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REDISTRIBUTION OF STRESSES IN THE HEADER–PGV-1000 STEAM GENERATOR CONNECTOR WELDMENT UNDER LOADING AFTER THERMAL TREATMENT

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Additional heating of a thickened portion of the steam generator connector during postrepair thermal treatment of the header-connector weldment leads to a decrease in residual tensile stress levels. It is shown that during hydrostatic tests performed after thermal treatment inelastic strains on the inner connector surface are reduced, which inhances the cycle life of the weldment.

Keywords: header, steam generator, thermal treatment, hydrostatic tests.

Introduction. The relief of undesirable residual stresses induced by welding during repair jobs of the header–PGV-1000 steam generator connector weldment of a WWER-1000 reactor is provided by thermal treatment, including heating, holding at elevated temperature for residual welding stress relaxation, and further cooling. The phenomenon of residual stresses arising during thermal treatment of the header-steam generator connector weldment is not completely understood, which determines a current interest in investigation of this problem.

Earlier data [1] on the optimization of thermal treatment of the header-steam generator connector weldment after repairment were used to propose its conditions that ensure a decrease in maximum residual stresses. These calculations account for the bending moment effect on the weldment on the side of the main circulation pipe (MCP), but do not take into consideration the rigidity of MCP–reactor pressure vessel (RPV) connection and stress redistribution under further service loadings.

The present communication reviews refined calculation results for stress-strain state kinetics in the header–steam generator connector weldment, with simulation of thermal treatment and further service loading, including hydrostatic tests and normal operations.

Choice of a Calculation Scheme. Kinematic ties of elements (steam generator, MCP hot branch, and RPV) of "small"- and "large"-series reactors are similar and differ only in their layout. The calculation model of a small-series steam generator is shown in Fig. 1. The loading scheme accounts for the rest of the steam generator and RPV on rollers and a support collar, respectively, as well as the rigid fixing of the MCP end in the RPV wall. The weldment design, its most loaded element being the thinned portion of the steam generator connector, including the weld joint, is depicted in Fig. 2. This connector portion takes up loads, affecting the steam generator on the MCP side, the weight of structural elements, connected with the header, and of a coolant, as well as pressure-induced loads in the primary and secondary steam generator circuits.

The calculations were performed with SPACE software [2], providing the solution of the three-dimensional problem of thermoplasticity with the account of loading history.

Physicomechanical properties of the steam generator metal were assumed to be dependent on temperature. Inelastic deformation of the material during relaxation by the end of holding was measured by the equation of isotropic strain hardening with the account of the temperature effect [3]

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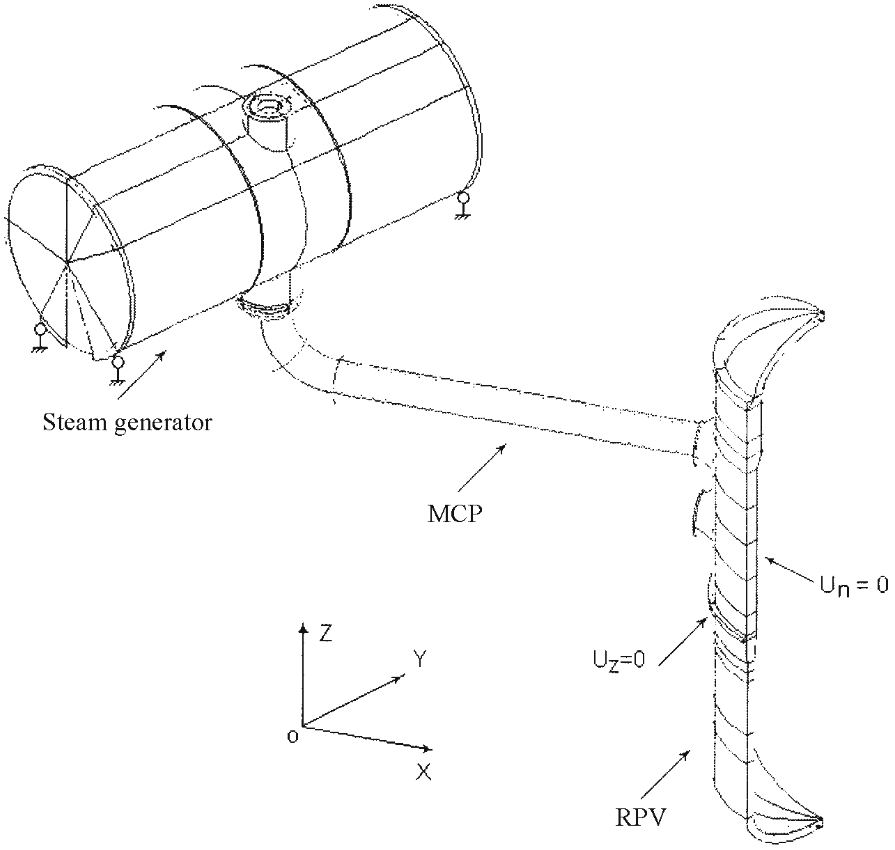

