INVESTIGATION OF STRESS-STRAIN STATE OF WELDED STRUCTURES FROM AUSTENITIC STEEL AT RADIOACTIVE IRRADIATION

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Nuclear reactor reflection shield is exposed to high doses of radiation, leading to its noticeable deformation and closing of the clearance between the reflection shield and cavity wall. This leads to a change of heat exchange in the reactor core that may have hazardous consequences in terms of violation of temperature mode of reactor operation. To evaluate the radiative swelling of the reflection shield, a 2D finite element model was constructed, using calculation algorithms well-tested at the E.O. Paton Electric Welding Institute, in which isotropic volumetric deformations were assigned as radiative swelling. The model non-linearly takes into account the dependence of radiative swelling of the reflection shield material on irradiation temperature, stressed state and plastic deformations. The model also describes the change of yield limit of welded cavity wall, as a function of irradiation temperature and accumulated radiation dose. After 25 years of reactor operation the maximum value of swelling deformations in reflection shield material is equal to 1.3 %, reaching 1.8 after 40 years, and 3.7 after 60 years. Maximum radial displacements of the reflection shield outer surface during reactor operation are equal to 11.2 mm after 25 years, 12.9 mm after 40 years, and 16.1 mm after 60 years. In a more conservative model, not allowing for the history of volumetric deformation accumulation, reflection shield swells by 26 % over 60 years of operation that corresponds to even greater radial displacements of reflection shield outer surface in the outward direction. Results on swelling and radial deformations of the reflection shield derived allowing for the stressed state are indicative of a possible contact of reflection shield with the cavity welded wall during reactor operation. Such a contact can greatly affect the stress-strain state of the cavity welded structure, therefore, it requires a more detailed study. 9 Ref., 2 Tables, 14 Figures.

Keywords: *welded metal structures, austenitic steel, stress-strain state, reflection shield, reactor service life, radiative swelling, numerical model, cavity wall*

In a nuclear reactor the energy source are rod-like radioactive fuel elements (FE). They are grouped into fuel element assemblies (FEA), forming the reactor core, which is surrounded by a steel shell of a cylindrical shape — the reflection shield (Figure 1), made from austenitic steel by forging. In its turn, FEA and reflection shield are placed into the welded structure of reactor cavity and are fastened to its faceted girth. The main purpose of the shield is FEA grouping into the core, reducing the intensity of neutron flux to reactor case, and ensuring core coolant circulation along the design circuit [1].

Height of reflection shield of WWER-1000 reactor (Figure 2) is 4070 mm. It consists of five rings of the same height pinned to each other. The ring inner surface is faceted. Shield radius in the place of ring joining is 1742.5 mm. The shield is cyclically symmetrical relative to a 60° sector that essentially simplifies the modelling process.

Shield cross-section (normal to the axis) is shown in Figure 3. Diameter of small channels is 70 mm, large channel diameter is 130 mm.

Reflection shield and wall of welded cavity of nuclear reactor are exposed to high doses of radiation, which causes a whole range of defects, leading to degradation of physico-mechanical properties. In chromium-nickel steels microstructural transformations take place under the conditions of heating up to 400–550 °C with partial transition from austenitic into ferritic state with formation of carbides of chromium, titanium, molybdenum and other impurity metals [2]. Nonetheless, the main phase (austenite) preserves about 90 % of the total volume. So, at high-temperature irradiation by intensive neutron fluxes, vacancy pores initiate and grow in austenitic steels and nickel-, titanium-, molybdenum- and beryllium-based alloys, leading to a noticeable increase of the metal volume — radiative swelling. This process largely depends on radiation dose, irradiation temperature and stresses and plastic deformations in the material caused by swelling [1–3].

Radiative swelling of reflection shield material leads to its deformation and closing of the

