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Results of Operation and Current Safety Performance of Nuclear Facilities Located in the Russian Federation

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Abstract—After the NPP radiation accidents in Russia and Japan, a safety statu of Russian nuclear power plants causes concern. A repeated life time extension of power unit reactor plants, designed at the dawn of the nuclear power engineering in the Soviet Union, power augmentation of the plants to 104–109%, operation of power units in a daily power mode in the range of 100-70-100%, the use of untypical for NPP remixed nuclear fuel without a careful study of the results of its application (at least after two operating periods of the research nuclear installations), the aging of operating personnel, and many other management actions of the State Corporation "Rosatom", should attract the attention of the Federal Service for Ecological, Technical and Atomic Supervision (RosTekhNadzor), but this doesn't happen.

The paper considers safety issues of nuclear power plants operating in the Russian Federation. The authors collected statistical information on violations in NPP operation over the past 25 years, which shows that even after repeated relaxation over this period of time of safety regulation requirements in nuclear industry and highly expensive NPP modernization, the latter have not become more safe, and the statistics confirms this. At a lower utilization factor high-power pressure-tube reactors RBMK-1000, compared to light water reactors VVER-440 and 1000, have a greater number of violations and that after annual overhauls. A number of direct and root causes of NPP mulfunctions is still high and remains stable for decades. The paper reveals bottlenecks in ensuring nuclear and radiation safety of nuclear facilities. Main outstanding issues on the storage of spent nuclear fuel are defined. Information on emissions and discharges of radioactive substances, as well as fullness of storages of solid and liquid radioactive waste, located at the NPP sites are presented. Russian NPPs stress test results are submitted, as well as data on the coming removal from operation of NPP units is analyzed.

Keywords: nuclear power plants, radioactive waste, spent nuclear fuel, nuclear and radiation safety

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WORLD NUCLEAR POWER IN 2014

The data of IAEA on the nuclear reactors in the world (as of October 31, 2014) both in operation and under construction, taking into account the changes that have taken place in December 2014 (launch of a new unit in Russia and unit shutdown in the United States), are provided in Table 1.

As of December 31, 2014, 438 nuclear power units with total rated capacity of 375 910 MW (e) net were operating in the world. During 2014, five new units were connected to an electrical grid: three in China—Nigde-2 on January 4, Fuqing-1 on August 20, and Fangjashan-1 on November 4; one in Argentina—Atucha-2 on June 27; and one in Russia—Rostov-3 on December 27. There were 70 power units under construction. The construction of three has begun: CAREM 25 in Argentina on February 8, Belarusian-2 in the Republic of Belarus on April 26, and Barakah-3 in the United Arab Emirates on September 24.

PLACE OF NUCLEAR POWER IN RUSSIA

In late December 2014, Russia's nuclear fleet had 34 power units with total rated capacity of 24654 MW (e) net, and nine power units with a capacity of 7371 MW (e) were under construction.

Russian nuclear power plants developed a record amount of electricity, 180.458 billion kWh, in 2014; the nuclear share in the total national electricity production was 17.5%.

The target of Rosatom (175 billion kWh) and annual task of FTS of Russia on power generation were fully implemented by the Russian nuclear power plants ahead of schedule—on the nights of December 21 to 22 and December 11, 2014, respectively. The significant achievement in 2014 was the launch of the third unit of the Rostov NPP, which gave its first current on December 27. Since January 11, 2015, the constant power output into the mains in the single power system of Russia was carried out. Presently, the unit is operating at 35% power, and it was planned to increase

Table 1. NPPs in the world both in operation and under construction

Country	Operating		Under construction		Power generation in 2014	
	number of units	power, MW (net)	number of units	power, MW (net)	TW-h	% of the total
Argentina	3	1627	1	25	5.7	4.4
Armenia	1	375			2.2	29.2
Belarus			2	2218		
Belgium	7	5927			40.6	52.1
Bulgaria	2	1906			13.3	30.7
Brazil	2	1884	1	1245	13.8	2.8
United Kingdom	16	9243			64.1	18.3
Hungary	4	1889			14.5	50.7
Germany	9	12068			92.1	15.4
India	21	5308	6	3907	30.0	3.5
Iran	1	915			3.9	1.5
Spain	7	7121			54.3	19.7
Canada	19	13500			94.3	16.0
China	23	19056	26	25756	104.8	2.1
Mexico	2	1330			11.4	4.6
Netherlands	1	482			2.7	2.8
UAE			3	4035	—	—
Pakistan	3	690	2	630	4.4	4.4
Russia	34	24654	9	7371	180.5	17.5
Romania	2	1300			10.7	19.8
Slovakia	4	1815	2	880	14.6	51.7
Slovenia	1	688			5.0	33.6
United States	99	98476	5	5633	790.2	19.4
Ukraine*	15	13107	2	1900	78.2	43.6
Finland	4	2752	1	1600	22.7	33.3
France	58	63130	1	1630	405.9	73.3
Czech Republic	6	3884			29.0	35.9
Switzerland	5	3308			25.0	36.4
Sweden	10	9474			63.7	42.7
RSA	2	1860			13.6	5.7
South Korea	23	20721	5	6370	132.5	27.6
Japan	48	42 388	2	1325	13.9	1.7
Total**	438	375 910	70	67125	2377.7	

* See more information on the state of nuclear power in Ukraine in: V.M. Kuznetsov and M.S. Khvostova "Prospects of Development and Current State of Nuclear and Radiation Safety of the Nuclear Power Plants Located in Ukraine"//Reliability and Safety of Power. 2015. no. 28 (1). Pages 2–9.

** The total number of units in operation and under construction include six operating with a capacity of 5033 MW and two under construction units with a capacity of 2600 in Taiwan. The generation in 2014 was 39.8 TW-h and 19.1% of the total electricity production in the country.

up to 50% in April. The beginning of commercial operation of the unit is expected in summer 2015.

At present, there are ten nuclear power plants with 34 power units in the territory of the Russian Federation (Fig. 1).

In operation:

Pressurized water reactors VVER-1000—12 pieces; and VVER-440—six pieces.

Pressure tube reactors RBMK-1000—11 pieces; and EGP-6—four pieces.

Fast-neutron reactors BN-600—one piece.

Stopped to prepare for close-down:

Pressure tube reactors AMB-100—one piece; and AMB-200—one piece.

Pressurized water reactors VVER-210—one piece; and VVER-365—one piece.

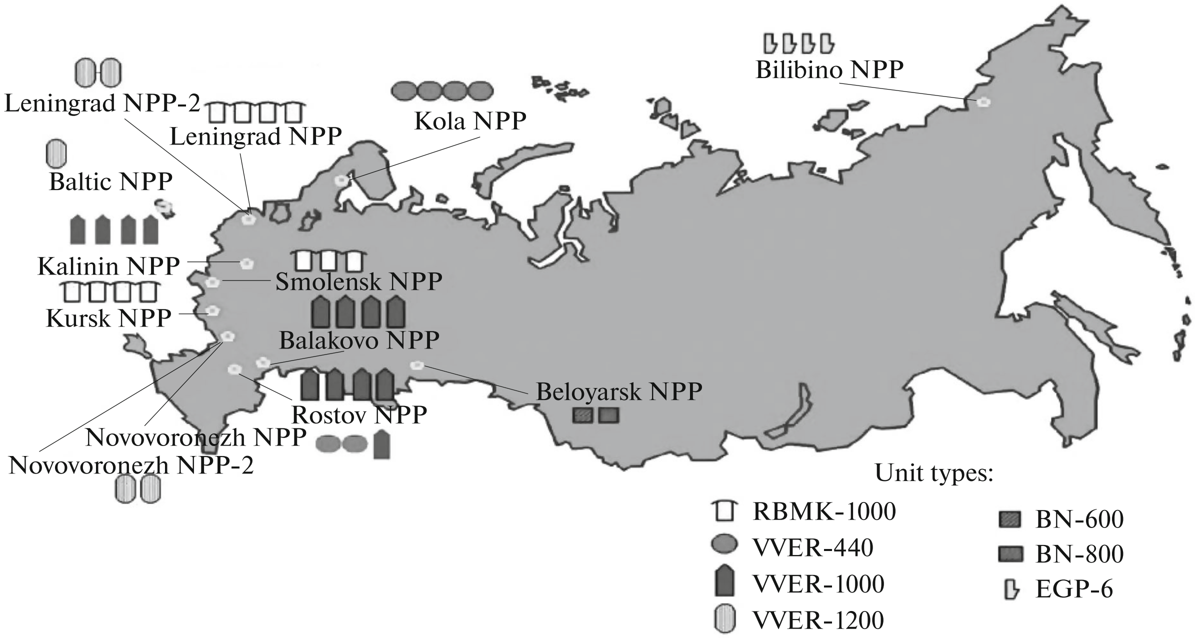

Fig. 1. Scheme of arrangement of nuclear power plant units in Russia.

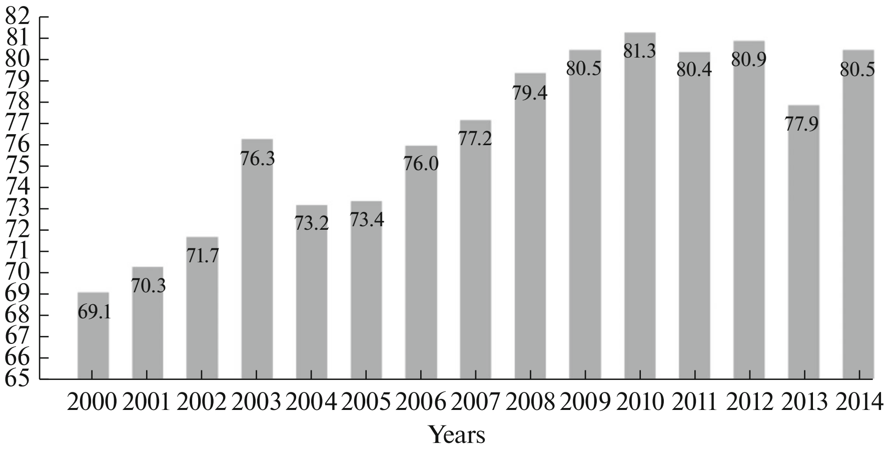

Fig. 2. Installed capacity factor (ICUF) of NPPs.