Fig. 1. Calculation model of the reactor with the steam generator, MCP, and RPV.

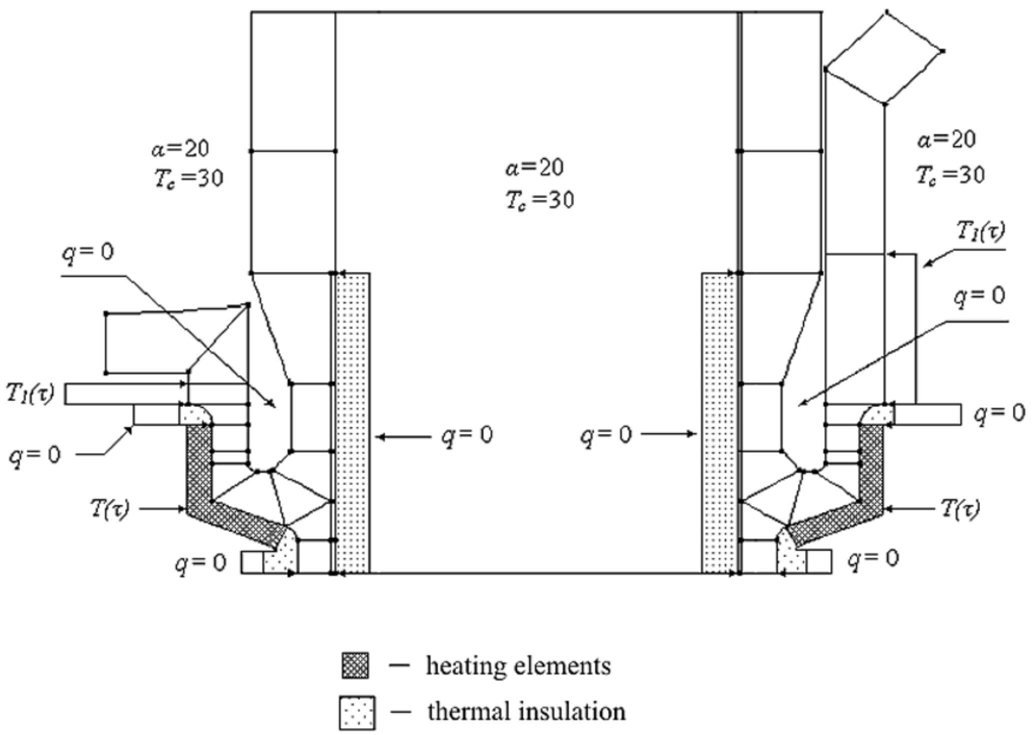

Fig. 2. Heating scheme for optimum thermal treatment.