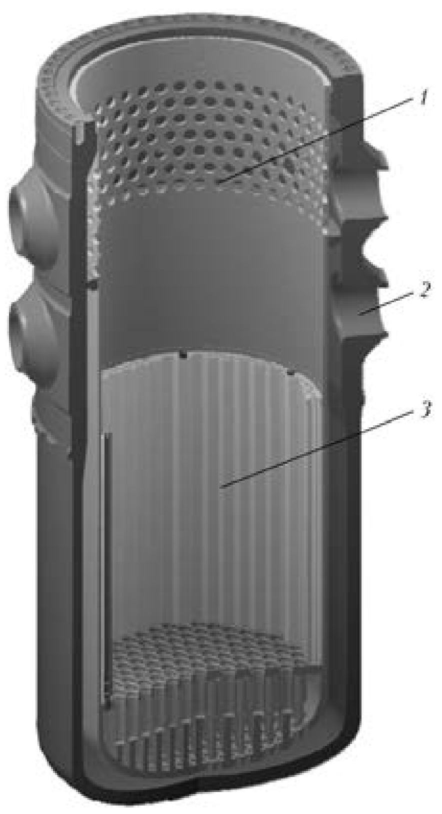

Figure 1. Reactor design: *1* — cavity; *2* — vessel; *3* — reflection shield

clearance between it and cavity wall, thus resulting in a change of heat exchange in the core, which may have hazardous consequences in terms of violation of temperature mode of reactor operation. Complete closing of the clearance between the reflection shield and cavity wall and further swelling of reflection shield leads to a considerable deformation of cavity wall and stress increase that may result in its failure. Pre-

Figure 2. General view of reflection shield

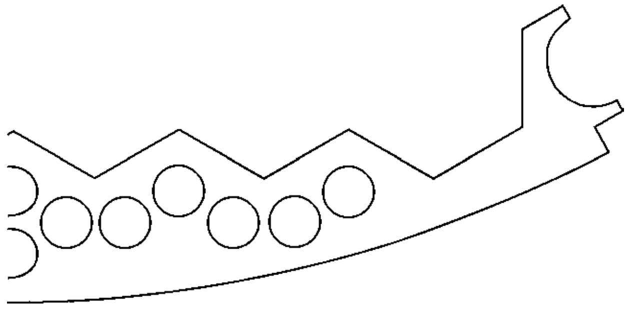

Figure 3. Section of reflection shield, 30° sector

diction of the change of stress-strain state (SSS) of the reflection shield and welded structure of cavity wall in operation, in particular for substantiation of extension of service life of operating WWER-1000 reactors up to 60 years, is an extremely urgent task today.

Reflection shield material is austenitic steel 08Kh18N10T of the following composition, wt.%: 0.8 Si; 0.3 Cu; 2 Mn; 10 Ni; 0.4 Ti; 0.035 P; 18 Cr; 0.02 S. Physical properties of 08Kh18N10T steel, given in Table 1, correspond to the initial (nonirradiated) state.

In order to assess radiative swelling of the reflection shield, a 2D finite element model was constructed (Figure 4). A section, where the values of damaging dose and energy evolution are maximum, was specifically selected for shield behaviour modelling. Conditions of cyclic symmetry for shield sector of 60°, and symmetry relative to a straight line dividing this sector into two equal sectors of 30° were applied. Each of the respective mechanical problems was solved under the conditions of generalized plane strain. Model constructed from linear four- or three-node elements in the form of rectangles or triangles, contains 10486 nodes and 9748 elements.

Temperature distribution in the reflection shield during swelling calculation is constant and is determined by preliminary nonstationary thermodynamic calculation (reactor reaching maximum power mode). Assigned as boundary conditions are coolant temperatures in the channels and on free surfaces of reflection shield (Figure 5, Table 2), as well as respective heat transfer co-

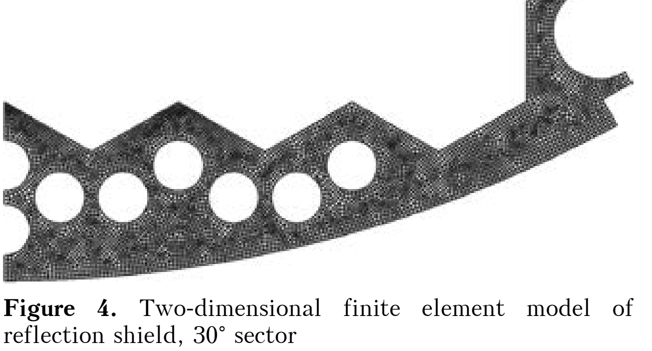

Figure 4. Two-dimensional finite element model of reflection shield, 30° sector

Table 1. Physical properties of 08Kh18N10T steel [4, 5]*

Temperature T, °C	Young's modulus E, GPa	Coefficient of linear expansion α^t, $\cdot 10^{-6}$ K^{-1}	Heat conductivity λ, W$\cdot$m$^{-1}\cdot$K^{-1}	Specific heat capacity c_p, J$\cdot$kg$^{-1}\cdot$K^{-1}	Density ρ, kg/m^3
20	205	–	16.6	478	7900
100	200	16.6	17.2	495	7862
200	190	17.0	18.0	516	7821
300	180	17.4	18.7	537	7778
400	170	17.8	19.4	558	7732
500	165	18.2	20.1	579	7684
600	160	18.5	20.8	600	7634

*Poisson's ratio ν = 0.3 [1].

