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Static strength calculation of DN 350 branch pipe cutting-in in the main circulation pipeline of reactor plant WWER-1000

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Abstract. Nowadays the total electricity generated in nuclear power plants in Russian Federation is approximately 18% of all power generation. There are 36 reactors in operation in Russia, 19 of which are reactor plants WWER-1000. A planned operation lifetime of these plants is 30 years and most of them have served for this period. To extend reactor working lifetime it is necessary to carry out the calculation for possibility justification of continued operation of reactor equipment and pipelines. The paper presents the static strength calculation of DN 350 branch pipe cutting-in in the main circulation pipeline of reactor plant WWER-1000. According to calculation results a following conclusion is made: if the static strength of DN 350 branch pipe cutting-in meets the requirements of technical standard, the continued operation of this pipeline section will be possible.

1. Introduction

The main circulation pipeline (figure 1) is an element of reactor plant primary circuit designed for a coolant circulation from nuclear reactor to steam generator and backwards. It connects plant main equipment together forming a circulation loop.

The pipeline is made from pipe units connected by welding. The pipe outer diameter is 990 mm, the nominal wall thickness is 70 mm, the basic metal (steel 10GN2MFA) thickness is 65 mm and the platting layer thickness is 5 mm [1].

The main circulation pipeline forms 4 circulation loops, either of which includes:

- A "hot" leg – a pipeline section connecting reactor outlet branch pipe with steam generator outlet branch pipe.
- A "cold" leg consisting of two pipeline sections connecting steam generator outlet branch pipe with main circulation pump outlet branch pipe and main circulation pump outlet branch pipe with reactor outlet branch pipe.

In order to realize the reactor plant technological process the main circulation pipeline is equipped with branch pipes to connect pipelines of normal operation systems, safety systems and impulse lines of control and measuring instruments.

The outer diameter size (850 mm) is chosen according to the conditions of ensuring the acceptable friction loss of main circulation circuit. A "hot" leg of loop No. 4 is connected with pressurizer by the connecting pipeline 426x40 mm. The connecting pipeline inner diameter is chosen according to the limiting conditions of pressure difference acceptable value (0.39 MPa) between the pressurizer and the main circulation pipeline in non-stationary modes without the integrity loss of primary or secondary circuit. A coolant is removed from a "cold" leg of loop No. 1 by the pipeline 219x19 mm to the pressurizer spray [1].

The paper presents the static strength calculation of section of DN 350 branch pipe cutting-in in the main circulation pipeline (figure 2).

