) CRCs withdrawal at reactor start up	Scram failure	NN	VL
1 CRC withdrawal at 100% power	Scram failure	NN	VL
1 CRC withdrawal at 20% power	Scram failure	NN	VL
Stop feed water at 100% power	Scram failure	NN	VL
Stop feed water at 100% power	Scram + active trains of emergency heat removal systems failure	NN	VL
	Scram + all trains of emergency heat removal system failure	Restoration of one heat removal train	4 - 5 h
Primary pipeline rupture at 100 % power	Two trains of high pressure and two trains low pressure water injection systems + all trains of emergency heat removal systems failure	NN	VL
	All trains of high and low pressure water injection + all heat removal systems failure	Restoration of one injection train	5 - 6 h
	All trains of high and low pressure water injection failure	Restoration of one injection train	10 - 12 h

[1] NN - not necessary
[2] VL - very long

Table 3. FNNP VOLNOLOM - 3 operating shift schedule

Location at the FNPP	Field of Responsibility	Graduation Status	Number of Persons
Control Room	Head of shift	E[1]	1
	Reactor control	E	2
	Electric systems	E	1
	I&C	E	1
	Radiological safety	E	1
Equipment Compartments (local posts)	I&C	T[2]	1
	Radiological Safety	T	1
	Electric Systems	T	1
	Turbine/Generator	T	1
		M[3]	1
		W[4]	1
	Chemical systems	W	1
	Ship auxiliary systems and structures	W	2
		Total	15

[1] E - engineer
[2] T - technician
[3] M - mechanic
[4] W - worker

More promising way for that is staffing reduction due to joining operator functions. Preliminary assessment showed that it could result for VOLNOLOM-3 in a reduction of staff in the plant operating shift by half.

Construction and operation of small reactors with minimized staffing and/or remote monitoring is not only a technical issue. Psychological problems including public acceptance is also very important. Step by step approach would be the best way to achieve public acceptance in the area in question. Therefore, discussing at current stage staffing reduction, instead of staffing minimization and/or reactor remote monitoring, would be mote practical. In any case it is very important and actual to elaborate coherent international approach to this problem.

References

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