In the construction stage:

Pressurized water reactors VVER-1200—five pieces; VVER-1000—one piece.

Fast-neutron reactors BN-800—one piece.

Activities for the placement are conducted:

Pressurized water reactor VVER-1200—11 pieces.

The technical and economic operating characteristics of the Russian NPPs are presented in Figs. 2 and 3.

The power units of NPPs located in the territory of the former Soviet Union depending on the type of reactor installation and generation of the project are presented in Table 2 [1].

In Russia, the operating nuclear power plant units are constructed on projects of three generations—the 1960s, 1970s, and 1980s and were put into operation in the period from 1971 to 2011. Ensuring the safety of the operating NPPs is the main condition for the operation of nuclear power. The units with the same capacity constructed at different times on different projects, satisfy the modern nuclear safety regulations to varying degrees, since, in each of the specified periods of creating projects, there was its own set of normative documents (ND) on safety (at present, the basic requirements are defined in nuclear safety regulations in the use of nuclear power and other NDs included in the list of Gosatomnadzor of Russia P-01.01.2006). At the same time, the requirements of NDs in time were more and more tightened. The operation duration of nuclear power plant units located in the territory of the former Soviet Union is presented in Fig. 4.

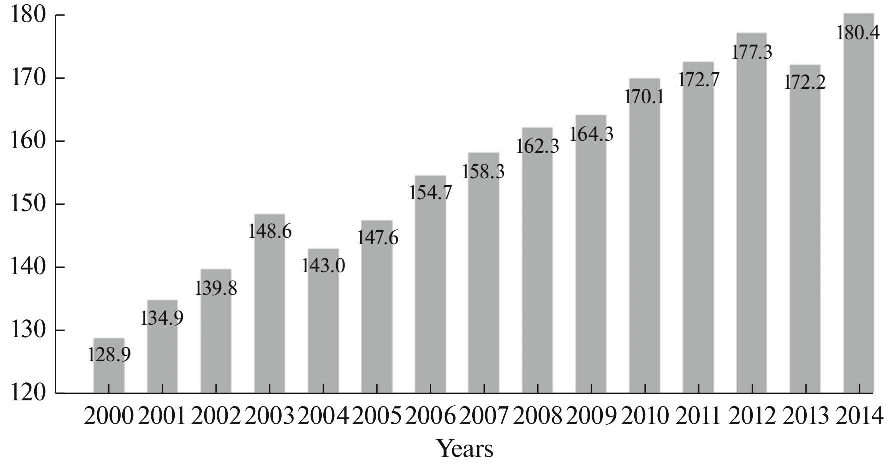

Fig. 3. Power generation in NPPs.

First-generation power units—16 power units with reactors of different types (power unit nos. 1–4 of the Novovoronezh NPP, nos. 1 and 2 of the Kola NPP, nos. 1 and 2 of the Leningrad NPP, nos. 1 and 2 of the Kursk NPP, four power units of the Bilibino NHPP, and nos. 1 and 2 of the Beloyarsk NPP) with a total capacity of 6537 MW. They were all designed and constructed before publication of the main normative documents for safety in nuclear power.

Second-generation power units—17 power units with reactors of different types (power unit nos. 1–3 of the Balakovo NPP, nos. 1–3 of the Kalinin NPP, nos. 3 and 4 of the Kola NPP, nos. 3 and 4 of the Kursk NPP, nos. 3 and 4 of the Leningrad NPP, no. 5 of the Novovoronezh NPP, nos. 1–3 of the Smolensk NPP, and 3 and 4 of the Beloyarsk NPP) with total capacity of 16 480 MW. The units are designed and constructed according to the normative documents that reflect approaches of ND (GSR-73-82/88 and NSR-04-74).

Third-generation power units—four power units (no. 4 of the Balakovo NPP, power unit nos. 1–3 of the Volgodonsk NPP, and power unit no. 4 of the Kalinin NPP), with a capacity of 1000 MW each, the projects are modified taking into account the requirements of ND (GSR-88/97 and NSR RS NP-89).

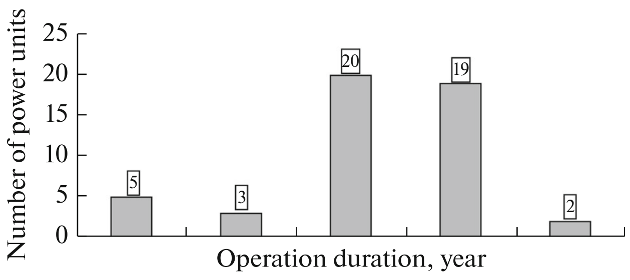

Fig. 4. Operation duration of nuclear power plant units located in the territory of the former Soviet Union (Ukraine, Armenia, Kazakhstan, Lithuania, and Russia).

Third+ generation power units—power unit no. 1 of the Baltic NPP, power unit nos. 1 and 2 of the Leningrad NPP-2, and the power unit nos. 1 and 2 of the Novovoronezh NPP-2. All of them are under construction.

The first-generation power units constructed in the Soviet Union do not correspond with a number of indicators to the modern domestic and foreign requirements of NDs. In addition, their useful life is completed and the close-down of NPPs is required.

The second-generation power units generally correspond to the safety requirements existing in the 1980s. However, the reconstruction is required for many of them to approximate these power units to the safety level regulated by GSR-88. The analysis of design decisions and operational experience of NPP with VVER-440 of the first and second generations was carried out both by the domestic specialists and by the experts of IAEA. As a result, the concept of a stage improvement of the first and second units of the Kola NPP, as well as the third and fourth units of the Novovoronezh NPP without the shutdown of units for a long time was developed. The possibility of replacing the nuclear fuel at the low temperature with a fundamentally lower shutdown of radioactivity in emergencies was additionally considered. The equipment is developed and annealing of all reactor vessels of the first generation VVER-440 is carried out for the first time in the world.

The nuclear power development program in the Russian Federation for the next decade is focused on the construction, first of all, of power units of the 3+ generation VVER-1200, which should replace outdated power units of the first and second generations.

The concept of creation of power units is based on the development of the technology of reactors VVER

Table 2. Units of NPPs located in the territory of the former Soviet Union

Name of NPPs	Unit number	Reactor type	Operation date	Reason of the close-down; operation duration, years	Generation of a nuclear unit
Armenian	1	VVER-440	Dec 28, 1976	Stopped Feb 25, 1989	I
	2	VVER-440	Dec 31, 1979	35	I
Balakovo	1	VVER-1000	Dec 20, 1985	29	II
	2	VVER-1000	Oct 27, 1987	27	II
	3	VVER-1000	Dec 31, 1988	25	II
	4	VVER-1000	Dec 20, 1994	20	III
Zaporizhia	1	VVER-1000	Dec 26, 1984	30	II
	2	VVER-1000	Oct 31, 1985	29	II
	3	VVER-1000	Dec 31, 1986	28	II
	4	VVER-1000	Dec 31, 1987	27	II
	5	VVER-1000	Aug 14, 1989	25	II
	6	VVER-1000	Dec 31, 1995	19	II
Kalinin	1	VVER-1000	May 10, 1984	30	II
	2	VVER-1000	Dec 31, 1986	28	II
	3	VVER-1000	Dec 31, 2004	10	II
	4	VVER-1000	Dec 12, 2011	3	III
Kola	1	VVER-440	Aug 15, 1973	41	I
	2	VVER-440	Dec 21, 1974	40	I
	3	VVER-440	Mar 24, 1981	33	II
	4	VVER-440	Oct 11, 1984	30	II
Novovoronezh	1	VVER- 210	Dec 30, 1964	Stopped Aug 6, 1984	I
	2	VVER- 365	Dec 15, 1969	Stopped Aug 29, 1990	I
	3	VVER- 440	Dec 24, 1971	43	I
	4	VVER- 440	Aug 24, 1972	32	I
	5	VVER-1000	May 30, 1980	34	II
Novovoronezh-2	1	VVER-1200	Construction		III+
	2	VVER-1200	Construction		III+
Rivne	1	VVER- 440	Dec 22, 1980	34	I
	2	VVER- 440	Dec 22, 1981	33	I
	3	VVER-1000	Dec 31, 1986	28	II
	4	VVER-1000	Oct 10, 2004	10	II
Khmelnitskiy	1	VVER-1000	Dec 31, 1987	27	II
	2	VVER-1000	Aug 8, 2004	10	II
South Ukraine	1	VVER-1000	Dec 31, 1982	32	II
	2	VVER-1000	Jan 5, 1985	29	II
	3	VVER-1000	Sept 20, 1989	25	II
Rostov	1	VVER-1000	Dec 25, 2001	13	III
	2	VVER-1000	Mar 18, 2010	4	III
	3	VVER-1000	Dec 28, 2014		III
	4	VVER-1000	Construction		III
Beloyarsk	1	AMB-100	Apr 26, 1964	Stopped Dec 10, 1981	I
	2	AMB-200	Dec 31, 1967	Stopped Dec 31, 1990	I
	4	BN-800	In preparation for power start-up		II

Table 2. (Contd.)