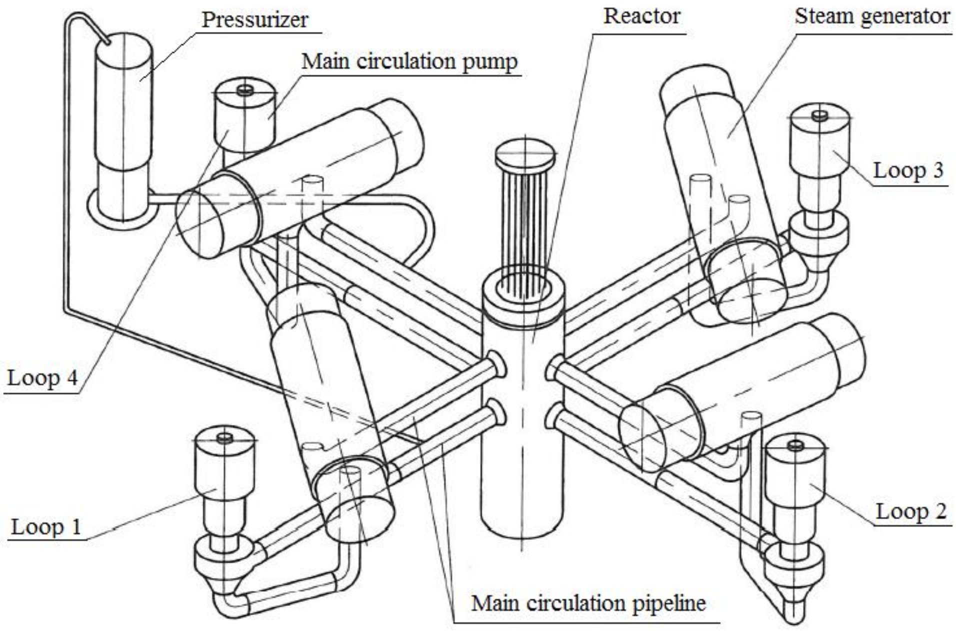

Figure 1. The overview diagram of main circulation pipeline.

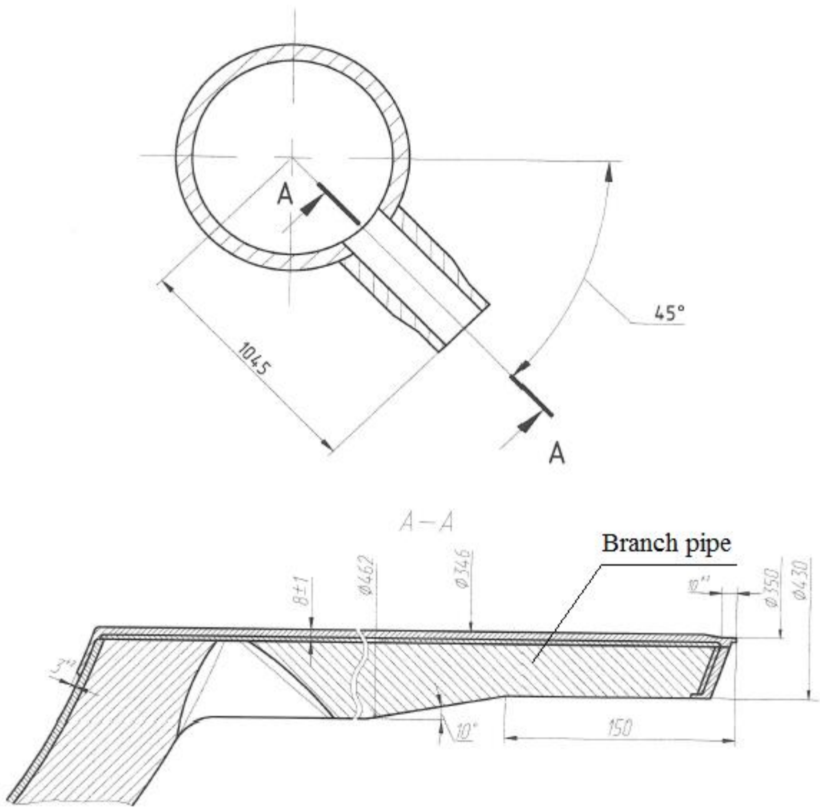

Figure 2. The section sketch of DN 350 branch pipe cutting-in in the main circulation pipeline.

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2. Operation conditions

At the start of work the main calculation parameters which are necessary for carrying out the strength calculation were chosen [2]. The choice of these parameters is conditioned by the fact that these values characterize all operation modes of nuclear plant. The main calculation parameters are listed in table 1.

Table 1. The main calculation parameters.

Parameter	Value
Primary circuit coolant pressure [MPa]	15.7
Calculation pressure [MPa]	17.6
Hydrostatic tests pressure [MPa]	24.5
Hydrostatic tests pressure for a view [MPa]	19.6
Primary circuit coolant temperature [°C]	
• Reactor inlet temperature	290.0
• Reactor outlet temperature	320.3
Calculation temperature [°C]	350.0
Hydrostatic tests temperature [°C]	135.0

In order to determine a fatigue of branch pipe cutting-in material it is necessary to form the list of calculation modes where the material is influenced in a greater degree by the primary circuit coolant during a reactor plant operation.

