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Validation of BN Reactor Plant Long-Term Operation

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Introduction

- Possible long-term operation of BN reactor plant (RP) depends mainly on life characteristics of non-replaceable equipment, first of all, vessel and reactor in-vessel metal structures.
- During operation, most of this equipment is inaccessible for NDT to detect the defects and to repair them.
- Therefore, the design analysis is very important to validate the operability of this structures.
- In view of the above-mentioned and due to specific operation conditions of some BN reactor metal structures (high temperatures and intensive neutron flux), it was required to develop the new methodology (as compared with the "Codes for NPP Equipment and Piping Strength Analysis" PNAE G-7-002-86) for validation the increased operation life of BN-600 and BN-800 RP (up to 45 years).
- This methodology allows for radiation effects, degradation of mechanical properties of structural materials within the time up to (3-5)$\cdot 10^5$ hours and under irradiation as well as growth of postulated crack-like defects.
- One of the main objectives for BN-1200 RP is provision of 60-year operation life. So, it is provided to extend steel 16Cr-11Ni-3Mo in reactor vessel and heat exchange components and new steel 12Cr-Ni-Mo-V-Nb in SG carrying out the required material and methodological studies.

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BN-600 reactor "critical" non-replaceable components

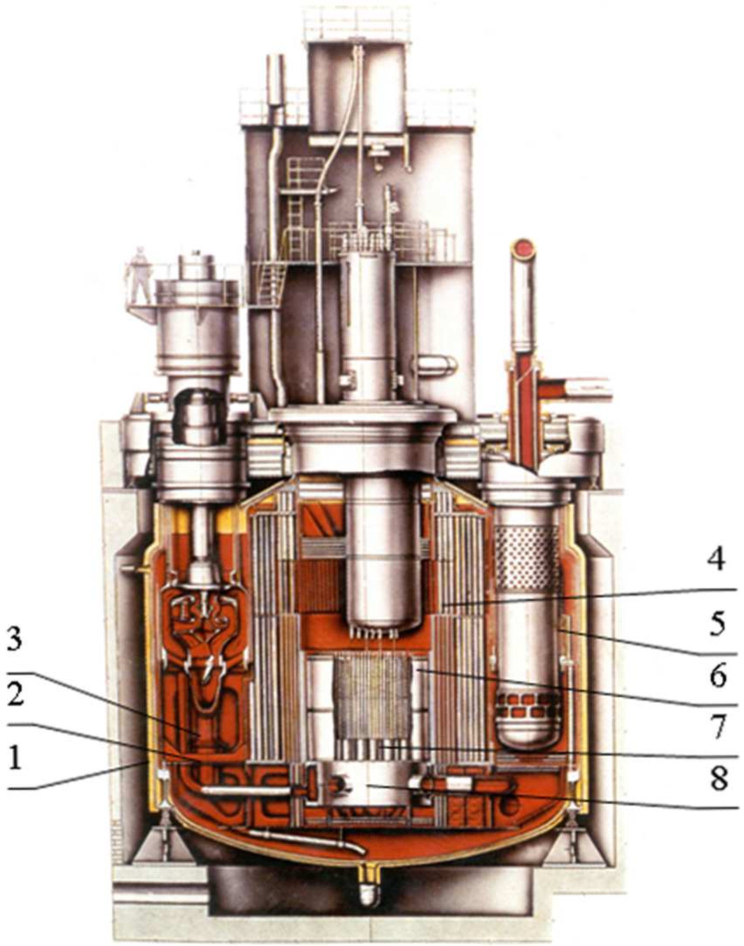

Fig.1

The list of "critical" non-replaceable BN RP components, which determine the plant life time, was made based on the following criteria:

- **safety effect;**
- **impossibility to replace and repair;**
- **inaccessibility for visual inspection and technical condition monitoring;**
- **maximum values of main damaging factors - irradiation, primarily, as well as temperature and thermo-cyclic load impacts.**

1. **Vessel**
2. **Support belt**
3. **Pressure pipe unit**
4. **Side shielding pipes**
5. **IHX support**
6. **Reflector (core restriction shell)**
7. **Headers**
8. **Pressure chamber**

The operation conditions and main damage mechanisms for BN-600 reactor components