Name of NPPs	Unit number	Reactor type	Operation date	Reason of the close-down; operation duration, years	Generation of a nuclear unit
Bilibino	1	EGP-6	Jan 14, 1974	40	I
	2	EGP-6	Dec 27, 1974	40	I
	3	EGP-6	Dec 23, 1975	39	I
	4	EGP-6	Dec 27, 1976	38	I
Ignalina	1	RBMK-1500	Jan 8, 1984	Stopped Dec 10, 2004	II
	2	RBMK-1500	Aug 30, 1987	Stopped Dec 31, 2009	II
Kursk	1	RBMK-1000	Dec 19, 1976	32	I
	2	RBMK-1000	Jan 28, 1979	29	I
	3	RBMK-1000	Dec 17, 1983	25	II
	4	RBMK-1000	Dec 21, 1985	21	II
	5	RBMK-1000	Construction is stopped		II
Kursk-2	1	VVER-1200	Construction		III+
Leningrad	1	RBMK-1000	Jan 7, 1974	40	I
	2	RBMK-1000	Oct 18, 1975	39	I
	3	RBMK-1000	Dec 28, 1979	35	II
	4	RBMK-1000	Feb 10, 1981	33	II
Leningrad-2	1	VVER-1200	Cconstruction		III+
	2	VVER-1200	Construction		III+
Smolensk	1	RBMK-1000	Dec 25, 1982	32	II
	2	RBMK-1000	May 31, 1985	29	II
	3	RBMK-1000	Dec 31, 1989	25	II
Chernobyl	1	RBMK-1000	Sept 26, 1977	Stopped Nov 30, 1996	II
	2	RBMK-1000	Dec 21, 1978	Stopped Oct 11, 1991	II
	3	RBMK-1000	Dec 3, 1981	Stopped Dec 11, 2000	II
	4	RBMK-1000	Dec 22, 1983	Accident Apr 26, 1986	II
Shevchenko	1	BN-350	Dec 22, 1980	Stopped Jan 1, 1999	I
Baltic	1	VVER-1200	Construction		III+

and provides to achieve a higher level of safety with a reduction in the calculated frequencies of damage and in an active zone and emergency emissions to the less sizes than the reference points GSR-88/97, mainly due to the performance of the main safety functions by differently principled systems (active and passive); the presence of elements and devices of direct action in the structure of safety systems; the optimum combination of safety functions and normal operation by the NPP systems; and the equipment of localizing safety systems designed to perform safety functions not only in the design-basis, but also in the beyond design basis accidents.

The improvement of technical and economic characteristics in the power units is provided by: increase of efficiency in the use of fuel; decrease in specific capital investments for the construction; increase in design life of NPP to 40–50 years; reduction of the volumes of the main buildings; and simplifications of circuit designs and choice of more rational layout decisions.

The priority tasks on the decision of which the future of nuclear power depends include safe operation of existing power units, safe and economically expedient life extension of power units produced a regulation resource, and gradual replacement of operating power units in the third-generation installations.

SAFETY OF NUCLEAR POWER PLANTS

When characterizing a safety performance of the operating Russian NPPs, we should note that the operation of these NPPs is carried out according to the requirements of nuclear safety regulations, which were in effect at the time of their creation, and accordingly, were implemented in their projects.

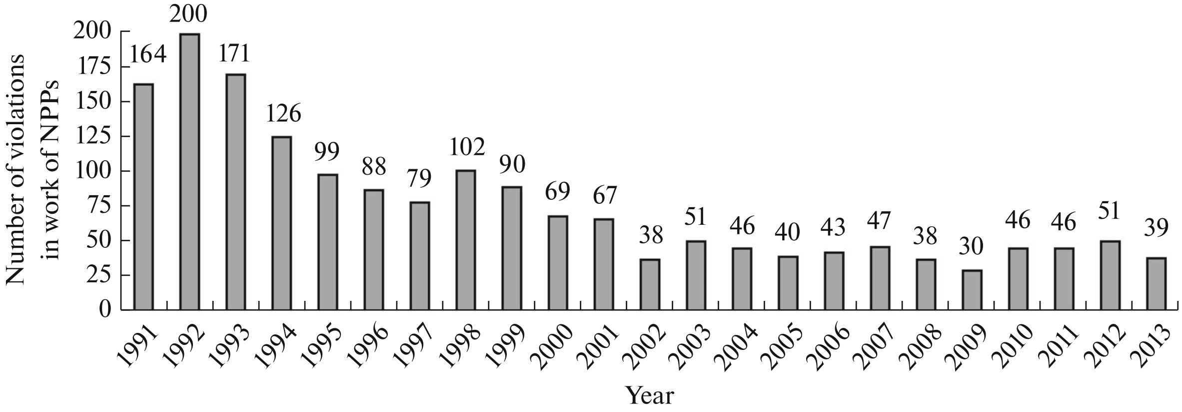

Fig. 5. Statistical data for the period from January 1, 1991, to December 31, 2013, on violations in work of NPPs.

Modern safety requirements are based on the principle of protection in depth (the series system of distribution barriers of radioactive substances to the environment and the system of technical and organizational measures for the protection of barriers).

This principle does not satisfy NPPs with power units of the first generation VVER-440 (3 and 4 of the Novovoronezh and 1 and 2 power units of the Kola NPPs), power units of the first generation RBMK-1000 (1 and 2 power units of the Leningrad and Kursk NPPs), power units of the Bilibino NHPP, as well as power unit of the Beloyarsk NPP BN-600, related to NPP of the second generation. Other operated power units largely meet modern requirements, but it is necessary to solve a number of questions to ensure safety for them (increase of membrane tightness, effectiveness of control systems, control and power supply, operational life of steam generators, improvement of staffing by diagnostic tools, etc.). The action plans to improve the safety of NPPs accepted in the former Soviet Union, providing development of projects and reconstruction of a number of power units ("Summary Actions to Improve the Safety of Power Units in NPPs—86, 88, and 90"), have not been implemented in full.

The problems arising during the operation of plant units are solved in accordance with the established procedure. For example, in the power unit no. 1 of the Leningrad NPP with the RBMK-1000 reactor of the first generation, there was a problem connected with the cracking of graphite stacking, which resulted in change of geometry of a graphite stack and a change of curvature of technological channels (TC) and channels of rods of protection and control (CPS) by the reactor for the established regulation values. In this regard, power unit no. 1 of the Leningrad NPP was stopped for carrying out actions to compensate the degradation of the graphite stack properties.

The Rosenergoatom concern has developed a technology of recovery of resource characteristics of the graphite stack (RRC GS) of the reactor. The set of documents proving safety of power unit no. 1 was submitted to Rostekhnadzor. Examination of the safety case has established the correspondence of submitted documents to the requirements of federal rules and regulations in the nuclear energy use and to the modern development level of science and technology.

As a result of the performed works, the sagging deflection of graphite columns and TC, respectively, and CPS channels were given to the regulation values that has confirmed the efficiency of the chosen technology of recovery of resource characteristics of the graphite stack RRC GS.

Based on the performed work by RRC GS Rosenergoatom, the documents containing the justification for the safe operation of the power unit no. 1 of the Leningrad NPP at power were prepared. By results of the safety case examination carried-out by the organization of scientific and technical support, it was established that the operation of the power unit no. 1 of the Leningrad NPP after RRC GS at power is proven and meets the requirements of federal rules and regulations in the nuclear energy use. Rostekhnadzor, based on the positive results of the examination and the obtained results of IPC, introduced changes to the license action terms authorizing the operation of the power unit no. 1 at power. Currently, 100% power is mastered in the power unit no. 1 of the Leningrad NPP in compliance with the safety measures and actions to control a state of elements in the reactor core. Information on the parameters of the reactor plant equipment presented by JSC Rosenergoatom Concern showed the correspondence to their requirements of normative documents, Technological Regulations for Operation, In-depth Safety Assessment Report, and Reactor Plant Sheet. At present, RRC GS of the power unit no. 2 of the Kursk NPP is executed on similar technology. As a result of the performed works, the sagging deflection of graphite columns and TC, respectively, and CPS channels were given to the regulation values. Based on the performed work by RRC GS Rosenergoatom, the documents containing the justification for the safe operation of the power unit no. 2 of the Kursk NPP at power, which

Table 3. Statistical data on violations in work of NPPs

NPP	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008*	2009	2010	2011	2012	2013
BalNPP	50	69	36	24	10	4	5	5	6	5	9	4	6	4	0	3	3	6	1	2	5	4	3
BelNPP	1	2	1	1	4	2	0	0	2	1	1	1	1	2	0	1	1	1	0	0	0	0	2
BilNPP	7	8	8	7	8	2	8	11	4	2	1	3	1	2	1	0	2	5	1	2	3	1	2
NVNPP	14	29	32	27	19	17	21	10	15	15	8	3	11	7	8	5	12	12	5	3	8	8	1
KolNPP	25	35	44	38	20	19	7	10	11	1	7	3	4	3	1	4	4	2	4	3	9	3	5
KlnNPP	17	14	7	8	11	11	10	9	6	5	1	3	6	2	18**	10	3	2	4	6	3	16	5
LenNPP	19	14	14	5	4	11	4	8	9	14	7	8	2	12	3	7	4	6	6	10	4	6	8
KurNPP	20	17	16	10	11	14	14	26	21	19	11	7	10	11	5	6	8	9	2	8	5	6	5
SmoNPP	11	12	13	8	12	8	10	23	16	7	14	5	9	1	3	5	7	3	5	1	2	6	4
Total:	164	200	171	126	99	88	79	102	90	69	59	39	51	46	40	42	47	38	30	46	46	51	39

* Violations in work of NPPs were investigated according to the Regulation on the Procedure for Investigation and Accounting of Violations in Work of Nuclear Power Plants (NP-004–97) [the Regulation on the Procedure for Investigation and Accounting of Violations in Work of Nuclear Power Plants (NP-004–08) was introduced on December 1, 2008].
** By reducing the total number of violations in NPPs by six cases in NPPs with the VVER reactors, there was an increase in the number of violations compared to 2004 by ten violations. Increasing the number of violations is connected, generally, with the commissioning of the power unit no. 3 of the Kalinin NPP, in which there were 12 violations. The largest number of violations in work of the power unit no. 3 of the Kalinin NPP took place on the stages of power start-up and pilot development and is caused by the elimination of shortcomings identified at the pilot development stage of PCS of the power unit based on the programmable facilities.