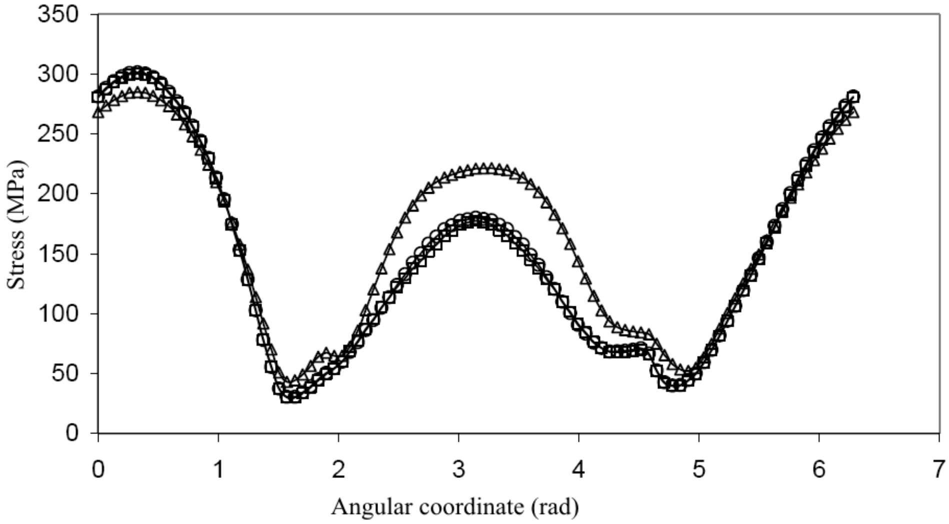

Fig. 3. Distribution of residual stress intensities on the pocket wall along the angular coordinate at a 20-mm distance from the pocket bottom after optimum thermal treatment, hydrostatic tests, and normal operations. Here and in Figs. 4 and 5: (△) σ_i after optimum thermal treatment, (○) σ_i after hydrostatic tests, and (□) σ_i after normal operations.

$$\sigma = \sigma_Y (1+\varepsilon)\left(1-\frac{\Delta T}{T^*}\right),$$

where σ_Y is the yield stress at 20°C, ΔT is the heating temperature, and T^* is the material parameter. The parameters of this equation determine a linear decrease in stresses as a result of relaxation during preset holding, from $\sigma_Y = 340$ MPa ($T = 20$°C) to $\sigma_Y = 100$ MPa ($T = 650$°C).

Calculations of stress-strain state kinetics in the weldment during thermal treatment is performed for its optimum conditions on the basis of earlier simulation results [1]. They envisage heating of the thinned connector portion and a half of the surface of its thickened portion (Fig. 2). Such a treatment can reduce the level of maximum residual stresses in the fillet zone of the header-steam generator connector weldment.

The calculations allow for temperature changes (heating from 20 to 650°C for 9 h, holding at constant temperature for 7 h, cooling down to 20°C for 11 h), corresponding to optimum thermal treatment.

For determining the stress-strain state, the nonstationary problem of heat conduction was first solved with the account of the temperature dependence of thermal properties. Temperature fields were determined at preset time from the onset of loading, these fields were used for solving the problem of thermoplasticity.

To make calculations less time-consuming, a reduced calculation model was proposed in which the MCP connection with RPV was replaced with the MCP rigid fixing. The values of residual circumferential (σ_φ), axial (σ_z), and equivalent (σ_i) stresses on the “pocket” wall in the fillet zone of the weldment, obtained with complete (steam generator, MCP, and RPV) and reduced models, differ inconsiderably (less than 1%). Therefore, further calculations of optimum thermal treatment, hydrostatic tests, and normal operations, were performed with the reduced model as more economic.

Calculation Results for Redistribution of Residual Stresses in the Weldment during First Hydrostatic Tests and Normal Operations after Thermal Treatment. For simulation of hydrostatic tests, the steam generator was subject to a pressure of 25 MPa in the primary circuit and 11 MPa in the secondary circuit. In case of normal operations, it was 16 and 6 MPa, respectively.

Calculation results for residual stress intensites in the large-series header-steam generator weldment after optimum thermal treatment and their redistribution after hydrostatic tests and normal operations are presented below.

