Optimization of design solutions on safety and economy for power unit of NPP with WWER reactor of new generation

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Abstract. Development of new generation WWER reactors is being carried out in Russia. These new projects with WWER reactors aim to achieve increased levels of safety and reduced costs. This paper describes these designs and discusses the main factors leading to the safety level increase and the improved economics.

1. INTRODUCTION

Since 1988 the projects of NPP power unit with WWER reactors of new generation have been developed. Their construction and commissioning is expected within the period after 2000. Nowadays the project of power unit with WWER-1000/V-392 reactor has been developed and licensed in Gosatomnadzor of RF.

The construction of two power units under this project is expected to start at Novoronezhsky site and basic solutions on safety are used in the project "Kudankulam" in India and in a 1500 MW nuclear power plant (WWER-1500) being developed nowadays.

The concept of new projects of NPP with WWER reactors is aimed at the achievement of two main targets:

- Increase of safety level;
- Increase of power production efficiency and cuts of expenses for construction and commissioning.

Below is presented a brief description of the basic design solutions resulting in realization of these targets.

2. DESIGN SOLUTIONS ON SAFETY LEVEL INCREASE

Design solutions on safety for power unit of NPP with WWER reactor of new generation are aimed at erection of NPP with higher safety level to minimize the risk of NPP use to a reasonable possible level. In doing so all requirements of current normative documents on safety, accepted in Russia, as well as recommendations of IAEA. In particular an assignment of the requirements for design values of probabilistic safety parameters in NV NPP –2 project is based on the requirements of Item 1.2.17 of OPB-88/97 in accordance with which a value of limiting accidental release frequency should not exceed a value of 1.0E-7 / per reactor year. Maximum accidental release (MAR) is a release of such amount of radioactive products which will demand the population evacuation beyond the distances specified by current norms of NPP disposition /2/.

The second requirement for risk level limitation is a requirement of Item 4.2.2 of OPB-88/97 in accordance with which a core damage (CD) frequency should not exceed 1.0 E-5 / per reactor year.

It should be noted that the frequencies of MAR and CD are evaluated according to the results of probabilistic safety assessment (PSA) of the first and second level as cumulative frequency values for all accident sequences which can result in such occurrences during internal (equipment and components failure), on-site (fire, flooding, etc.) and external events and impacts (of natural and technological character).

Development of design solutions on safety increase in the project of NV NPP-2 is based on realization of basic principles of defense-in-depth concept which includes the erection of several physical barriers to prevent radioactive release and high level reliability of these physical barriers to protect them from damage. When developing design solutions for NV NPP-2 the experience in design and operation of a serial unit of NPP with WWER-1000/V-320 has been considered. Nowadays in Russia, Ukrane and Bolgaria 14 power units with V-320 reactors are in operation and power units in NPP "Temelin" (Chechia) and in Rostov (Russia) will be commissioning in 2000. Use of NPP with V-320 reactors offered the prospect of achievement of high level safety as during the total period of these power unit operation (270 reactor/year) not a single serious accident has occurred. But the shortages, revealed through results of NPP experience and results of probabilistic safety assessment, showed the necessity of improvement and modifications to be implemented into reactor facility in order to meet all requirements of current defense-in-depth concept including decrease of core damage frequency and maximum emergency release frequency.

A new reactor facility has been used in NV NPP-2 project and new safety structure has been developed.

2.1. Reactor facility

In comparison with the V-320 reactor the following improvements have been made in the project NV NPP-2:

- The efficiency of mechanical system of reactor emergency protection has been increased providing fast transition of the reactor into a subcritical state and maintenance of this state up to temperature less than 100-120 °C without boric acid supply. This has been achieved by increase of the number of operating components from 61 for V-320 to 121 for V-392;
- The system of automatic suppression of xenon oscillations has been developed;
- A new main cooling water pump ГЦН-1391 has been used in which water is used for lubricating and cooling of bearings and in which the strength seals is increased and which can operate without damage during not less than 24 hours under conditions of cooling loss;
- Steam generator design has been improved providing considerable leakage frequency decrease through heat exchangers and collectors of steam generators;
- Core design has been improved allowing to increase the reliability level and reduce its component damage;
- Safety valves are used capable to operate with use of steam and water mix;