Table 4. Failure distribution by equipment type

Equipment type	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Electrotechnical	48	50	33	24	23	22	25	31	8	11	14	17	12	6	14	17
Thermomechanical	75	92	46	45	84	34	53	46	33	17	10	15	–	–	–	–
Electronic	55	15	23	8	11	8	2	11	10	5	5	–	–	–	–	–
CMD&A	17	8	19	12	8	1	4	5	2	10	5	10	7	4	3	3
Others	11	4	19	10	8	4	7	9	16	16	3	8	27	30	25	27

undergo safety review, were prepared and submitted. Similar problems in other nuclear power plant units with RBMK-1000 reactors of the first generation will be addressed as they arise according to the well-proven technology.

Statistical data for the period from January 1, 1991, to December 31, 2013, on violations in work of NPPs are shown in Fig. 5 and Table 3.

The failure distribution from January 1, 1991, to December 31, 2013, on nuclear power plant units is shown in Table 3. The failure distribution by equipment type from January 1, 1992, to December 31, 2007, is presented in Table 4[1]. The violations in work of NPPs depending on the type of reactor plant equipment (as a percentage of the total number of failures)[2] are shown in Table 5 and Fig. 6. The violations in work of NPPs depending on the generation of the nuclear power plant project are presented in Fig. 7. The violations in work of NPPs on the immediate and root causes are presented in Tables 5 and 6.

We see from the statistics that the power units of the first generation with graphite-uranium reactors (RBMK-1000 and EGP-6) and the power units with VVER-440 have a significant number of failures.

Design studies of the reconstruction versions of power units of the first generation have shown that it is almost impossible and economically inexpedient to bring the level of their safety to requirements of the modern NDs. This was also confirmed by the works on the reconstruction of individual power units carried out in 1990–1994 that did not give the desired result. However, at the same time, from the above mentioned statistics, we see that the power units of the first generation with RBMK-1000 (the first stages of the Kursk and Leningrad NPPs) and the Bilibino NPP with the reactor plant equipment EGP-6 have a resistant fail-

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[1] After 2007, Rostekhnadzor ceased to publish information on the distribution of failures by type of failed equipment.

[2] Data on 2009 were not provided by Rostekhnadzor.

Table 5. Failure distribution by type of reactor plant equipment (as a percentage of the total number of failures)*

Project	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2010	2011	2012	2013
VVER-440	27	32	39	26	33	18	16	18	16	15	14	25	13	13	19	21	13	11	13	13	13
VVER -1000	46	37	38	35	35	37	18	20	22	22	3	30	26	58	36	32	24	43	48	51	33
RBMK-1000	22	25	17	27	32	35	55	46	58	54	69	41	53	28	43	41	48	41	24	34	44
EGP-6	4	5	6	8	2	10	11	4	3	2	10	2	4	3	0	2	13	4	7	2	5
BN-600	1	1	1	4	2	0	0	2	1	2	4	2	4	0	2	4	2	0	0	0	5

* Data on 2009 were not provided by Rostekhnadzor.

ure trend; therefore, it is necessary to deploy works on the development of projects on a decommissioning (DC) now for them.

The power units with RBMK-1000 of the first generation (blocks nos. 1 and 2 of the Kursk NPP) did not correspond to requirements of the working regulations. The fact that there are no containment systems in them forces the imposition of restrictions of their useful life. That is why a power limitation in the power unit no. 2 of the Kursk NPP to 70% of N_n is in force for considerable time.

The requirements to the choice of the main and welding materials and the quality of welded joints are not met fully in the projects of power units of the first generation. In this regard, the life extension of these power units can be considered only with condition of annual metal control of the equipment and pipelines. For example, the operational condition control of pipeline welds D_u-300 RFCC, in which 370 intolerable flaws, such as cracks, were found, was carried out in unit no. 3 of the Leningrad NPP during the capital repair (1996–1997). The main causes of defects in pipelines RFCC are: intergranular stress corrosion cracking (IGSCC), fatigue, and presence of stress concentrators. The root cause is that, when designing the possibility of combining, the following factors determining the IGSCC mechanism are not taken into account:

(1) presence of residual voltage in welded joints cracking zone;

(2) influence of the environmental conditions: corrosive medium (by the content of oxygen, chlorine, and pH value), pressure, and temperature; and

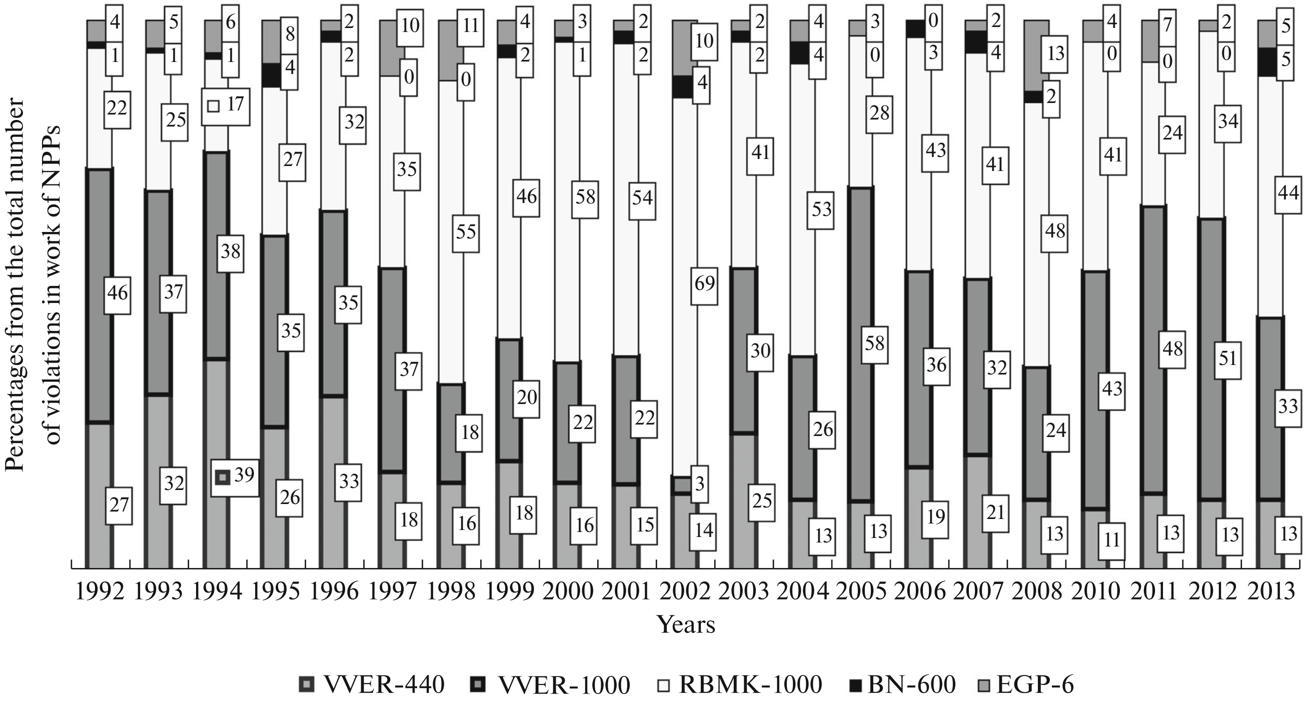

Fig. 6. Distribution of violations in work of the NPPs by type of the reactor installation (in percentages from the total number of failures), bottom-upwards: VVER-440, VVER-1000, RBMK-1000, BN-600, and EGP-6.

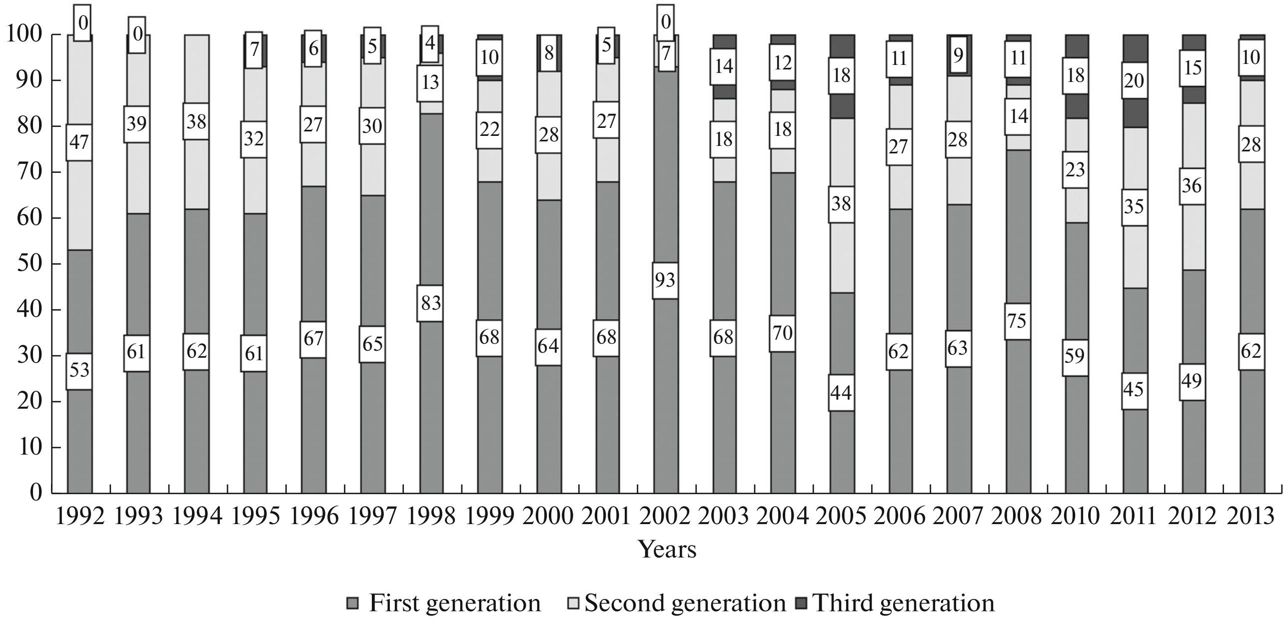

Fig. 7. Distribution of violations in work depending on the generation of the NPP project.