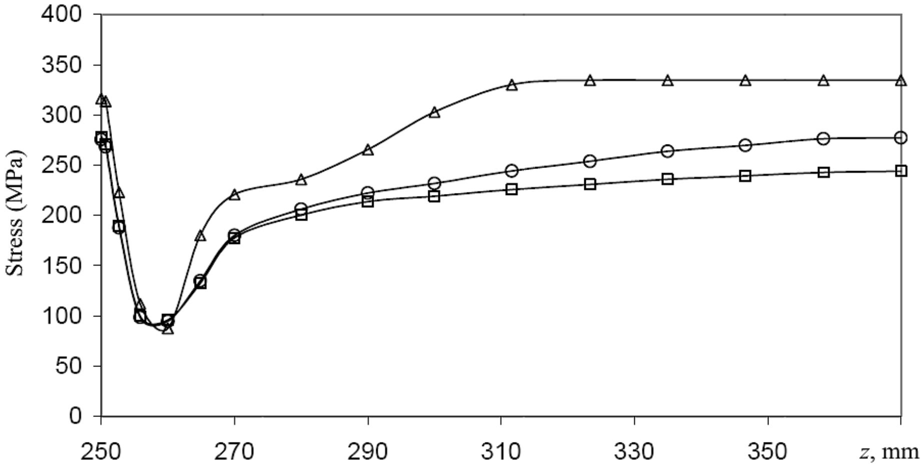

Fig. 4. Distribution of residual stress intensities on the pocket wall in the fillet zone of the large-series steam generator after optimum thermal treatment, hydrostatic tests, and normal operations ($\varphi = \pi$, $z = 250$ mm near the pocket bottom).

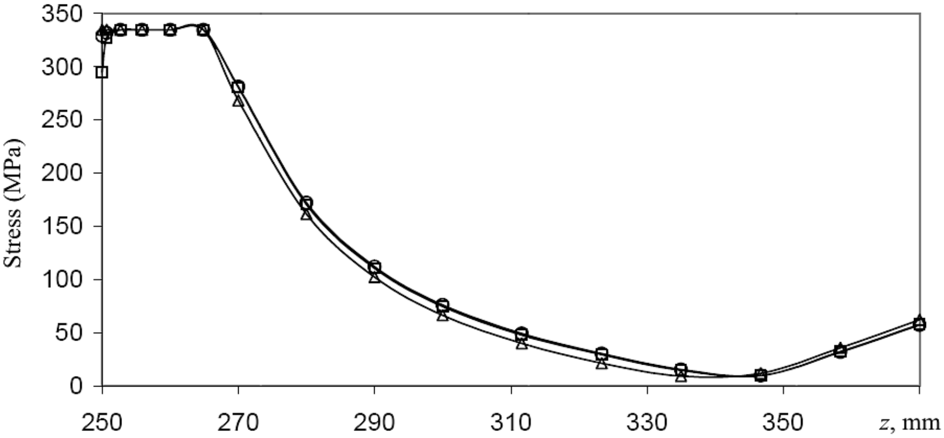

Fig. 5. Distribution of residual stress intensities on the pocket wall in the fillet zone of the large-series steam generator after optimum thermal treatment, hydrostatic tests, and normal operations ($\varphi = 0$, $z = 250$ mm near the pocket bottom).

Distribution of residual stress intensities over the pocket wall along the angular coordinate at a 20-mm distance from its bottom after optimum thermal treatment, hydrostatic tests, and normal operations is depicted in Fig. 3. As is seen, residual stress intensities are distributed very nonuniformly. They reach the highest values near the areas adjacent to the short and long connector portions at all the stages of the loading cycle.

Distribution of residual stress intensities after optimum thermal treatment and their redistribution after the first hydrostatic tests and normal operations for short and long connector portions in the meredian sections, corresponding to $\varphi = \pi$ and $\varphi = 0$ angles are shown in Figs. 4 and 5, respectively.

Maximum values of residual stress components after optimum thermal treatment, hydrostatic tests, and normal operations in the fillet zone ($z = 250$–270 mm) for the short and long connector portions are summarized in Tables 1 and 2, respectively.

Plastic strain intensities on the pocket wall in the fillet zone after optimum thermal treatment, hydrostatic tests, and normal operations ($\varphi = \pi$ and $\varphi = 0$ for the short and long connector portions, respectively) are shown in Fig. 6.

TABLE 1. Residual Stresses in the Short Connector Portion

Stress, MPa	After optimum thermal treatment	After hydrostatic tests	After normal operations
σ_φ	$\frac{150}{150}$	$\frac{171}{171}$	$\frac{172}{172}$
σ_z	$\frac{223}{223}$	$\frac{180}{180}$	$\frac{173}{173}$
σ_i	$\frac{221}{316}$	$\frac{180}{276}$	$\frac{176}{278}$

Note. Here and in Table 2: stresses on the pocket wall (20 mm from its bottom) are cited over the line, maximum stresses in the fillet zone are given under the line.