Table 2. Coolant temperature and values of heat exchange coefficients for different surfaces of reflection shield [1]

Surface number acc. to Figure 5	Surface temperature, °C	Heat exchange coefficient, W/(m$^2\cdot$K)
1, 6, 8	291.7	2308
2–5, 2–7	292.1	1331
9	291.7	1115
10	291.7	15900
11	320.0	39017

efficients. Volumetric heat generation in reflection shield material is taken into account (Figure 6).

Heat flows (q, W/m^2) are determined by the formula

$$q = -h(\theta_{in} - \theta_{out}), \qquad (1)$$

where θ_{in} is the surface temperature, °C; h is the heat-transfer coefficient, W/(m$^2\cdot$K); θ_{out} is the coolant temperature, °C.

Calculation method is used to find the values of stresses and strains in the reflection shield, arising at reactor reaching the full power mode. This SSS is incorporated into swelling calculations as initial conditions.

Result of temperature field calculation is given in Figure 7. The pattern and absolute values of temperature are in complete agreement with the results given in [1].

Then, in order to evaluate the change of the shield shape during 60 years of reactor operation, tracing in time of initiation and development of radiative swelling deformations and of the respective SSS change under the conditions of constant temperature distribution was performed. Periodical cooling of the shield at reactor shutdowns was not taken into account, as it was determined by calculations for one cooling–heating cycle that this does not cause any redistribution of residual deformations. PWI has accumulated extensive experience of solving non-linear problems of tracing the initiation and development of plastic strains in welding and subsequent cooling [6]. Therefore, this problem was solved with application of well-tested calculation algorithms,

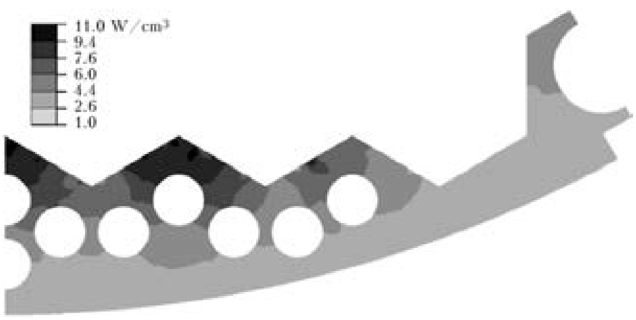

Figure 6. Volumetric heat evolution in reflection shield at reactor running at full power

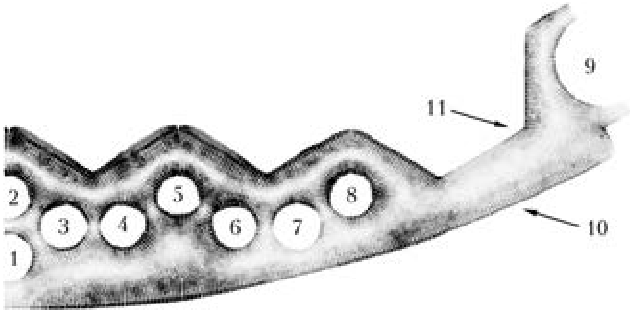

Figure 5. Heat flows in reflection shield: 1–9 — channel surfaces; 10, 11 — free surfaces

Figure 7. Temperature distribution in reactor reflection shield at operation at maximum power

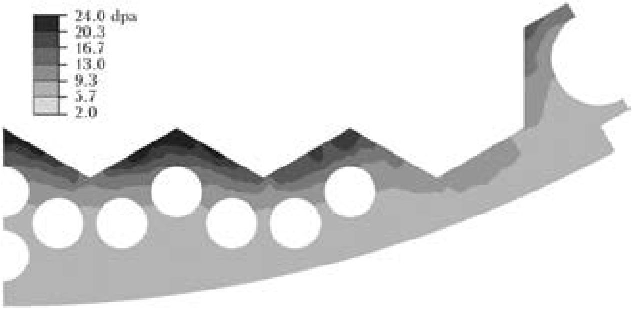

Figure 8. Damaging irradiation dose, 22nd fuel cycle

in which radiative swelling deformations in the form of isotropic volumetric deformations were assigned as bulk effects. Material swelling increment is calculated in each time step. Values of damaging dose (Figure 8), yield limit, average stresses and plastic strains in each finite element are recalculated at the same time. Size of time step is 1 year, that ensures sufficient accuracy at calculation of reflection shield swelling for the cases of 15, 40 and 60 years of reactor operation.