- Specific measures are implemented to protect from damage the boundaries of reactor coolant system and associated components including use of constructional materials, observation of operation requirements and control of reactor body state, equipment and pipelines during operation as well as necessary strength margins. Reliability of the reactor coolant system boundaries is justified by experience and results of specific design strength analysis including the evaluation of leakage occurrence and equipment and pipeline damage frequencies on the basis of probabilistic and strength models. In particular the reactor design shows that the calculated frequency value of a reactor body break does not exceed 1.0 E-7 1/year within the increased period of operation since 30 years for V-320 to 60 years for V-392.

2.2. Safety system

Protection of physical safety barriers which are fuel for NPP with WWER (fuel matrix and fissile elements), the boundary of reactor coolant circuit and containment is provided by use of engineering systems intended for execution of the following safety functions:

- Reactivity control that is the reactor transition into a subcritical state and maintenance of this state for all operating parameter range;
- Heat removal from fuel in a core and spent fuel in a fuelling pool;
- Maintain of coolant store in a core during LOCA accidents;
- Limitation of radioactive release into environment.

Achievement of high level reliability of safety functions in NV NPP-2 project is based on use of basic engineering principles and requirements for structure and construction of safety systems, presented in OPB-88/97 and INSAG-3 which are supported by results of qualitative analysis of reliability and PSA of 1 and 2 levels. Special attention has been paid for the following basic principles during development of safety structure systems:

- Protection from common cause failure (CCF);
- Extended use of passive systems;
- Use of functional and structural variety;
- Protection from human errors;
- Protection from internal and external impacts.

It should be noted that, as PSA showed, not sufficient development of these principles in the project of NPP with WWER-320 is the main reason of level safety limitation for existing unit of NPP with WWER-1000.

As a result of realisation of these principles in NV NPP-2 project the safety system structure has been developed based on use of mutual reserving and fully independent active and passive safety systems each is able to execute each separate safety function in full measure. The detailed list of safety functions is given in Table I. with the list of active and passive systems intended for execution of each safety function. The principal structural schemes of safety systems in NV NPP-2 project are given in Fig.2.2-1 and 2.2.-2.

Use of mutual reserving active and passive systems allows to provide the high level reliability of function execution due to reduction of common cause failure (use of functional and structural variety) and due to reduction of human errors (operation of passive systems does not require operator's actions).

Additionally auxiliary measures to reduce impact of common cause failures and human errors are used in the active system design.

TABLE I. FUNCTIONS AND SAFETY SYSTEMS

Safety functions	**Safety systems**	
	Active	**Passive**
1.Transfer the reactor into a subcritical state and keep this state in a range of operating parameters	Reactor emergency protection system with 121 operating mechanisms	Fast boron injection system
2. Heat removal from reactor through the 2-nd circuit	Four-channel system of emergency heat removal through a steam generator with the structure of 4 x100% (one channel is able to execute functions in full measure). 2 channels of the system are used during normal operation for coolant purification of the secondary circuit. Two channels are in standby mode.	Four-channel passive heat removal system through steam generators with the structure 4x33% (three channels are able to execute functions in full measure).
3. Maintenance of coolant store in a core during LOCA	Four-channel system of emergency core cooling with the structure of 4 x100%. 2 channels of the system are used during normal operation for heat removal from spent fuel in fuelling pool. Two channels are in standby mode. The system operates in pressure range of 0.1-8.0 Mpa in the primary circuit	Hydraulic tanks of the first stage with the structure 4x33% and pressure of 6.0 Mpa and water capacity 50 m^3 in each tank. Hydraulic tanks of the second stage with the structure 4x33% and water capacity designed for maintenance of core coolant store during 24 hours in the situation when the active system failed completely.
4. Isolation of steam generators from main steam collector	Each steam generator has fast-acting isolating valves with electric drives.	
5. Limitation of pressure in the primary circuit.	Safety valves in the pressurizer capable to operate both as active and passive systems.	
6. Limitation of pressure in steam generators and the secondary circuit.	Fast-acting reduction systems for steam release to air.	Safety valves of steam generators
7. Confinement of radioactive products inside the containment	Four-channel sprinkling system. The system of isolating valves of the containment. Ventilation system and clean-up system in annulus space between internal and external containment	Double containment of full pressure. Passive system of hydrogen removal. The trap system for melt fuel.