Component	Maximum temperature, °C	Maximum neutron fluence (E>0.1MeV) for 45 years, cm^{-2}	Main damage accumulation mechanisms
Vessel	430	$2.5 \cdot 10^{18}$	LCF*
Pressure chamber	370	$6 \cdot 10^{19}$	LCF
Reflector	530	$\sim 10^{23}$	Swelling, creep, LCF, embrittlement
Headers	385	$\sim 10^{22}$	Embrittlement, LCF
Support belt	450	$< 10^{18}$	LCF
Pressure pipe unit	375	$< 10^{18}$	LCF
IHX support	540	$\sim 10^{18}$	HCF**, creep
Side shielding pipes	540	$4 \cdot 10^{19}$	HCF, creep

* LCF – low-cycle fatigue;

** HCF – high-cycle fatigue.

Variations in the materials for BN equipment as a function of maximum operation parameters

Component	Material/temperature (°C)/ neutron fluence (cm^{-2})		
	BN-600	BN-800	BN-1200
Reactor vessel	18Cr-9Ni/430/$2.5 \cdot 10^{18}$	18Cr-9Ni/430/$6 \cdot 10^{17}$	16Cr-11Ni-3Mo/480/10^{13}
Reflector	18Cr-9Ni/530/10^{23}	16Cr-11Ni-3Mo/460/$7 \cdot 10^{22}$	18Cr-9Ni/415/~10^{17}
IHX (tube sheets, shells)	18Cr-9Ni/550	16Cr-11Ni-3Mo/550	16Cr-11Ni-3Mo/550
Hot pipelines of the secondary circuit	18Cr-9Ni/518	16Cr-11Ni-3Mo/505	16Cr-11Ni-3Mo/527
SG: - evaporator; - superheater	(sectional) 2Cr-Mo/452 18Cr-9Ni/518	(sectional) 2Cr-Mo/386 2Cr-Mo/505	(module-vessel) 12Cr-Ni-Mo-V-Nb/527 –

Material and methodological studies for BN-600 service life prolongation

Were carry out since 2004 to 2007 by CRISM “Prometey” together with “Afrikantov OKBM”.

The activities were emphasized for austenitic steel 18Cr-9Ni:

- creep-rapture strength and ductility within the time period up to $3{\cdot}10^5$ hours;
- to take account of irradiation impact on swelling, ductility, creep, fracture strength and crack growth rate.

There were developed and approved the procedures for analysis of limiting states:

- initiation of crack under cyclic loading as per fatigue mechanism;
- initiation of crack under long-term static and cyclic loading at creep and fatigue;
- unstable development of possible initiated or technological crack-like defects;
- loss of bearing capacity or leak tightness of pressure vessel or pipeline;
- inadmissible forming of structure components.

The results of studies formed the basis of standard “Procedure of strength analysis for main components of sodium cooled fast neutron reactor plants” (RD EO 1.1.2.09.0714-2007).

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Material and methodological studies for BN-800 RP 45-year operation life

Since 2008 to 2010 by "Prometey" together with OKBM were performed material studies of steel 16Cr-11Ni-3Mo, which is used for the reflector, IHX and secondary coolant circuit hot pipelines.

This steel as compared with steel 18Cr-9Ni is:

- **more radiation-resistant;**
- **more heat-resistant;**
- **has lower regulatory requirements for austenization of welds (for operation temperature).**

The temperature-dose dependencies for steel 16Cr-11Ni-3Mo properties as a function of damaging dose (up to 65 dpa) were including in updated Procedure (RD EO 1.1.2.09.0714-2011).