According to parameter variations in the primary circuit in reactor plant design conditions the modes which describe with desired precision all possible temperature states of considered section are chosen.

The analysis of parameter variations in design conditions showed that in order to justify the section fatigue strength of auxiliary systems cuttings-in in the main circulation pipeline it is enough to consider the modes presented in table 2 [3].

Table 2. The forming of calculation modes for cutting-in section of connecting pipeline in the main circulation pipeline.

Calculation mode	Number of repetitions
"Cold" state	–
Heating-up to hydrostatic tests temperature	130
Hydrostatic tests	130
Planned heating-up from "cold" state	130
"Hot" state	–
Reactor plant power increasing	733
Reactor plant power decreasing	200
Planned cooling to "cold" state	71
Reactor protection system dropping	100
Steam generator safety valves testing	640
Main circulation pump shutdown	120
Nuclear power plant blackout	5
Closing of monoblock turbine stop valves	250
Reactor plant accelerated cooling with the speed of 60 [°C]	10
Heat transfer tube rupture	10
Pipelines rupture of primary circuit DN 850	6
Steam generator steam line rupture	16
Prompt main circulation pump jamming	4

3. Static strength calculation procedure

The static strength calculation of considered section was carried out using the program complex ANSYS Mechanical [4]. At the calculation start a section finite-element model of connecting pipeline branch pipe cutting-in in the main circulation pipeline was developed (figure 3). To consider a model in more details its enlarged fragment is presented in figure 4.

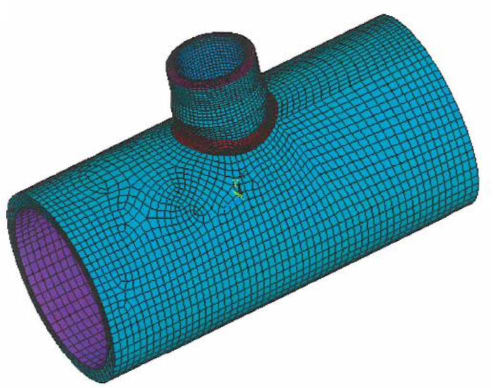

Figure 3. The section finite-element model of connecting pipeline branch pipe cutting-in in the main circulation pipeline.

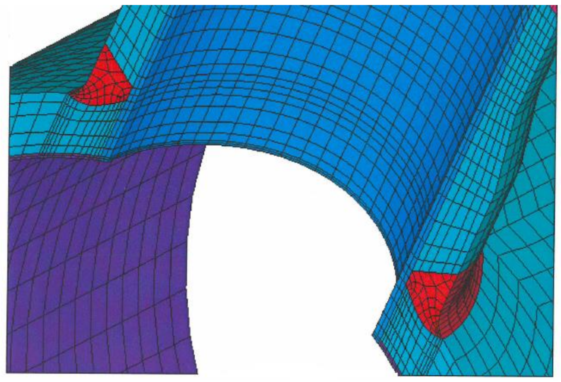

Figure 4. The enlarged fragment of section finite-element model of connecting pipeline branch pipe cutting-in in the main circulation pipeline.

During the model developing following features were taken into account: features of geometric design parameters of considered section, features of external forces impact, a physical properties non-uniformity of materials used for section producing and features of temperature influence on cutting-in section elements caused by working media.

A pressure loading is set at inside section surfaces. A tension stress appeared because of closed-loop volume where pressure acts is set at the end surfaces. The stress quantity acting at the end surfaces is calculated using the following formula:

$$[\sigma]$$

$$\sigma_t = p \cdot \frac{d_{in}^2}{d^2 - d_{in}^2} \qquad (1)$$

где σ_t – tension stress [MPa], p – inner pressure [MPa], d – outer diameter [m], d_{in} – inner diameter [m].

During the static strength calculation a fulfillment of strength conditions is being verified as applicable to the considered section under the influence of calculation loads [5]. The stresses determined during the static strength calculation as applicable to the considered section must not exceed the corresponding allowed stresses presented in tables 3 and 4.