Dependence of swelling S_i of the considered material at a certain moment of time can be presented in the following form [2, 7, 8].

$$S_i = C_D D_i^n f_0(T) f_1(\sigma_m) f_3(\kappa), \quad S_i > 0, \tag{2}$$

where D_i^n is the irradiation dose, displacements per atom (dpa); $f_0(T) = \exp\,(-r(T - -T_{max})^2)$; $f_1(\sigma_m) = 1 + P\sigma_m$; $f_3(\kappa) = \exp\,(-\eta\kappa)$; C_D, n, r, P, η are the dimensionless constants ($C_D = 1.035{\cdot}10^4$, $n = 1.88$, $r = 1.1{\cdot}10^{-4}$, $P = 4{\cdot}10^{-3}$ MPa^{-1}. $\eta = 8.75$); $T_{max} = 470$ °C; T is the irradiation temperature, °C; $\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$ are the average stresses; $\kappa = \int_0^D d\varepsilon_i^p$, where $d\varepsilon_i^p$ is the intensity of plastic deformation increments equal to

$$d\varepsilon_i^p = \frac{\sqrt{3}}{2}\sqrt{d\varepsilon_{ij}^p d\varepsilon_{ij}^p}, \quad i, j = 1\text{–}3.$$

Total swelling in all N time steps is sought as a sum of swelling increments in each step:

$$S_\Sigma = \sum_{i=1}^{N} dS_i, \quad dS_i > 0.$$

This model allows for the history of accumulation of volumetric deformations as a result of radioactive irradiation.

Yield limit of materials of reflection shield and cavity changes under the impact of temperature and radioactive irradiation by the following dependence [2]:

$$\sigma_{0.2} = 153 + 239\exp\,(-2.22{\cdot}10^{-3}(T + 273)) + 365\left(\frac{T}{T_{ir}}\right)^{-2.2}\left[1 - \exp\left(-0.47\,\frac{D}{D_0}\right)\right]^{0.5}, \tag{3}$$

where $T_{ir} = 450$ °C; $D_0 = 4.55$ dpa.

So, after the reactor has reached full power mode, when the irradiation dose is still negligibly small, material yield limit decreases (Figure 9). At the same time, stressed state is intensified, thus leading to initiation of a plastic region in the reflection shield (Figure 10). At this stage the yield limit value is completely determined by the first two addends from dependence (3).

At increase of accumulated irradiation dose the influence of the third addend from dependence (3) on the yield limit is also increased. So, during the first year of reactor operation the yield limit of reflection shield material increased from 220 MPa in the region of the temperature maximum up to 480 MPa in the region of the maximum of accumulated damaging dose (Figure 11).

General pattern of volumetric swelling deformations in the reflection shield remains approximately the same during the entire operation period of the reactor (Figure 12), but the absolute value of swelling increases. After 25 years of reactor operation, the maximum value of swelling

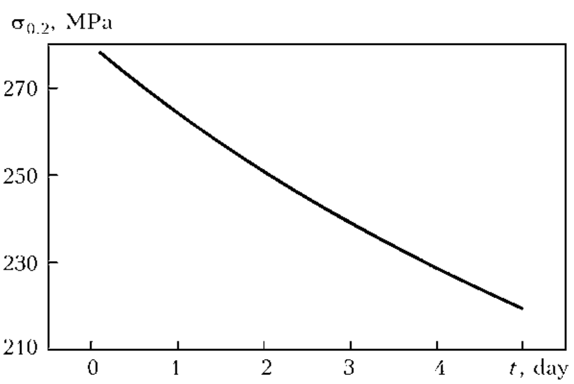

Figure 9. Lowering of yield limit at heating of reflection shield when reaching the working mode (maximum temperature mode)