(3) influence of the chemical composition and properties of metal of pipelines themselves.

The power units with RBMK-1000 (units no. 3 and 4 of the Kursk NPP) are closer to the modern requirements, i.e., they already have the containment system, although it does not cover top of the reactor, rooms of steam drums, and feed pipelines. The introduction of “special,” partial (with the power reduction), execution mode is also necessary in the units of this group. Besides, there are other objective reasons, which are a constraint for the further operation of nuclear power plant units. These include the 100% occupancy of near-station storages of radioactive (liquid and hard) wastes as well as lack of facilities for the utilization of this waste and spent nuclear fuel.

HANDLING OF FRESH AND SPENT NUCLEAR FUEL

Handling of spent nuclear fuel (SNF) in the Russian nuclear power plants is carried out according to the Federal Target Program “Nuclear and Radiation Safety in 2008 and for the Period up to 2015” and the Concept for Handling of Spent Nuclear Fuel of the Rosatom State Corporation, approved by the order as of December 29, 2008 no. 721. The principle of a closed fuel cycle is the basis of the Russian state policy in the field of spent nuclear fuel. Currently, depending

Table 6. Failure distribution in work of NPPs on immediate causes*

No. in order	Immediate causes of violations	2007	2008	2010	2011	2012	2013
1	Mechanical damages	17	15	15	10	14	19
2	Failures in the electrical power system	17	13	16	27	18	12
3	Chemical action or connected with reactor physics	0	0	0	0	0	0
4	Hydraulic action	0	0	2	1	3	2
5	Failures in the instrumentation systems	3	3	5	0	8	2
6	Environment (internal actions—abnormal conditions in NPPs)	0	0	2	0	0	0
7	Environment (external actions—abnormal conditions out of NPPs)	1	0	0	1	0	0
8	Human factor	7	7	5	6	8	3
9	Not established	2	0	1	1	0	1
	Total:	47	38	46	46	51	39

* Data on immediate causes of violations in work of NPPs in 2009 are absent.

Table 7. Failure distribution in work of NPPs on root causes*

No. in order	Root causes	2007	2008	2010	2011	2012	2013
1	Implementation error	9	7	2	5	9	4
2	Design error	3	4	9	7	9	2
3	Manufacturing deficiency	8	8	11	9	4	8
4	Construction shortcomings	0	0	1	0	0	0
5	Assembling shortcomings	1	2	2	4	2	3
6	Adjustment shortcomings	0	0	1	1	0	0
7	Shortcomings of the maintenance, which is carried out by third parties	3	3	1	1	1	1
8	Shortcomings of design, construction, and other documentations	1	2	1	1	2	3
9	Deficiencies in management of NPPs and deficiencies in operation management	15	11	9	13	19	16
10	Not established	7	1	9	5	5	2
11	Total:	47	38	46	46	51	39

* Data on root causes of violations in work of NPPs for 2009 are absent.

on the final stage of the fuel cycle, handling of SNF in NPPs is carried out as follows: the closed fuel cycle is realized in NPPs with VVER-440 and BN-600, the intermediate storage of SNF in the at-reactor cooling ponds (CP) is carried out, and then exports from the territory of NPPs to the processing enterprise; SNF of NPPs with VVER-1000 after the nuclear waste holdup in at-reactor cooling ponds are transferred to storage in the Krasnoyarsk Mining and Chemical Combine (MCC) with the prospect of further processing; and SNF of NPPs with RBMK-1000, EGP-6, and AMB, which is not subject to processing now, is stored in special on-site spent fuel storages. On the sites of NPPs, SNF is located in the at-reactor CPs, as well as special in cooling ponds of special freestanding storages (FSSFS and ISFSI). Leaking SFAs are contained in CPs in separate canisters. SNF of the VVER-440 reactors, after the nuclear waste holdup in CP, is transported to the Mayak Production Association for processing at the RT-1 plant. According to authors' estimates, the total activity of SFA with SNF exported from four power units of the Leningrad NPP to the SNF storage is approximately 2.1×10^{19} Bq. The total activity of SNF stored in at-reactor cooling ponds (CP) of four power units of the Leningrad NPP is evaluated at 2.3×10^{19} Bq, including 0.4×10^{19} Bq in first power unit, 0.4×10^{19} Bq in the second power unit, 0.8×10^{19} Bq in the third power unit, and 7×10^{19} Bq in the fourth power unit. The storage of fresh nuclear fuel in assemblies of fresh fuel of NPPs and spent fuel is carried out according to the technological regulations of operation of power units and the industrial instructions establishing requirements for nuclear and radiation safety during storage, transportation, and transshipment of nuclear fuel.

All transportation and processing operations with SNF and fresh fuel are carried out according to the programs determining the operating procedures and technical and organizational measures to ensure the safety of the persons responsible for carrying out the works.

The use of new types of fresh fuel assemblies in NPPs was carried out according to the applicable regulatory technical documents. The operating organization documented, in accordance with established procedure, a license to use nuclear materials for carrying out R&D, or formed changes in action conditions of current licenses.

Filling of the ISFSI or FSSFS storages with spent nuclear fuel—fuel assemblies (FA) with spent fuel in NPPs with the RBMK reactors—is shown in Fig. 8. The summarized data on accumulation and processing of spent nuclear fuel in NPPs are given in Fig. 9.

From the unresolved questions connected with the storage of spent nuclear fuel, the following should be noted:

The Beloyarsk NPP[3] (unit nos. 1 and 2): absence of exports of spent nuclear fuel from NPP; absence of storage for SFA of the AMB reactors; removal of spillages of spent nuclear fuel from the equipment and communications of power units; the Bilibino NPP: the problem of the final stage of handling of SNF of the EGP-6 reactors in the Bilibino NPP is not solved;

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[3] One of the key features of power units with the AMB-type reactors in terms of SFA handling is extremely wide range of the spent FAs. In these reactors, more than 40 FA types were operated and seven types of fuel were used. The majority of nuclear fuel elements contain a disperse fuel composition representing fuel-phase particles (uranium-molybdenum alloys of U-3% Mo, U-9% Mo, UO_2 or UC) in the matrix material from magnesium, copper-magnesium alloy, or calcium. AMB fuel is characterized by the high chemical activity of its components (magnesium, calcium, and uranium) and the corrosion rate in water. The nuclear fuel elements have a tubular construction and are enclosed into a graphite sleeve as part of FA.

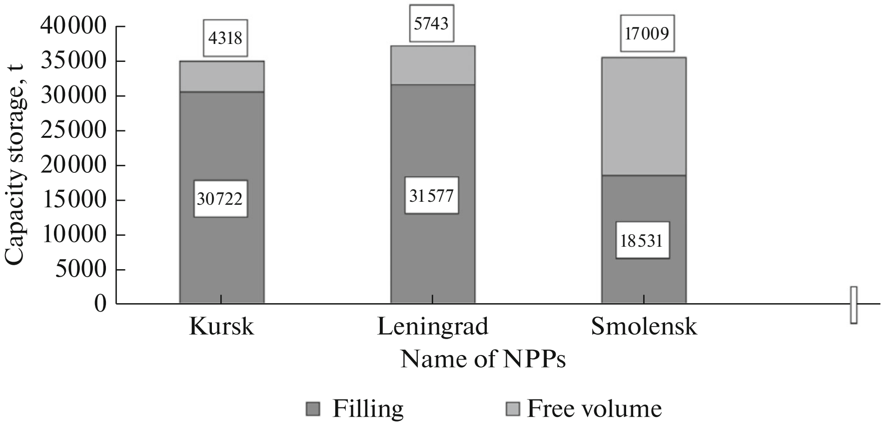

Fig. 8. Filling of SNF storages on RBMK.

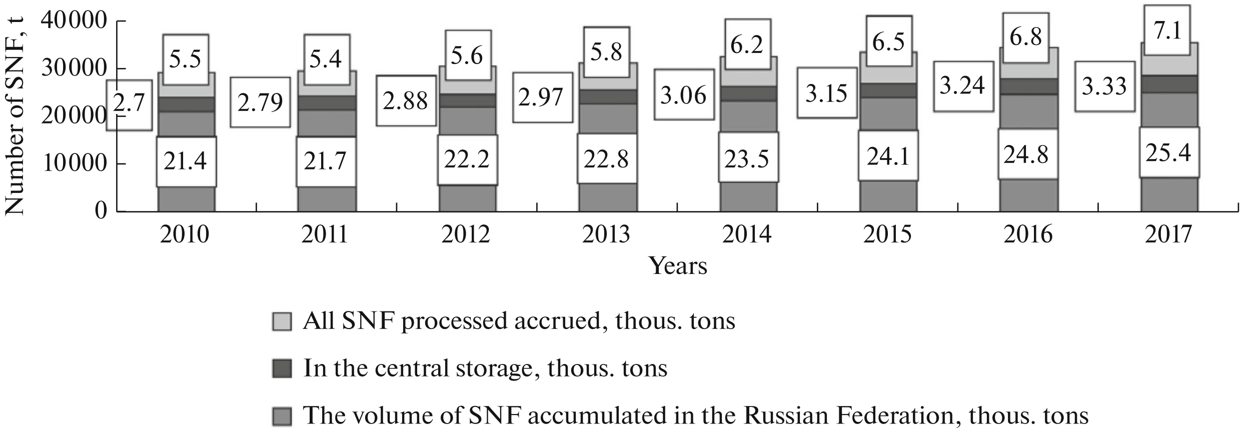

Fig. 9. Accumulation and processing of SNF, bottom-upwards: the volume of SNF accumulated in the Russian Federation, thous. tons; in the central storage, thous. tons; and all SNF processed accrued, thous. tons.

the storage of SNF in units 1 and 2 of the Beloyarsk NPP is carried out in CP-1 and CP-2, nuclear safety at storage is provided. Commissioning of the water purification system in CP of units 1 and 2 allowed significantly reducing specific water activity and lowering the radiation dose on personnel operating the CP. The SNF storage of unit 3 is carried out in the at-reactor CP-3. SFAs with leak tight fuel elements are located in 35-seat jackets. SFAs with leaking fuel elements additionally are established in special leak tight canisters.