The strength calculation including external static and dynamic forces is carried out for the following loading combinations: normal operation, normal operation + design basis earthquake, normal operation + design basis accident + design basis earthquake, normal operation + maximum calculation earthquake.

According to the analysis of stressed states obtained from corresponding loadings impacts by the calculation the most stressed zones of considered sections are chosen (figure 5). Then the corresponding stress categories (general membrane, local membrane, etc.) are calculated in these zones using a stress linearization method.

The element static strength will be regarded as ensured if the calculation reduced stresses of basic stress groups determined from the maximum-shear theory do not exceed the corresponding allowed stresses [6].

Table 3. The allowed stress values of different categories.

Material grade	Calculation case	Calculation stress group	Allowed stresses [MPa]	
			Definition	Value
Steel 10GN2MFA	Normal operation	$(\sigma)_1$	$\left[\sigma\right]$	188.5
		$(\sigma)_2$	$1.3 \cdot \left[\sigma\right]$	245.1
	Hydrostatic tests	$(\sigma)_1$	$1.35 \cdot \left[\sigma\right]^{Th}$	271.4
		$(\sigma)_2$	$1.35 \cdot k \cdot \left[\sigma\right]^{Th}$	341.7

$\left(\sigma\right)_1$ – Reduced stresses determined from components of general membrane stresses [MPa].

$\left(\sigma\right)_2$ – Reduced stresses determined from components total amount of general or local membrane stresses and general flexural stresses [MPa].

$\left[\sigma\right]$ – Nominal allowed stresses [MPa].

$\left[\sigma\right]^{Th}$ – Nominal allowed stresses at hydrostatic tests temperature [MPa].

k=1.3 – Coefficient of other geometric form.

Table 4. The loading combinations and the allowed stresses.

Material grade	Calculation case	Calculation stress group	Allowed stresses [MPa]	
			Definition	Value
Steel 10GN2MFA	Normal operation + maximum calculation earthquake,	$(\sigma_s)_1$	$1.4 \cdot \left[\sigma\right]$	263.8
	Normal operation breakdown + maximum calculation earthquake,	$(\sigma_s)_2$	$1.8 \cdot \left[\sigma\right]$	339.2
	Normal operation + design basis accident + design basis earthquake. Normal operation + design basis earthquake,	$(\sigma_s)_1$	$1.2 \cdot \left[\sigma\right]$	271.4
	Normal operation breakdown + design basis earthquake.	$(\sigma_s)_2$	$1.6 \cdot \left[\sigma\right]$	341.7

$\left(\sigma_s\right)_1$ – Reduced stresses determined from components of general membrane stresses including seismic impacts [MPa].

$\left(\sigma_s\right)_2$ – Reduced stresses determined from components total amount of general or local membrane stresses and general flexural stresses including seismic impacts [MPa].

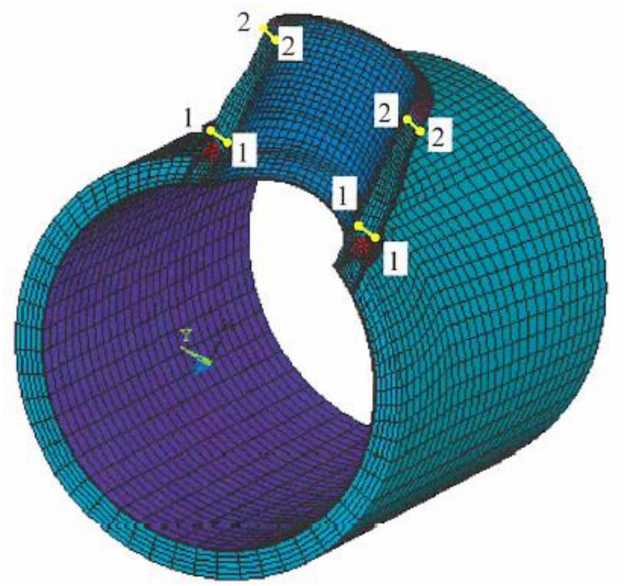

Figure 5. The position of reference lines in the section finite-element model of connecting pipeline branch pipe cutting-in in the main circulation pipeline.