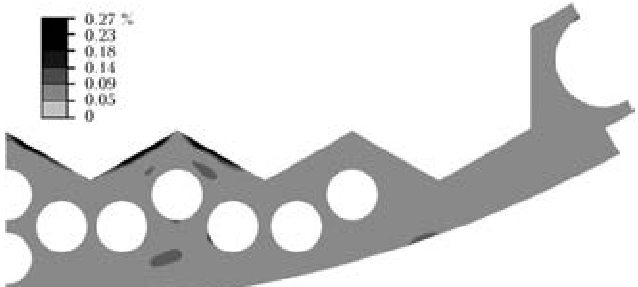

Figure 10. Intensity of plastic deformations in reflection shield after reactor reaching the required mode

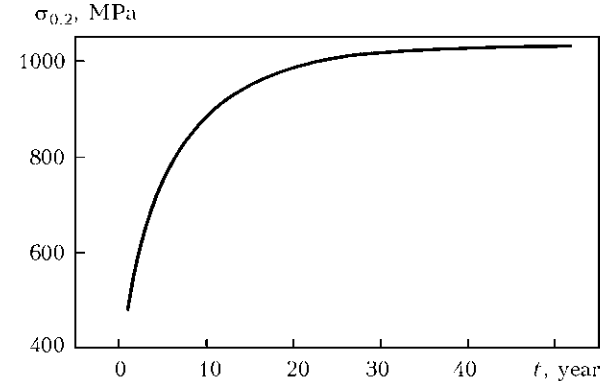

Figure 11. Increase of yield limit at accumulation of irradiation dose during reflection shield operation (in the zone of maximum of accumulated damaging dose)

deformations is equal to 1.3, after 40 years it is 1.8 and after 60 years — 3.7 %.

Because of non-uniform heating and swelling, radial deformations in the reflection shield are unequal. Radius increment is maximum in the region of large channel 9, and minimum in the region of channel 1 (Figure 13). Their difference is noticeable already when the reactor reaches full power mode, even when the swelling value is negligibly small. Increment of radius on the shield outer surface at reactor running at full capacity is positive everywhere, but at swelling accumulation the shield outer surface in the region of channel 1 moves inside, while the radius in the large channel mode continues growing.

Radial displacements of the shield outer surface after reactor going into normal operation mode are equal to 11.2 mm for the MAX region, and 9.4 mm for MIN region. After 25 years of operation MAX(MIN) radial displacements are equal to 12.9 (8.8 mm); after 40 years — 14.1 (7.9); and after 60 years — 16.1 (7.1), respectively.

In a number of currently available publications [1] it is proposed to perform calculation of volumetric deformations resulting from radiative swelling by the following formula:

$$S = \Delta V/V = 0.55(D + 0.1T - 67) \exp\,(-2.9\cdot10^{-4}\,(T - 485)^2), \tag{4}$$

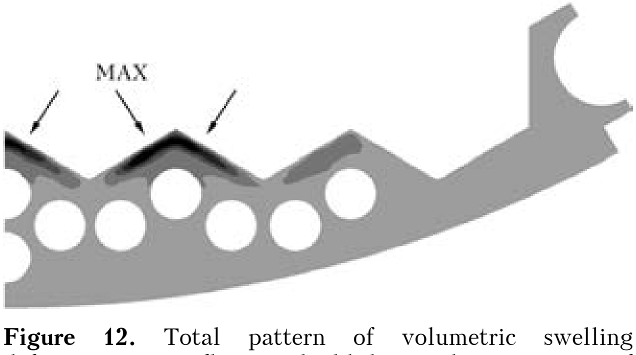

Figure 12. Total pattern of volumetric swelling deformations in reflection shield during the entire term of reactor operation

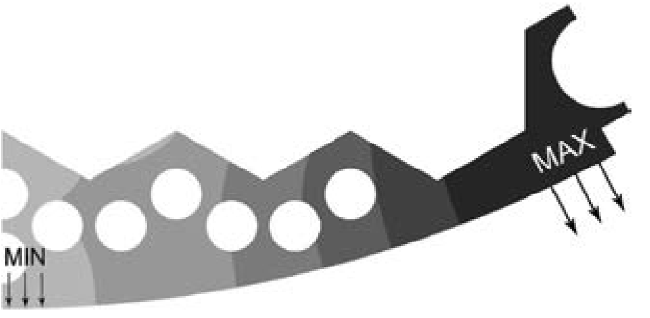

Figure 13. Regions of maximum and minimum increment of radius in the reflection shield during operation

where S is the relative radiative swelling, %; $\Delta V/V$ is the volumetric swelling of the reflection shield, %; D is the damaging irradiation dose, dpa.