RADIOACTIVE EMISSIONS AND DISCHARGES

The sizes of radioactive emissions of inert radioactive gases (IRG) and aerosols in the Russian nuclear power plants compared with the annual maximum permissible emissions (MPE), established by local RTN according to the Decree of the Government of the Russian Federation of March 2, 2000, no. 183 "On Emission Standards of the Repugnant (Polluting) Substances into the Atmosphere and Adverse Physical Impact on it," are given in Table 8 by the example of data for 2013.

The gas-aerosol emissions from NPPs were lower than MPE and did not exceed according to IRG — 1.3% (Bilibino NPP); I-131—0.3% (Kursk NPP); Co-60—0.4% (Novovoronezh NPP); Ss-134—0.3% (Novovoronezh NPP); and Cs-137—0.4% (Novovoronezh NPP).

The volumes of liquid discharges into the environment and the intake of radionuclides in surface water in relation to the admissible discharge (AD) calculated and approved for each NPP by Rostekhnadzor according to the Decree of the Government of the Russian Federation of July 23, 2007, no. 469 "On the Draft Standards for Allowable Discharge Rates of Substances and Microorganisms in Water Bodies for Water Users," are shown in Table 9. Data for all NPPs, except Bilibino, are provided by Cs-137, which gives the main contribution (up to 70%) in the total activity of discharge water. Data on the radioactivity of dis-

Table 8. Values of radioactive emissions of inert radioactive gases (IRG) and aerosols in the Russian NPPs in 2013 with the assessment in relation to the annual permissible emissions (PE)

NPP	IRG	I-131	Co-60	Cs-134	Cs-137
	TBq (%)	MBq (% MPE)			
NPP with VVER-1000 and VVER-440					
Kalinin	3.7 (0.03)	682 (0.02)	1.4 (0.001)	10.9 (0.1)	16.4 (0.04)
Novovoronezh	8.2 (0.1)	74 (0.02)	600 (0.4)	51 (0.3)	140 (0.4)
Rostov	3.9 (0,1)	21.4 (0.02)	LSI***	–	0.3 (0.003)
Kola*	LSI	LSI	LSI	LSI	LSI
Balakovo	LSI	LSI	2.6 (0.01)	0.01 (0.0003)	1.3 (0.02)
NPP with RBMK-1000					
Kursk*	552 (0.8)	50.39 (0.3)	LSI	LSI	LSI
Leningrad	73 (0.1)	LSI	75 (0.2)	3.1 (0.01)	8.1 (0.01)
Smolensk*	35.4 (0.05)	12 (0.001)	74.9 (0.2)	LSI	1.4 (0.002)
NPP with AMB-100, 200 and BN-600					
Beloyarsk	2.8 (0.2)	LSI	0.02 (0.0001)	LSI	1.2 (0.01)
NPP with EGP-6					
Bilibino	486 (1.3)	LSI	Lower or equal 14.6** (3.8)		

* MPE of the Kola, Kursk, and Smolensk NPPs are at the stage of registration and approval; thus, MPE of these NPPs in this article are established according to the regulations SR NP-03.

** The content of Co-60, Cs-134, and Cs-137 in the emissions of the Bilibino NPP is lower than the minimum detectable activity. Therefore, the total activity of long-lived radionuclides in the emissions is presented in the table.

*** LSI is the low sensitivity of instrument.

Table 9. Volumes of liquid discharges into the environment and intake of radionuclides in surface water in relation to PD calculated and approved for each NPP

NPP	Volume of discharged water, m^3	Intake of radionuclides, MBq
NPP with VVER-1000 and VVER-440		
Balakovo*	17970	2.2 (2)
Kalinin	3081	10.8 (0.3)
Novovoronezh	69000	39 (0.9)
Rostov*	62500	142 (17.3)
Kola	7547	0.2 (0.0005)
NPP with RBMK-1000		
Kursk	52300	LSI
Leningrad**	–	–
Smolensk	47329	4.4 (0.2)
NPP with AMB-100, 200 and BN-600		
Beloyarsk	86469	62 (2.1)
NPP with EGP-6		
Bilibino	2291	4.8 (0.03)

* Residual waters of the Balakovo and Rostov NPPs come to the spray cooling ponds.

** Residual waters of the Leningrad NPP come on the cooling towers of the Radon Leningrad Specialized Integrated Plant.

Table 10. Information on filling of LRWSF in the Russian NPPs

NPP	LRWSF capacity, m^3	Amount of LRW, m^3	Filling of LRWSF, %
VVER-1000 and VVER-440			
Balakovo	3800	1196	31.5
Kalinin	3436	2444	71.1
Novovoronezh	17891	6710	37.5
Rostov	800	401	50.1
Kola	8896	6593	74.1
NPP RBMK-1000			
Kursk	70400	43325	61.5
Leningrad	21920	17622	80.4
Smolensk	19400	17168	88.4
NPP with AMB-100, 200 and BN-600			
Beloyarsk	6050	4180	69.1
NPP with EGP-6			
Bilibino	1000	697	69.7

charge water are provided by Co-60, whose contribution to the total activity of discharge is 75% for the Bilibino NPP.

The actual values of radionuclide activities in liquid discharges of NPPs are less than the admissible and did not exceed 17.3% of the AD sizes (Rostov NPP).

RADIOACTIVE WASTE

The main objectives of handling of radioactive wastes (RW) in NPP are maximum possible reduction in the amount of RWs subject to processing, development and implementation of a new generation of technically efficient and economically reasonable means of curing the liquid radioactive wastes, and development of RW storage and disposal technologies.

In all operating nuclear power plants of Russia, there are established devices in cleaning and processing of RWs that allow reducing activity of radioactive wastes and decreasing their volumes. The deep evaporation devices run in the Balakovo and Novovoronezh NPPs and the deep evaporation device with cementing and packing of a cement compound in metalconcrete containers run in the Rostov NPP.

In the Kola NPP, the complex for processing of the liquid radioactive waste (LRW) with installations of ozonation, ion-selective cleaning, and cementing was put into commercial operation. Input of LRW solidification facilities is planned in 2014–2016 in the Kursk, Leningrad, Beloyarsk, Smolensk, and Novovoronezh NPPs. A bituminization facility operates in the Leningrad NPP. The technology of ion-selective sorption for cleaning of LRW has been introduced in the Beloyarsk NP and is prepared to be introduced into the rest of other NPPs. In addition, commissioning of installation of deep decontamination of spent ion-exchange resins in the Kalinin NPP is planned. The Center for Waste Processing (CRWP) in the Balakovo NP, which includes the installations of sorting, burning, pressing, and cementation, is in operation. The pressing installations operate in the Balakovo, Beloyarsk, Kalinin, Kola, Kursk, Smolensk, and Novovoronezh NPPs. The burning installations operate in the Balakovo, Beloyarsk, Kalinin, Kola, Kursk, Smolensk, and Leningrad NPPs. Information on filling of liquid (LRWSF) and solid (SRWSF) radioactive waste storage facilities in NPPs of Russia as of December 31, 2013, is shown in Tables 10 and 11.

The heavy percentage of filling of radioactive waste storage facilities confirms the need to revise by JSC Rosenergoatom Concern the programs of RW handling in NPPs, as well as the complex solution of RW processing problems before the expiry of the term of the RW intermediate storage for the purpose of conditioning for further disposal.

RESULTS OF STRESS TESTS

In Europe, the assessment of resistance of all NPPs was carried out in three stages—by operators of NPPs, by atomic national agencies, and by experts from the European Commission and the EU Council. Ukraine and other European countries, which are operating nuclear power plants but are not included at that time in the EU, followed the EU Council's recommendations and carried out stress using ENSREG techniques and assessments of the independent European experts. Russia did this work independently without the involvement of external experts in record time (2–

Table 11. Information on filling of SRWSF in the Russian NPPs

NPP	SRWSF capacity, m^3	Amount of SRW, m^3	Filling of SRWSF, %
VVER-1000 and VVER-440			
Balakovo	42300	19240	45.5
Kalinin	21302	10035	47.1
Novovoronezh	54543	47336	86.8
Rostov	8678	691	8
Kola	47068	13366	28.4
NPP with RBMK-1000			
Kursk	34985	28517	81.5
Leningrad	50242	41991	83.6
Smolensk	16060	13747	85.6
NPP with AMB-100, 200 and BN-600			
Beloyarsk	22160	14932	67.4
NPP with EGP-6			
Bilibino	6330	4006	63.3

3 weeks), although similar tests are carried out in Europe and the United States by now.

In March–April, 2011, Rostekhnadzor, by order of the Government of the Russian Federation, carried out unplanned inspections of the operating NPPs in the following areas: protection from external extreme influences of natural and technogenic origin, including from influences with the intensity, which are considered in design bases of NPPs, as well as protection from combinations of external influences (both the interdependent, and the independent); readiness to the beyond-design-basis accident management with a complete blackout of its own nuclear power needs; readiness to manage accidents with loss of heat removal systems from nuclear fuel, which is in reactors, as well as in SNF storages, to an ultimate heat sink; and readiness to manage severe accidents (i.e., when there was a significant damage of nuclear fuel with the excess of design limits, accompanied by a significant release of radioactive substances from fuel element cans). The results of these unplanned inspections were not published [5].