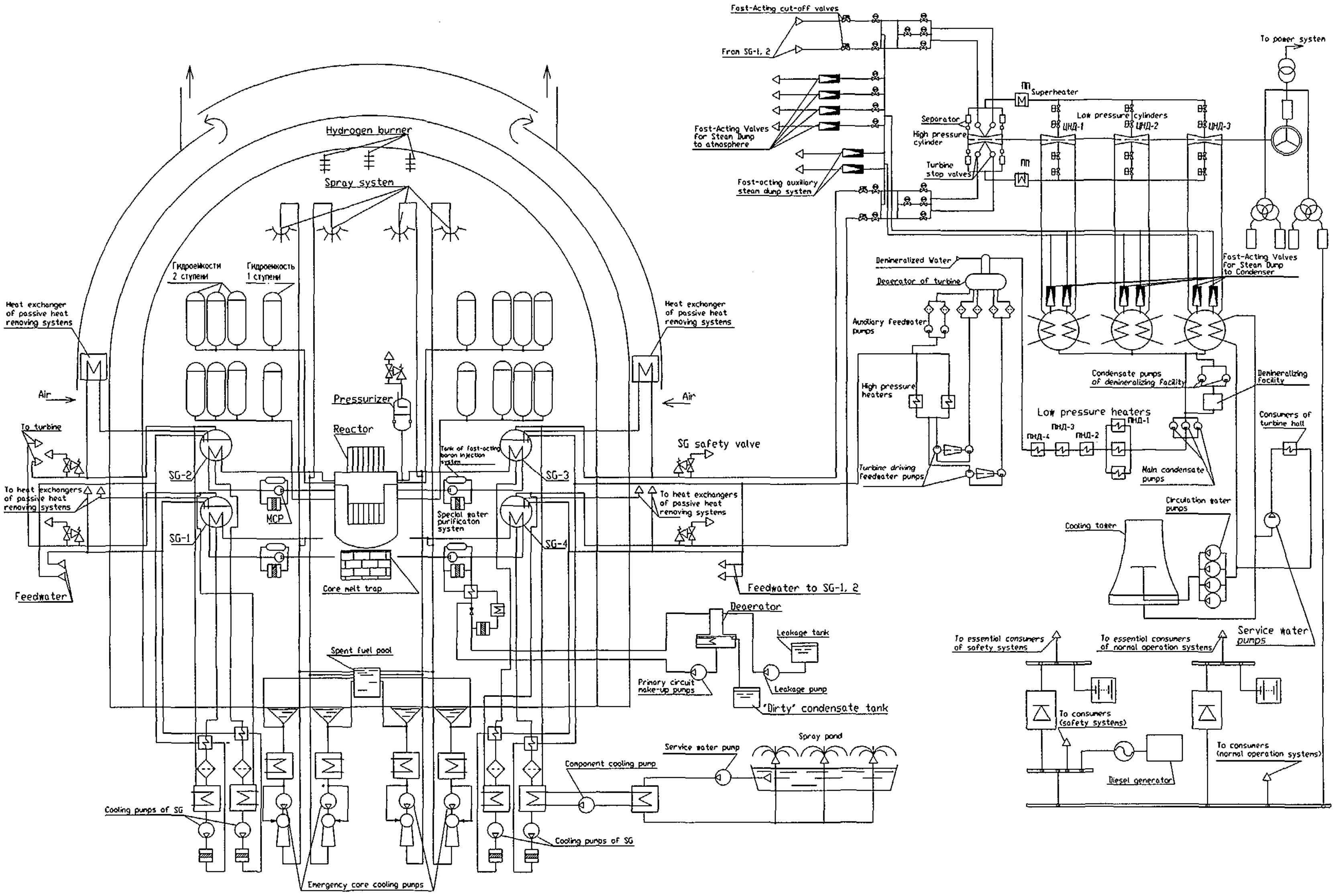
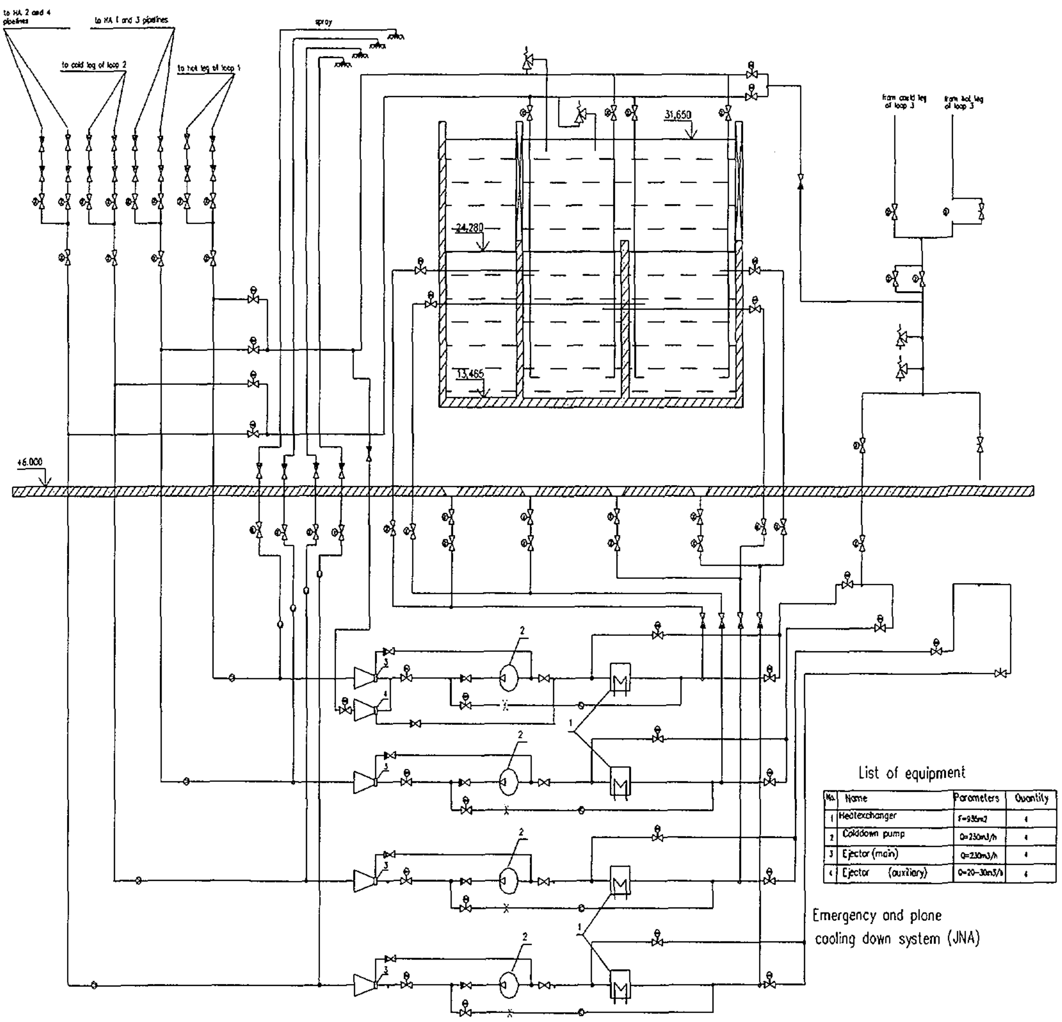