TABLE 2. Residual Stresses in the Long Connector Portion

Stress, MPa	After optimum thermal treatment	After hydrostatic tests	After normal operations
σ_φ	$\frac{172}{14}$	$\frac{14}{208}$	$\frac{14}{208}$
σ_z	$\frac{-56}{-182}$	$\frac{-68}{-192}$	$\frac{-66}{-192}$
σ_i	$\frac{67}{335}$	$\frac{76}{332}$	$\frac{74}{335}$

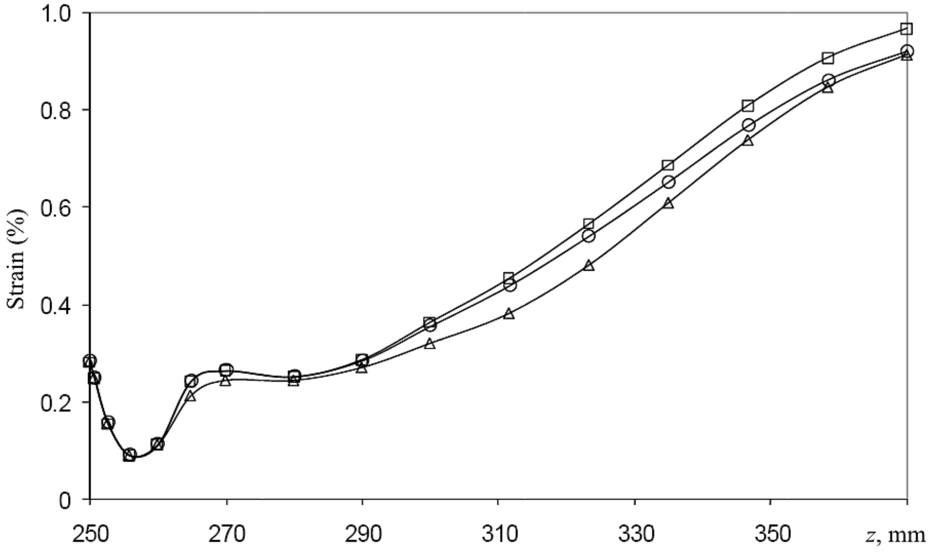

Fig. 6. Distribution of plastic strain intensities on the pocket wall in the fillet zone of the large-series steam generator after optimum thermal treatment, hydrostatic tests, and normal operations ($\varphi = \pi$, $z = 250$ mm near the pocket bottom): (△) ε_{ip} after optimum thermal treatment, (○) ε_{ip} after hydrostatic tests, and (□) ε_{ip} after normal operations.

Calculation results show that loading during normal operations after hydrostatic tests does not result in significant changes of residual stress and plastic strain intensities over the pocket surface (along the header axis and along the circumferential coordinate), except for the narrow zone near the short connector portion. It may be suggested that during hydrostatic tests and normal operations residual stresses are redistributed, as a result the level of inelastic strains decreases during the loading cycle.

Plastic strain intensities on the pocket wall in the fillet zone at $\varphi = 0$ after optimum thermal treatment do not change during hydrostatic tests and normal operations.

CONCLUSIONS

1. The applicability of the reduced calculation model (with the rigid fixing of the MCP end on the RPV side) has been demonstrated. It accounts for the bending moment effect on the weldment on the MCP side and provides refined estimation of the stress-strain state during thermal treatment.

2. Additional heating of the thickened connector portion during thermal treatment reduces the level of maximum residual tensile stresses in the weldment. Hydrostatic tests after such a treatment lead to a decrease in inelastic strains and, as a result, to an increase in a number of cycles to fracture, determined by the ultimate metal plasticity.

3. Loading during normal operations after hydrostatic tests does not give rise to inelastic strains on the pocket surface, except for local areas in the fillet zone. Changes of inelastic strain intensities in those areas during the first loading cycle of normal operations do not exceed 0.03% and are accompanied by a decrease in residual stress intensities.

4. It may be suggested that the redistribution of residual stresses during further loadings would result in less intensive accumulation of inelastic strains during the loading cycle of normal operations, which would exert a beneficial effect on the period of safe operation of the steam generator. Estimation of such an effect is the goal of further investigations.

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