SEISMIC RESISTANCE

It is noted that the nuclear power plants overcome the sizes of the design and the maximum operating basis earthquakes without prejudicing security. However, it is necessary to implement additional design solutions to ensure the seismic resistance of some equipment, which is not a basic but necessary for the security of the facilities. By results of the analysis, updating of justifications of its seismic resistance is planned for a number of the equipment, which is important for safety (for example, the on-shore pumping stations and canals of pipelines of the service water system in the Kola NPP and the certain building constructions of the main building in the Bilibino NPP).

In addition, it is noted that it is additionally necessary to carry out analysis of the influence on the equipment of nuclear units of seismic influences with greater intensity than is put in the project. It is revealed that the systems of seismometric control and signaling cannot influence the emergency protection system and other controls of the control and protection system in the several NPPs (Bilibino, Kola, Kursk, and Novovoronezh).

Nothing is reported about the planned works on the research of seismicity of buildings, constructions, and equipment of SNF cooling ponds. In addition, there is no information on the results of testing the simultaneous impact of earthquakes and other natural factors (for example, floods and hurricanes) on NPPs.

RISKS OF FLOODING

It is noted that the sites of the Russian NPPs are not affected by the tsunami. In the study of the possibility of flooding caused by other causes (emergency situations on hydraulic engineering structures, such as break of dams, washout of dams, extreme precipitation, etc.) than tsunami, experts have come to the conclusion that there are no flooding probabilities for the majority of NPPs.

However, the emergency situations (for example, dam break) could lead to flooding of the pump station of cooling towers in power unit nos. 3 and 4 of the Novovoronezh NPP. The negative impact of this factor is offset by measures to equip NPPs with the risks of loss of external power supply by the mobile systems of heat removal to the ultimate heat sink (diesel pumps, engine-driven pumps, quick-assembly pipes, etc.).

OTHER NATURAL AND MAN-MADE IMPACTS

It is noted that the stress tests carried out confirmed the security of the Russian nuclear power plants from external impacts, which are accounted in the station projects. In addition, when carrying out stress tests, the influence of a combination of external factors, the probability of which is recognized by experts, was studied.

However, for the individual NPP (Novovoronezh, Smolensk), the conclusion was drawn on the need to perform additional specifying calculations concerning the resistance of building constructions to hurricanes and tornadoes as well as to extreme snow loads.

The stability of the roof in the generator hall from exposure to hurricane wind with a speed of over 35 m/s is not provided in power unit nos. 3 and 4 of the Novovoronezh NPP. The stability of switchyard (OSG) from exposure to tornado of the class 3.2 on the Fujita scale[4] is also not provided.

The insufficient resistance of the separate external enclosing structures to the airshock effect over 1.5 kPa is identified in the Smolensk NPP.

In addition, there is no information on the results of the possible impact of external fires, extreme high/low temperatures, extreme winds (shock waves), and flying objects at the same time.

ENSURING ELECTRIC POWER SUPPLY

It is noted in official reports that, by results of stress tests, it is planned to equip all nuclear power plant units with additional technical means, including mobile diesel generators, the use of which will provide long-term maintenance of nuclear power plant units in a safe state in blackout. In addition, the achievement of computational and experimental justification of the possibility of passive (air) core cooling is also planned for units with RBMK reactors. The additional measures to improve the reliability of electric power supply in normal operation (from the power system), as well as the actions for the reserve (additional) cooling systems for the operating emergency diesel generators are planned in some NPPs. Detailed information about at which NPPs such measures are planned could not be found.

ENSURING HEAT REMOVAL

The problem of heat removal is the main problem that must be solved to ensure the safety of the nuclear power plant. It does not matter what kind of impact on NPP (natural or man-made) can take place, but there is a problem of ensuring heat removal from a reactor core or a cooling pond of SNF under any influence in the longer term.

According to the results of stress tests in the Russian NPPs, the need to equip all NPP units with special technical devices, such as mobile engine-driven pumps, dry pipe sprinkler systems, and motor tank trucks, was identified. In addition, it is also necessary to equip intake points of the cooling water from reservoirs and tank farms, enabling to organize, if necessary, unexpected water supply scheme for cooling cores, cooling ponds, and spent fuel storage facilities, and, thus, to exclude transition of the accident with the loss of heat removal systems to the ultimate heat sink in a heavy stage.

This could mean that such means in the Russian NPPs were absent or were not enough before the accident in the NPP Fukushima Daiichi.

SEVERE (BEYOND DESIGN BASIS) ACCIDENT MANAGEMENT SYSTEM

The organization of technical measures for the severe accident management system was checked during stress tests. It was found that, in a number of nuclear power plant units (the NPP list is not disclosed), it is necessary to realize additional measures, such as retrofitting nuclear power units by systems of hydrogen explosion protection and control of gas concentrations forming a fuel mixture, arrangement of the leak-tight enclosure of units of water-to-water energetic reactors by pressure relief systems, and modernization of plant units by a set of instrumentations ensuring safe operation under severe accident conditions.

Moreover, it is revealed that it is necessary in the Russian NPPs to carry out a probabilistic analysis of safety of the second level. Within this analysis, it is necessary to develop strategies for the severe accident management systems and to prove the sufficiency of the technical means existing for this purpose or planned for implementation. It was also proposed to develop guidelines on the severe accident management system in those nuclear power plant units (the NPP list is not disclosed) for which these guidelines are not yet developed.

Stress tests have shown that, within improvement of the accident management, both severe and other, it is also necessary to execute the following measures: to ensure reliable operation of the communication means in the conditions of beyond design basis accidents (both on the NPP site and for the interaction with the crisis centers); to increase the security of personnel workplaces (first of all—control centers of nuclear power units); to complete the accident-prevention documentations, including for the reflection of scenar-

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[4] See parameters of the Fujita scale in the “Safety in Technosphere” magazine, 2013, no. 5.

ios in it, in which a violation of the normal operation (accident) affects several units of the multiunit NPP.

PRESENCE AND SUFFICIENCY OF THE REGULATORY FRAMEWORK

According to the stress test results, it was recognized that it is necessary to execute completion of the Russian regulatory framework in a part of: additions of requirements to the accident-prevention documentation; requirements to recording external impacts of natural and man-made character in nuclear power plant projects (including to the safety protection of NPPs at influences, the intensity of which exceeds the taken into account in the projects); requirements to the choice of sites of nuclear power plants; design rules of the seismic NPPs: in a part of requirements to the volume and content of reports on the justification of safety of nuclear power plants, as well as in a part of implementing the "leak before break" safety concept in nuclear power plant units.

As a result of carrying out stress tests of the Russian NPPs, the conclusions are drawn that it is necessary in the Russian NPPs to carry out additional technical, scientific, and organizational measures to improve their safety in light of the events in Fukushima-1.

After studying the materials of the Russian authorities, as well as the IAEA materials and other international institutions available for the analysis and working in the field of nuclear energy, it seems that the Russian side has formally implemented all recommendations developed by the international community after the events in Fukushima. How responsibly and in full as if it was done in practice, only time will show. It should also be noted that, as in the EU, the stress tests in Russia are not covered nuclear fuel cycle enterprises (NFC) including those in which radiation accidents have resulted from influence of natural anomalies earlier (JSC Mayak Production Association, 1966 and 1967). Tests in the enterprises of the nuclear industry operating nuclear research installations (JSC RIAR, Krylov State Research Centre, NRC Kurchatov Institute, etc.), disposal points of radioactive wastes (the former enterprises of the Radon system), nuclear icebreaking fleet and vessels of nuclear maintenance, as well as shipbuilding plants engaged in construction, repair, modernization, and disposal of ships with nuclear power stations, are not carried out.

DECOMMISSIONING OF NPPs

The existing "Concept for the Decommissioning of Nuclear Installations, Radiation Sources, and Storage Facilities" was approved by the General Director of the Rosatom State Corporation S.V. Kirienko in February 2008.

According to this document, the decommissioning of nuclear and radiation hazardous facilities (NRHF) is an activity (a complex of organizational and technical measures) that is carried out after a final NRHF shutdown, excluding its use for the target project purpose and aimed at ensuring the safety of workers (personnel), population, and the environment, up to the achievement of decommissioning of a final safe state of the object, which is reasonable and determined by the project conclusion.

The Concept provides several variants to bring the facility to the required final state (the combination of the following options is possible).

Elimination of NRHF is a variation of NRHF decommissioning providing decontamination of equipment, buildings, and constructions; elimination of radioactive pollutions to the level accepted according to the norms; dismantle of equipment, systems, designs, and building constructions containing radioactive substances and materials; removal of all radioactive waste from the NRHF site; and rehabilitation of the NRHF site for the further use.

The creation of a final isolation object (disposal) on the location of the decommissioned NRHF (conservation) is a variation of NRHF decommissioning providing the localization of radioactively contaminated components of equipment, building constructions or RW on the place with the creation of the necessary physical barriers that exclude unauthorized access to a localization zone and an unregulated release of radioactive substances into the environment.

Conversion of NRHF is a complex of organizational and technical measures directed at changing the purpose of the main structures, buildings, engineering systems, and the equipment of NRHF to conduct other types of practice, including in the field of the use of nuclear energy. In fact, the conversion is a special case of the object elimination.

All decommissioned NRHFs can clearly be described as follows:

(1) the nuclear installations having the equipment with the induced activity, namely, nuclear power plant units and research reactors are removed according to the embodiment of *the delayed elimination*;

(2) the facilities referred to the category of the "special (unremovable) RW," namely, storage warehouses of LRW, industrial reactors, and tailings dams are decommissioned according to the embodiment of "*the creation of a final isolation object*";

(3) all other NRHFs are decommissioned according to the embodiment of *immediate elimination*.

For NRHFs at different stages of their life cycle, the use of different approaches to the organization of decommissioning is suggested.

For the new designed facilities—specification of the final state of object and environment, terms of its achievements; determination of cost of works on decommissioning and obligations of future NRHF owners, including financial.

This allows ensuring the functioning of the mechanism of necessary allocations for the facility decommissioning from the time of its launch.