Comparison steel 16Cr-11Ni-3Mo with 18Cr-9Ni

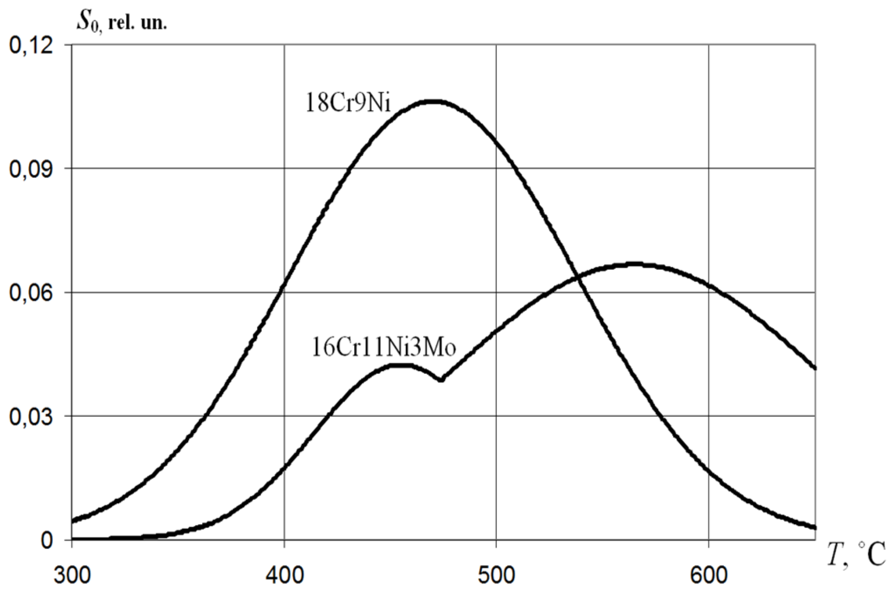

FIG. 2. **Dependences of swelling at F=10^{23} n/cm^2.**

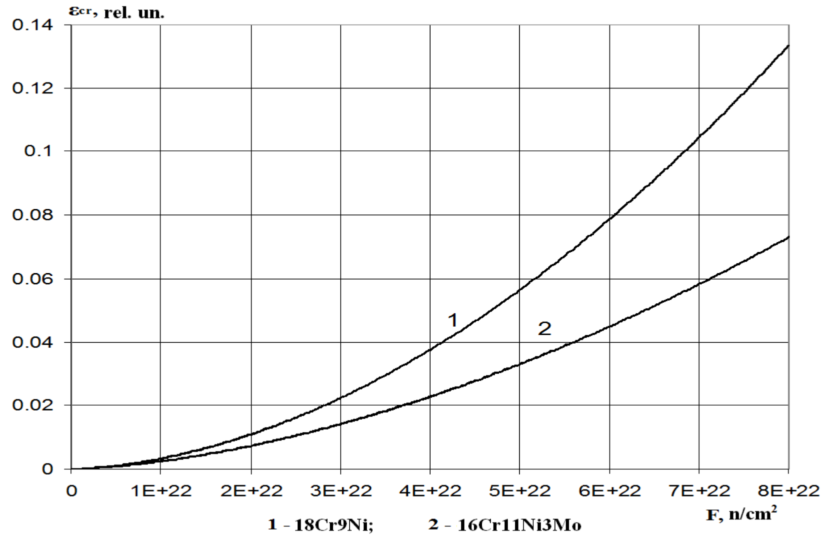

FIG. 3. **Dependences of radiation creep at T=455 °C.**

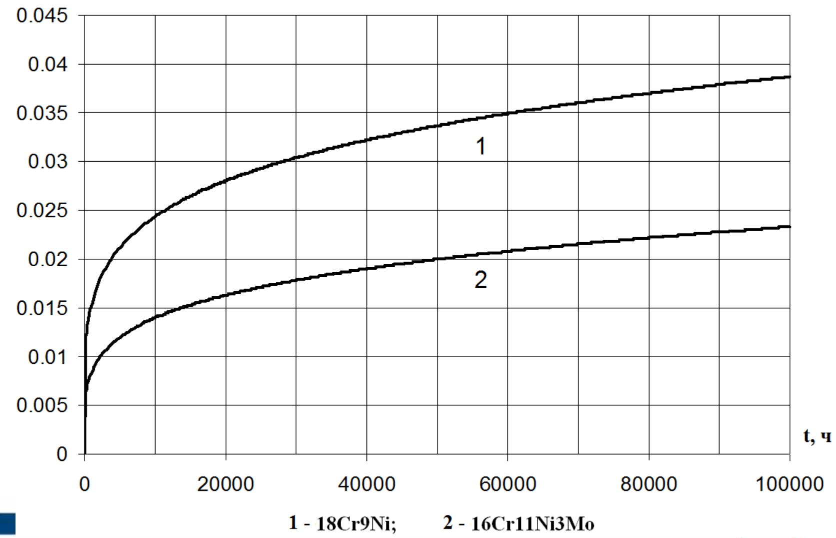

FIG. 4. **Dependences of thermal creep at T=550 °C and Φ=2·10^{13} n/cm^2·s**

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Material and methodological studies for BN-1200 RP 60-year operation life (1)

The requirements for structural materials of BN-1200 equipment being under design are stipulated mainly by maximum temperature and operation life - 60 years (~480 000 h).