Hydrogen burner
Spray system
Гидроемкости 2 ступени
Гидроемкость 1 ступени
Heat exchanger of passive heat removing systems
Heat exchanger of passive heat removing systems
Air
Air
Pressurizer
Reactor
To turbine
SG-2
SG-1
SG-3
SG-4
MCP
Tank of fast-acting boron injection system
Special water purification system
SG safety valve
To heat exchangers of passive heat removing systems
To heat exchangers of passive heat removing systems
Feedwater
Core melt trap
Feedwater to SG-1, 2
Deaerator
Leakage tank
Leakage pump
Primary circuit make-up pumps
'Dirty' condensate tank
Spent fuel pool
Spray pond
Service water pump
Component cooling pump
Cooling pumps of SG
Cooling pumps of SG
Emergency core cooling pumps
Fast-Acting cut-off valves
From SG-1, 2
Fast-Acting Valves for Steam Dump to atmosphere
Fast-acting auxiliary steam dump system
ПП
Superheater
Separator
High pressure cylinder
Turbine stop valves
ПП
Low pressure cylinders
ЦНД-1
ЦНД-2
ЦНД-3
To power system
Demineralized Water
Deaerator of turbine
Auxiliary feedwater pumps
High pressure heaters
Turbine driving feedwater pumps
Fast-Acting Valves for Steam Dump to Condenser
Condensate pumps of demineralizing facility
Demineralizing facility
Low pressure heaters
ПНД-1
ПНД-2
ПНД-3
ПНД-4
Main condensate pumps
Consumers of turbine hall
Circulation water pumps
Cooling tower
To essential consumers of safety systems
To essential consumers of normal operation systems
Service water pumps
To consumers (safety systems)
Diesel generator
To consumers (normal operation systems)