For the operated facilities—carrying out works in the fixed time on the determination of a final NRHF state; evaluation of costs of its decommissioning; justification of the division of responsibility between the former and current owners regarding future costs of decommissioning, with the establishment of the relevant sources of funds for its decommissioning.

For the earlier stopped facilities—creation of the legal prerequisites providing a possibility of the choice of safe and cost-effective implementation variations of the final stage of the life cycle, as well as a possibility of lending funds allotted for the decommissioning of the operating NRHFs and the creation of other incentives to attract investments in the decommissioning.

MAIN PROBLEMS AND WAYS OF THEIR SOLUTIONS

First of all, it should be noted that it is planned to 2030 to carry out works on decommissioning in an enormous amount of the most various facilities:

(1) 18 nuclear power plant units;

(2) 13 industrial uranium-graphite reactors;

(3) 24 research reactors; and

(4) other facilities, the solutions about which need to be taken in the short term (industrial water bodies, tailings dams, storage facilities, etc.).

At the same time, the problems that need to be solved in the very near future to construct the effective industry system of NRHF decommissioning are formulated as follows:

(1) the absence (incompleteness) of a regulatory framework regulating decommissioning;

(2) the absence of the long-term (strategic) program for decommissioning, as well as the reliable assessment of the volume of funds necessary for its realization, the assignment of the state responsibilities;

(3) the absence of the possibility of concluding contracts on a turn-key basis;

(4) the absence of a modern information support for works on NRHF decommissioning;

(5) the absence of a necessary infrastructure of RW handling; and

(6) the absence of a competitive market of services for decommissioning.

By 2015, it is planned the following activities:

(1) carrying out inventory of NRHF taking into account the unification of the "nuclear and radiation hazardous facility" concept" and the formation of the state NRHF register;

(2) the development of programs and projects of decommissioning for all facilities decommissioned during 2016–2025;

(3) the adoption of a federal law regulating the relations on decommissioning, in which the borders will be defined and the state responsibility for decommissioning of "objects of heritage" is consolidated, as well as the questions of ownership of these objects are solved, etc.;

(4) the development and the approval of the strategic plan-schedule (program) of NRHF decommissioning taking into account the criteria of priority with the definition of annual reasonable financing; and

(5) the formation of the state decommissioning control system.

As regards the synchronization with the unified state RW handling system, which was created within of the Federal Law adopted in July 2011 "On RW handling" (FZ-190), a "liquidation" of principle problems does not arise in relation to the decommissioning option.

In particular, the placement of RW arising from the decommissioning of NRHF on the sites of temporary storage is supposed before the creation of the necessary capacities for the final disposal.

As regards the "disposal onsite" option, it is planned that the work by this option will be coordinated with handling of "the special RWs" provided in FZ-190.

In particular, the decommissioning project by this option should provide the creation of "conservation point of the special RWs" as a final state of NRHF.

In regards to the synchronization of the NRHF decommissioning system with the SNF handling system, it should be noted that:

(1) The removal of conditioned and defective fuel from the facilities, which are subject to decommissioning, is included in the zone of responsibility of the SNF handling system, while the removal of spillages of nuclear material is included in the zone of responsibility of the decommissioning system.

(2) It is necessary to develop a coordinated plan-schedule of the SNF removal from the decommissioned facilities in the medium-term (2016–2025) and long-term perspective.

(3) It is necessary to provide correction of the operating normative base with a view to the possibility of the start of works on decommissioning providing that there are SNF and nuclear materials in the removed facility.

CONCLUSIONS

Ensuring the safety in NNPs is a priority state task, which requires purposeful systematic effort from personnel of dangerous productions; specialists of nuclear and radiation safety services; heads of industrial enterprises; research, engineering, and design organizations of industry, and experts and management of the Rosatom State Corporation. Based on the provided NPP safety analysis, it is necessary to formulate the following main conclusions:

(1) Describing the safety state of the operating nuclear power plants, it should be noted that the operation of these NPPs is carried out according to the requirements of the nuclear safety regulations, which affected for the duration of their creation, and, correspondingly, were implemented in their projects. However, none of stations currently meet modern safety requirements to the full.

(2) Today, none of the operating NPPs have the procedurally complete safety justification, which would contain conclusions about the safety performance and the analysis of potential impacts of operation violations in the power units.

(3) The probability of accident initiation will increase in the conditions of the life extension of power units of the first generation at the remaining imperfection of their projects. The reconstruction of the first stages of NPP with RBMK previously conducted and carried out at the moment by the Rosatom State Corporation demanded considerable means, time, experts, and equipment; however, for all that, the required level of safety has not been reached, first of all, due to the absence of the containment system and the accumulation of significant quantities of radioactive waste and spent nuclear fuel. Considering that the continuous operation of power units of the first generation can lead to a severe accident, it is necessary to begin to work on the early decommissioning already now. However, instead in different periods and at different levels there is a “concept” of removal of power units of the first stage to a nominal (100%) power that can put the RBMK devices of the first generation on the side of a new catastrophe. In order to avoid a catastrophe, similar to the Chernobyl, the RBMK reactors of the first generation must be taken out of service in view of the serious danger of a nuclear accident in the course of their operation. Until the decommissioning of units, the work of these power units should be carried out in the special partial execution mode (70% of N_n) with the implementation of additional organizational-technical measures.

(4) The storage capacity existing in NPPs can be exhausted, on average, in 5–7 years with the existing dynamics of the RW and SNF accumulation in the operation of NPPs and in the absence of their exports from the sites. The problem of ensuring nuclear and radiation safety is becoming one of the most important components of national safety of the state with this volume of the accumulated and ever-augmenting RW and SNF.

(5) The Rosatom State Corporation declares that Russia is in the top three best countries in nuclear power plant safety. The safety is estimated by the Rosatom State Corporation based on one indicator—the number of unauthorized operations of the automatic protection that caused shutdowns of reactors during the year. But the nuclear power plant safety in the world is decided on the estimate of a much larger number of parameters: it is occupancy of the on-site irradiated fuel storage facilities (SNF), volume of radioactive waste (RW) per unit of produced electricity, handling of RW, etc. Today, the SNF storages with RBMK are almost filled. According to these indicators, the Russian nuclear power plants are in outsiders among the countries operating the nuclear power plants. Focusing on the site of the operating SNF station, accumulated over 40 and more years of its operation, does not increase the NPP safety compared with other countries.

(6) Equipment reliability, quality of repair, and materials determine a number of authorized reactor stops, frequency, and duration of repairs that finally affects the value of the installed capacity utilization factor (ICUF), the most important economic indicator determining energy generated in a year per unit of installed capacity. And on this indicator, the Russian NPPs are also in outsiders among the countries operating the nuclear power plants. In 2013, ICUF of the Russian NPPs was ~80%, while the worldwide average is 86%, and is 89–92% in the advanced countries (United States, Germany, Japan, South Korea, Czech Republic, Finland, and even China). If ICUF of the Russian NPPs reached at least the worldwide average level, the stations would produce 14 billion kW/h in a year in addition that would save annually 4.6 billion cubic meters of gas.

Safety of nuclear power is also determined by the competence of senior management of the industry and the presence of independent supervision. The head of the operating organization of all Russian nuclear power plants—the Rosenergoatom concern, personally responsible for the safety—does not have the basic education or 10 years of work experience in the industry as was required by the standards of MNE and GosAtom-Nadzor (today—Rostekhnadzor) before the accession of S. Kirienko to the leadership of the industry. Today, among the senior management of the industry, only approximately ~20% are professionals, which have a subordinated role. They do not have the necessary volitional powers and have little effect on decision-making that are important for safety and development of the industry. Influence of the middle ranking of the heads is reduced almost to zero, there is no open discussion of scientific and technical problems, and any criticism is excluded under the pretext of corporate ethics. Public comments in mass media about the situation, not only in the industry but also in own enterprise, are forbidden for the heads of the Rosatom enterprises. All this contradicts the safety culture.

The absence of independent nuclear supervision with sufficient budget and labor expense of inspectors, which corresponds to the labor expense level of NPP heads, promotes corruption and leads to weakening of the control over the operation of NPPs and the quality of repair and construction of nuclear power units. The accident in the Sayano–Shushenskaya Dam occurred just because of these reasons. It is a terrible warning for the atomic scientists.

(7) For the safe operation of the input NPPs, there are not enough qualified personnel. Thus, for example, the average age of the operating personnel in the Leningrad NPP is ~53 years. The system of education and personnel retention in the nuclear industry, which has formed currently, is clearly insufficient for its large-scale development. Working pensioners are approximately 25%, young workers and experts are approximately 10%. In 3 years, the number of young specialists that have left has doubled. Training of personnel (acquisition of knowledge and competence) must advance the programs of planning and development of technologies and buildings of nuclear facilities and their commissioning. However, in the industry, there is still no system approach to solving the training problems. Today's situation with the personnel can be considered critical. The share of researchers aged over 60 years increases with the general decrease in the number of researchers (driving force of innovation development). The average age of leading industry experts (doctors of science) and professors of universities of a "nuclear" profile exceeds the level of the average life of men in the country.

(8) It is necessary to stop works to force the power in any reactors. This is especially against the transformation of VVER-1000 into VVER-1200. The only high-power reactor in the world is VVER-1000, which was designed with a large stock by the rate of MCP and a stock by the inlet temperature of the coolant. Boiling in the reactor core was practically not implemented in it, and, therefore, there were no such unpleasant phenomena as hydrogen absorption of claddings and oxidation of surfaces to a state of falling of the oxide coatings. In nuclear power, there are two efficiencies—one is responsible for the thermal efficiency of NPPs and another is responsible for the efficiency of fuel utilization. The single power of the same reactor is higher, the temperature of water and fuel is higher, and the fuel MCP is worse. Reducing the reactor power by 10%, cycle between refueling will grow for several days. And ICUF becomes more and the failure statistics will decrease.

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