4. Calculation results

In the course of calculation for normal operation conditions the loading with internal calculation pressure p=17.6 MPa and external loads acting on the branch pipe of connecting pipeline were considered.

The reduced stresses determined from components total amount of local membrane (σ_{mL}) and general flexural $\left(\sigma_f\right)$ stresses are shown below while the mechanical loads act on the reference lines 1-1 and 2-2:

$$(\sigma)_2 = 151.1\,MPa < 1.3 \cdot [\sigma] = 245.1\,MPa;$$

$$(\sigma)_2 = 240.9\,MPa < 1.3 \cdot [\sigma] = 245.1\,MPa.$$

Then the internal pressure loading of hydrostatic test and external mechanical loads from connected pipeline and main circulation pipeline were considered.

The reduced stresses determined from components total amount of local membrane (σ_{mL}) and general flexural $\left(\sigma_f\right)$ stresses are shown below while the mechanical loads act on the reference lines 1-1 and 2-2:

$$(\sigma)_2 = 172.8\,MPa < 1.7 \cdot [\sigma]^{Th} = 341.7\,MPa;$$

$$(\sigma)_2 = 340.6\,MPa < 1.7 \cdot [\sigma]^{Th} = 341.7\,MPa.$$

The loading combination of normal operation and design basis earthquake was considered including loads from external dynamic forces.

The reduced stresses determined from components total amount of local membrane and general flexural stresses during the loading combination of normal operation and design basis earthquake at the reference lines 1-1 and 2-2 are given below:

$$(\sigma_S)_2 = 155.9\,MPa < 1.6 \cdot [\sigma] = 301.5\,MPa;$$

$$\left(\sigma_S\right)_2 = 254.5\, MPa < 1.6 \cdot \left[\sigma\right] = 301.5\, MPa$$

The loading combination of normal operation and maximum calculation earthquake was considered including loads from external dynamic forces.

The reduced stresses determined from components total amount of local membrane and general flexural stresses during the loading combination of normal operation and maximum calculation earthquake at the reference lines 1-1 and 2-2 are given below:

$$\left(\sigma_S\right)_2 = 165.4\, MPa < 1.8 \cdot \left[\sigma\right] = 339.2\, MPa;$$

$$\left(\sigma_S\right)_2 = 257.8\, MPa < 1.8 \cdot \left[\sigma\right] = 339.2\, MPa.$$

The loading combination of normal operation breakdown and design basis accident with design basis earthquake was considered including loads from external dynamic forces.

The reduced stresses determined from components total amount of local membrane and general flexural stresses during the loading combination of normal operation breakdown and design basis accident with design basis earthquake at the reference lines 1-1 and 2-2 are given below:

$$\left(\sigma_S\right)_2 = 162.8\, MPa < 1.8 \cdot \left[\sigma\right] = 339.2\, MPa;$$

$$\left(\sigma_S\right)_2 = 256.2\, MPa < 1.8 \cdot \left[\sigma\right] = 339.2\, MPa.$$

5. Conclusions

The paper presents the static loading influence on DN 350 branch pipe cutting-in in the main circulation pipeline of reactor plant WWER-1000. The analysis of calculation results revealed that the reduced stresses in the main circulation pipeline and branch pipe did not exceed the allowed values for the following loading combinations: normal operation breakdown + design basis earthquake, normal operation breakdown + maximum calculation earthquake. Consequently, the static strength conditions of DN 350 branch pipe cutting-in in the main circulation pipeline meet the requirements of technical documentation. Therefore it can be concluded that the continued operation of DN 350 branch pipe cutting-in is regarded as possible.

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