The activities have been performed by "Prometey" and OKBM since 2009 and include:

- study of properties of 18Cr-9Ni and 16Cr-11Ni-3Mo, which worked as a part of BN-600 components (IHX, CRDM, reheater);
- study of long thermal ageing effect on structural changes, standard mechanical properties and crack formation for steel 18Cr-9Ni and 16Cr-11Ni-3Mo and weld joints;
- irradiation tests for creep and long-term strength of 18Cr-9Ni and 16Cr-11Ni-3Mo;
- development of the methodology to account the residual weld stresses in strength analyses, model of one-sided accumulation of deformations under cyclic loading, prediction of material surface damage depth at contact with sodium for a period of 60 years, etc.

Material and methodological studies for BN-1200 60-year operation life (2)

High-chromium steel 12Cr-Ni-Mo-V-Nb proposed to be used for BN-1200 SG refers to new materials. This steel has higher temperature and corrosion resistance as compared with pearlitic steel 2Cr-Mo used in BN-600 and BN-800 SGs.
It will allow increasing BN-1200 SG service life from 20 to 30 years.

Due to the fact that steel 12Cr-Ni-Mo-V-Nb is not included in the list of materials adopted for fabrication of NPP equipment, it is necessary to perform the integrated material studies to certify the base metal and weld joints.

As well, the activities are performed to develop the upgraded steels of 18Cr-9Ni and 16Cr-11Ni-3Mo type with increased content of nitrogen and decreased content of carbon for future application in commercial BN-1200 RP. It shall result in improved of corrosion resistance of these steels also retaining high creep-rupture strength, ductility and fatigue.

Validation of long-term operation life for non-replaceable components of BN-600

Damage evaluation under cyclic and long-term static loading showed that during 45 years, cracks initiation is possible in some non-replaceable components of BN-600:
- upper load-bearing shell of the reflector (in the increased temperature areas under the elevator supports);
- elevator supports (in the cut-out base for the guide tube);
- IHX support of isolated loop (near the lower part of inlet windows) under significant thermal pulsations during operation with two loops.
The analysis of postulated crack growth initiating during operation or propagating because of process defects showed that these cracks will not reach critical dimensions during BN-600 RP 45-year operation.

The significant radiation forming is anticipated only in upper load-bearing shell of the reflector. The analysis showed that this forming will not result in loss of operability of associated with it equipment: core fuel assemblies, elevators and refuelling mechanism.

Based on the validation presented in 2010 after 30-year BN-600 operation life expiration, the license of Rostekhadzor was received for operation life extension up to 2020.

Validation of long-term operation life for non-replaceable components of BN-800

The operability of non-replaceable components of BN-800 RP within the specified operation life of 45 year was validated as per "Codes for NPP … Strength Analysis" using the provisions of actualized Procedure (RD), referred to the long-term characteristics of structural materials.

As per the results of cyclic and long-term static strength analysis, the damages in non-replaceable components do not exceed the allowable values; and crack initiation is not expected.

The conditions of radiation and thermal loading of BN-800 reflector are significantly lower than that of BN-600. Together with application of radiation-resistant steel 16Cr-11Ni-3Mo as BN-800 reflector material, it results in substantial decrease of radiation-thermal deformation of the reflector shell as compared with BN-600 reflector shall made of 18Cr-9Ni.

Figs. 5 and 6 present 20-x increased deformation of BN-600 and BN-800 reflector load-bearing shells respectively after 45-year operation.

The irreversible change of main dimensions of BN-600 and BN-800 reflector shells

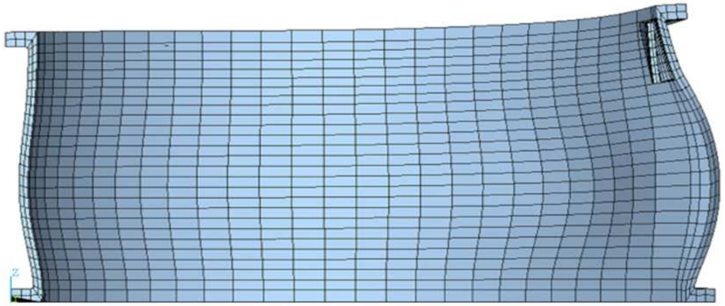

FIG. 5. Deformation of the upper load-bearing shell of BN-600 reflector after 45-year operation