Fig. 2.2-1.



No.	Name	Parameters	Quantity
1	Heatexchanger	F=935m2	4
2	Colddown pump	Q=230m3/h	4
3	Ejector (main)	Q=230m3/h	4
4	Ejector (auxiliary)	Q=20-30m3/h	4

Fig. 2.2-2.

As an additional measure for protection from common cause failure the use of separate channels of emergency core cooling and heat removal systems through the secondary circuit for normal operation is provided. Two out of four channels of these systems operate permanently and two others are in standby mode during unit power operation. Different modes of operation and different state of the equipment provide additional protection from common cause failures.

It should be noted that most part of the equipment of operating channels (pumps, valves etc.) are in the same state which is required for execution of the specific functions during emergency situations. Such solution allows to increase the level of safety systems readiness due to exclusion of concealed failures of operating components and provide additional protection from common cause failures due to various modes of component use.

Protection from human errors for active safety systems is provided due to more high level of automated control when their operation is needed during transition and emergency situations as well as due to passive systems use not requiring control actions.

Use of hydro accumulators of the 2-nd level capable to sustain coolant store in a core under LOCA during 24 hours gives the possibility to extend time for control of accidents beyond the design basis related to LOCA accidents resulted in complete failure of active system of emergency cooling.

Use of double reinforced concrete containment with a passive system of hydrogen removal, ventilation system and air purification in annulus gap space between the primary and secondary containment, sprinkling system and melt core retain system (a trap for melt fuel) reduces release and size of sanitary and protective area for design accidents and prevents exceeding of emergency release for accidents beyond the design basis including large-scaled accidents involving complete melt of fuel.

2.3. Results of PSA

The comparison of contribution in frequencies of MAR from different groups of internal initiating events (IE) for NV NPP-2 unit No. 1 with a reactor V-392 and unit 4 of Balakovsky NPP with the reactor V-320 is given in Table II. It should be noted that the results of frequencies of MAR for two units, given in the table2.3.-1, were obtained mostly with the use of the same initial data on reliability of components, probability of human errors and IE frequencies. Thus, the comparative analysis of the results is quite correct. Mainly it gives principal differences in design solutions in structure, principles and modes of safety system operation between the projects of NV NPP-2 and NPP with V-320.