Such a model does not allow for the stressed state, and it means that calculation does not depend on loading history. Expression $(D + 0.1T - 67)$ can take negative values, if irradiation dose has not reached a certain value, and in this case the swelling value is zeroed by the program. In keeping with this model, swelling begins in the 23rd year of reactor operation, when maximum value of the dose in the reflection shield $D = 67 - 0.1T = 25$ dpa. Incubation period [9], during which this dose will accumulate, is 23 years.

Evaluation of swelling by formula (4) over 60 years yields

$$S = 0.55(65.5 + 490/10 - 67) \exp\,[-2.9\cdot10^{-4}\,(490 - 485)^2] = 0.55\cdot47.5 \exp\,(-7.25\cdot10^{-3}) = 26\ \%.$$

Program calculation by formula (4) yields 17 %. Calculation result is given in Figure 14.

Calculation of volumetric deformations over 60 years of reactor operation performed in this work by a refined model (formulas (2) and (3)) allowing for SSS yields not 26 %, but a much lower value of 3.7 %. Thus, allowing for the loading history (stressed state) at evaluation of radiative swelling of the shield material and its radial deformations essentially influences the accuracy of the results.

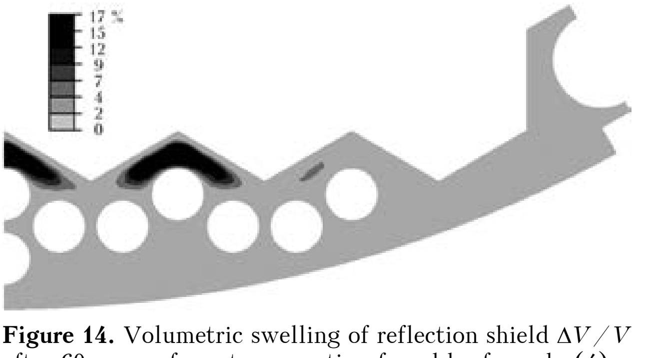

Figure 14. Volumetric swelling of reflection shield $\Delta V/V$ after 60 years of reactor operation found by formula (4)

Results on swelling and radial deformations of the reflection shell, obtained allowing for the stressed state, are indicative of the possible contact of the shield with the welded wall of the cavity during reactor operation period, with the initial minimum clearance between them being 2.5 mm. Such a contact can have an essential influence SSS of the cavity welded structure, so that it requires a more detailed study and construction of a 3D model of radiative swelling and contact interaction of the shield and cavity wall, allowing for distribution of irradiation dose and heating by structure height.

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NEWS

Technology and Equipment for Electroslag Welding of Busbars of Aluminium Electrolysers under Conditions of Service and Powerful Magnetic Fields

At present, when assembling the busbars in electrolysis shops the welding-on of outlet chutes to busbars is one of the most complicated and labor-intensive operations. Welding is realized under the conditions of effect of high-power magnetic fields, influencing negatively the welding process stability. Moreover, the work with busbars is performed without switching-off of the technological current.

The technology of electroslag welding (ESW) with consumable wire electrode is offered for mastering, allowing making welding of joints of sections from 60 × 800 mm up to 140 × 1000 mm under the conditions of operating shops and powerful magnetic fields. A rolled aluminium wire of diameter of up to 10 mm and fluxes, not containing lithium, and which are available in sufficient amounts at any enterprise of this profile, are used as welding consumables. Specialized equipment, rigging and technological processes are designed and developed to suit the conditions of the Customer.

ESW can be performed both at the de-energized area of busbar and also on the busbar, along which the technological current of up to 7 kA is passed. Inspection of electrotechnical properties of joints showed that the voltage drop (allowable to 20 mV) in joints, produced by ESW, was 5.2 mV (while in manual arc welding the voltage drop is 30 mV), and it is 4.8 mV at a monolithic busbar.

The given technology allows decreasing the losses of electric power in welded joints, reducing the expenses for manufacture and repair of aluminium busbars, improving the welding process efficiency and quality of aluminium welded joint of above-mentioned sections, improving greatly the labor conditions of the welders.

A number of foreign companies resumed the application of mechanical joints in the busbar design. At aluminium plants of CIS the manual arc welding with carbon electrode and method of filling with a molten aluminium are used. All the applied technologies do not provide a stable required quality of busbar joints.

New technology of ESW has been successfully tested at maximum magnetic fields (vertical component of a magnetic induction was $30\cdot10^{-4}$ T) using laboratory equipment at operating shops of aluminium plants of the Russian Federation.

Term of payback: not more than 12 months.