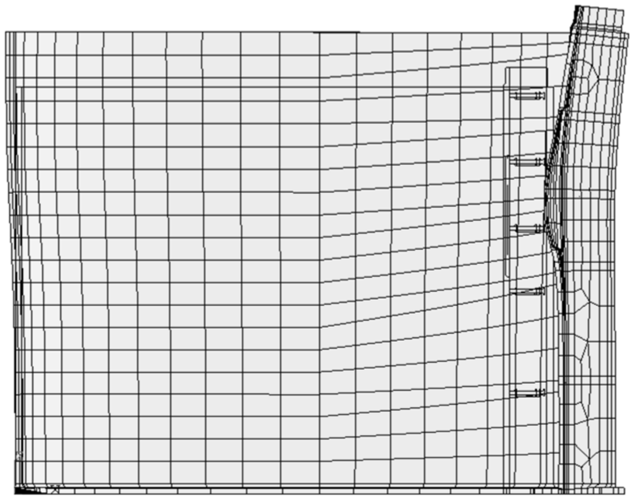

FIG. 6. Deformation of the load-bearing shell of BN-800 reflector after 45-year operation

Reactor	BN-600	BN-800
Height increase on the side of maximum irradiation, mm	21	2.2
Height increase on the opposite side, mm	4	0.2
Radius increase in elevator compartment direction, mm	52*	5.3**
Radius increase in elevator compartment opposite direction, mm	10*	0.1**
Radius increase in elevator compartment perpendicular direction, mm	2.5*	≈0*
Variation of the distance between shell axis and compartment wall, mm	+8**	-6.7*

* – in the centre of the core;
** – at the reflector top.

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Validation of long-term operation life for non-replaceable components of BN-1200 RP

To validate the operability of non-replaceable components of BN-1200 during 60-year operation life, the Procedure for strength analysis of BN RP components at the design stage is now under development.

The procedure will define the methods and procedures of analysis of limiting conditions, which will allow, on one side, decreasing conservatism in damage accumulation estimates in the most loaded RP components under long-term operation at the design stage as compared with "Codes for NPP … Strength Analysis", and, on the other side, taking into account of possible process defect development during long-term operation.

The Procedure will also provide the Appendices on the properties of main structural materials for RP equipment and pipelines (steels 18Cr-9Ni and 16Cr-11Ni-3Mo) in view of long-term operation up to 500000 hours.

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Development the lifetime operational monitoring system

This system shall provide receiving of actual, less conservative estimates of lifetime characteristics of RP equipment as compared with the design estimates due to:

- formation of list of equipment and components, which are critical by the conditions of strength, density, and technical, fire, radiation and/or nuclear safety;
- accounting of actual fabrication dimensions, design imperfections and initial defectiveness of material, which were revealed during RP equipment fabrication, installation and delivery trials;
- accounting of actual (certificated) properties of base and welding structural materials used to fabricate the certain equipment;
- monitoring of actual loading conditions of RP equipment during controlled stages of operation as per automated process control system data;
- status control of base and welding materials as per the results of periodical equipment inspection during operation and as per instrument inspection during planned preventive maintenance;
- definition of structural material behaviour under actual operational conditions as per the results of witness sample periodical tests;
- revision of the moment of limiting condition achievement in the equipment and its residual lifetime estimation;
- revision of limiting condition progress kinetics stipulated by load-bearing capacity loss or allowable leak sizes, based on the condition of RP safety provision.

Conclusion

- BN RP operation life time is mainly determined by resource of non-replaceable equipment.
- The new standard (RD) "Procedure of strength analysis for main components of sodium cooled fast neutron reactor plants" was developed to validate structure strength in view of radiation effects and degradation of material properties within the time period up to 300000 hours and under irradiation, as well as development of postulated crack-like defects.
- Using this RD, the extension of operation life of BN-600 reactor non-replaceable components from 30 to 45 years, as well as strength and durability of the most loaded non-replaceable components of BN-800 RP under construction were validated for the specified 45-year operation life.
- Wider application of steel 16Cr-11Ni-3Mo refers to new decisions in BN-1200 RP design that allow increasing of operation life of the most loaded non-replaceable components up to 60 years. High-chromium steel 12Cr-Ni-Mo-V-Nb is a new material, which was proposed for SG design to increase the operation life up to 30 years.
- In addition, the austenitic steels 18Cr-9Ni and 16Cr-11Ni-3Mo are now under upgrading for future application of them in commercial BN-1200 RP.
- To provide additional long-term reliable and safe operation of BN-1200 RP equipment and pipelines, it is planned to develop and implement the lifetime operational monitoring system.