TABLE II. CORE DAMAGE FREQUENCY FOR INTERNAL INITIATING EVENTS

Initiating	IE	CDF for NV NPP		CDF for Balakovo NPP	
Event (IE)	Frequency	Absolute 1/year	Relative %	Absolute 1/year	Relative %
SLOCA	3,20E-03	1,26E-09	~2,6	3,40E-07	~0,8
MLOCA	1,00E-03	3,64E-10	<1	8,30E-08	~0,2
LLOCA	3,20E-04	6,79E-10	~1,4	5,40E-08	~0,1
Leakage from primary to secondary curcuit	1,00E-03	1,26E-09	~2,6	1,10E-06	~2,6
General transients	1,00E-00	7,38E-09	~15	1,65E-06	~3,9
Loss of normal heat removal	1,00E-01	7,38E-09	~15	6,50E-07	~1,5
Loss of offsite power	1,00E-01	7,91E-09	~16	3,54E-05	~82,9
Nonisolable steam line leakage	1,00E-03	2,67E-11	<1	3,40E-06	~8,0
Isolable steam line leakage	4,00E-04	1,29E-10	<1	1,00E-10	~0
Loss of heat removal at shutdown	3,50E-05	1,07E-08	~22		
Loss of offsite power at shutdown	3,70E-03	1,12E-08	~23		
All IE		4,77E-08	100	4,27E-05	100

It is also should be noted that the solutions used in the project NV NPP-2 were based on the results of PSA for NPP with V-320. Table II. shows that cumulative frequencies of PSA for 7 groups of IE during reactor power operation are within 2.58xE-8 1/year for NV NPP-2 and 4.26x10-5 for unit 4 of Balakovsky NPP, that is the frequencies of PSA for the unit 1 of NV NPP-2 are approximately 1700 times less than for the unit 4 of Balakovsky NPP. Contribution into frequency of PSA from standby modes is approximately 2.2 E-8 1/ year for NV NPP-2.

Main contribution in MAR frequency for the unit 4 of Bal. NPP is made by initial events with power loss (83%), steam generator leakage in a part cut off from steam generator (8%), reactor outage (3.8%) and violation of heat removal in the secondary circuit (1.5%). Total contribution in MAR frequency is leakage from the primary into the secondary circuit (2.6%). Contribution of the primary circuit leakage inside the containment is 1%.

The main reasons of dominating contribution in MAR frequency because of initial events without the primary circuit leakage for NPP V-320 are as follows:

- Comparatively high frequency of realisation of such IE in comparison with primary circuit leakage;
- Comparatively low level of reliability of heat removal system from the secondary circuit and emergency power supply system from diesel-generators. It is explained by the fact that active three-channels safety systems are used in the project of NPP with B-320 based on the use of the components of the same design (diesel-generators, pumps, valves, return valves etc.) in separate channels of the safety system. Main contribution into indices of not readiness is made by common cause failures of the components of the same design and failures of diesel-generators;
- Comparatively low level of protection from human errors. For execution of main safety functions of long heat removal from the primary and secondary circuit as well as to control accidents beyond design basis (for instance, the mode of bleed and feed) the operator' actions are needed.

The main contribution in frequency decrease for unit No1 of NV NPP-2 in comparison with NPP V-320 is reached because of use of the following principally new design solutions:

- Use of mutual reserving passive and active systems for execution of main safety functions;
- Modified reactor emergency protection system with double number increase of operating mechanims in comparison with V-320 and fast-acting boron injection system for reactor transition \ into a subcritical state and keep this state in a wide range of operating parameters (maintenance of a subcritical state up to the temperature of 100° C);
- Active and passive systems of emergency heat removal in the secondary circuit. Both systems are able to remove heat during unlimited period of time while for NPP with V-320 CAP can operate during a limited period of time (about 30-40 hours) depending on the coolant stored in the tanks;
- Active system of the core emergency cooling system (ECCS) and hydraulic tanks of the first and second stages to maintain coolant in a core during the primary leakage. The hydraulic tanks of the second stage together with hydraulic tanks of the first stage reserve ECCS to maintain a core coolant during 24 hours after accident. This period of time can be used to renew serviceability of active ECCS during its failure.

It should be noted that the use of functional and constructional differences in safety system design allows to create the reliable protection from common cause failure and use of passive and active systems not requiring intervention of any operator allows to create in-depth protection from human errors.

2) Use of separate channels of active safety systems (CAP and ECCS) for normal operation. In doing so the most part of the components of these systems are in the same state as the states needed for execution of the required functions. Use of such systems allows to increase the level of their readiness and provide the additional protection from common cause failures.

3. DESIGN SOLUTIONS ON ECONOMICS IMPROVEMENT

The solutions aimed at the efficiency economical indices have been investigated together with the development and substantiation of solutions on safety increase in NV NPP-2 project. The design solutions for realisation of these targets can be divided into two groups:

- Design solutions aimed at cost decrease for NPP construction;
- Design solutions aimed at the increase of reliability of power production and cost decrease for operation.

3.1. Cost decrease for NPP construction

The calculations of basic economical parameters for new projects of NPP with WWER-1000 V-428 developed by the institute “Atomenergoproekt” for Tanvan NPP in Chine, V-392 for NV NPP in Russia and the reactor WWER-1500, the project of which will be developed after 2000 are given in Table III. As we can see, the project with V-392 exceeds considerably the economical parameters of the project V-348. In particularly specific capital investments in the construction under the project NV NPP-2 are 1.4 times less than for the project of NPP with the reactor V-428 and 1.6 times less than for NPP with V-320. The calculated frequency values of core damage for the project NV NPP-2 (4.8 E-8/reactor per year) are about 100 times less than for the project of Tanvan NPP (5.0 E-6 /reactor per year).

The main effect of economical indices improvement in the project NV NPP-2 has been achieved because of the use of combination principle that is the combination of safety and normal operation functions.

Thus the use of probabilistic system of core emergency cooling, combining in itself the function of coolant maintenance during high and low pressure in an active core, a function of sprinkling system and a function of heat removal from spent fuel allowed to exclude four channels of the core HP emergency cooling system, four channels of sprinkling system as well as the heat removal systems from fuelling pool.

Use of the emergency heat removal system in the secondary circuit with the purpose to purify the secondary coolant allowed to exclude the associated normal operation systems which are used in existing NPP with V-320 in the project of NPP with V-428.

It should be noted that the use of safety systems with the purpose of normal operation results in decrease of operation cost for periodic inspection because these periodic inspections are made through the recurrent change of operating channels of such systems.

TABLE III.EFFICIENCY OF THE PROJECT

Item	**Parameters**	**WWER-1000 (V-320)**	**WWER-1000 (V-392)**	**WWER-1000 (V-428)**	**WWER-1500**
1.	Unit power, MW	1000	1068	1060	1470
2.	Life-time (year)	30	40	40	50
3.	Power service consumption, %	6.11	5.8	6.1	5.7
4.	Specific physical parameters of the projects				
4.1	Specific construction volumes (m^3/kW)		530	520	478
4.2	Specific consumption of reinforced concrete (m^3/MW)		95.5	129.9	81.9
4.3.	Metal consumption of pipelines t/MW including stainless steel t/MW		3.6 0.6	3.8 1.25	3.1 0.9
4.4.	Material consumption of electric equipment t/MW		2.6	3.74	2.5
4.5.	Length of power cables: more than 1000 V (km/MW)		0.025	0.032	0.016
4.6.	Length of power cables: less than 1000 V (km/MW		0.8	0.89	0.7
4.7.	Length of test cables: (km/MW)		2.0	2.31	1.76
5.	Capital investments in the main building, total: million rubles including: § Constructional works § Assembly § Equipment § Other		1060 110.4 118	1446.7 130.9 191.8	1112.4 120.8 125.4
6.	Specific capital investments in the industrial construction, including main building rubl/KW	1411	920.1 500	1297.6 677.7	826.9 378.3
7.	Cost of power production, kopecks/kW	3.43	2.11	2.18	1.62