UNCONVENTIONAL PLUGGING TECHNIQUE OF A STEAM GENERATOR DEFECTIVE TUBE. THE MATHEMATICAL MODEL

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Although many of the component problems in Nuclear Power Plants have diminished considerably, those associated with the steam generators persist. Several strategies have been developed to minimize degradation problems and prolong steam generator life: water chemistry improvements, plugging, sleeving, cleaning, etc. Isolating a steam generator defective tube assumes installing a plug whose geometrical configuration allows the plastic deformation technique to be applied. The high-speed plastic deformation techniques applied do not produce localized heat and therefore, neither additional mechanical stress nor structural changes in deformed material. The paper contains a brief description of the plastic deformation technique by electro-hydraulic shock, the calculus method used in the experimental data analysis resulted from installing the experimental model of plug variants, designed and produced and a numerical model which will further be employed in parametric studies.

Keywords: NPPs steam generator, plugging procedure, electro-hydraulic shock, expansion socket, theoretical pressure peak

1. Introduction

For a CANDU nuclear system, the heat exchange between the primary and secondary systems takes place at the level of steam generators tubes lacing (over 3500 tubes with small diameter: less than 14 mm, inner diameter) ∩ shaped, mechanical rolled at both ends in a tube sheet. The steam generator is designed to allow the periodical inspection activities at the inner tube wall level and of the plugging operations, permitting the access for a short time in its water chambers (D2O inlet / outlet) and implicitly at tube sheet. The lifetime of this complex

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equipment, depends extensively on the behaviour in operation of its components adapted structured in the tube side and in the support assembly.

Utmost volume of the research and engineering activities performed in the degradation mechanisms are based on the research of behaviour in operation at ∩ shaped tube bundle, mechanical rolled at the ends in the tube sheet, before understanding the issues generated by other thermo-hydraulic components of secondary system, or by the mechanical vibrations induced and by fretting. The approach is natural because the steam generator tube form an important part of the pressure limit of the primary heat transport system [1]. Nowadays, all types of mechanical and corrosion degradation mechanisms generated in time for each material used in manufacturing the generator tubes are known and therefore one can highlight the significance of maintaining under control the fluids chemistry (primary and secondary). The small thickness of the tube wall, imposed by the heat transfer efficiency from the primary system to the secondary one, makes the steam generator tube vulnerable over time to the actions of mechanical and/or corrosion degradation mechanisms. It is important to isolate the defective tube before or right at the beginning of cracking initiation, if the leak of primary agent exceeds the preset threshold value. Plugging of the steam generator tube is performed, usually, by one of the mechanical deformation techniques known (conventional, for which the deformation speed is less than 100 m/s or unconventional for which the deformation speed exceeds away the value of 100 m/s), using a special plug, built in accordance with the chosen installing technique. The Institute for Nuclear Research of Piteşti is experimentally developing a plugging method of the steam generator defective tubes by an unconventional plastic deformation technique, i.e. installing the plug using an electro-hydraulic shock at low potential.

This paper describes the plastic deformation technique by electro-hydraulic shock deformation of the plug wall, the experimental setup, the mathematical procedure employed for evaluation of the pressure wave peak (it represents a significant indicator for technique application), and the numerical model developed based on the experimental results.

2. Description of the unconventional technique

The mechanical deformation technique by electro-hydraulic shock is treated in the literature very briefly hence, in order to gain useful data for technological development and deeper understanding of the electro-hydraulic phenomenon execution and control and of its effects is necessary to perform experimental tests.

The plastic deformation technique by electro-hydraulic shock is based on the pressure peak generated instantaneous by a plasma track obtained by vaporizing a fusible and a water volume surrounding it into a closed volume characterized mainly by the expansion socket of the plug (see Fig. 1) [2].

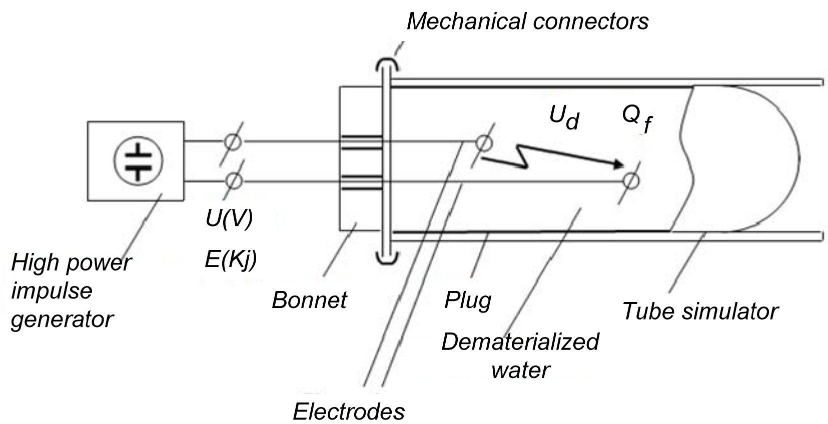

Fig. 1. Basic diagram of the plugging setup

A similar technique is the plastic deformation technique by explosion where the pressure peak is given by instantaneous burning of an explosive amount in a confined space.

Both techniques are basically characterized by a high propagation speed of the pressure wave and implicitly of the deformation speed, i.e. W >> 100 m/s. For such deformation speed values, the elastic theory of materials (Hooke's law) doesn't apply and the material is „flowing" into the joint maintaining the size and the grains shape, without heat transfer and, therefore, without mechanical stress due to restrained dilatation [3].

In our case, the plugging procedure itself consists of: a preparation stage (fitting-out) for installation of the experimental model plug, arrangement of the plug equipped for installation in the steam generator tube simulator; execution of the electric connections; installing process itself by discharging the high power impulse generator; dismantling and removing the additional components of the plug followed by cleaning the inner socket of the plug [4].

One of the most recent plug version (1), experimental model, and t steam generator tube simulator (2) are shown in Fig. 2.

Fig. 2. Plug experimental model before installation

The experimental model of plug, remain fitted by plastic deformation in the steam generator tube simulator, Fig. 3.

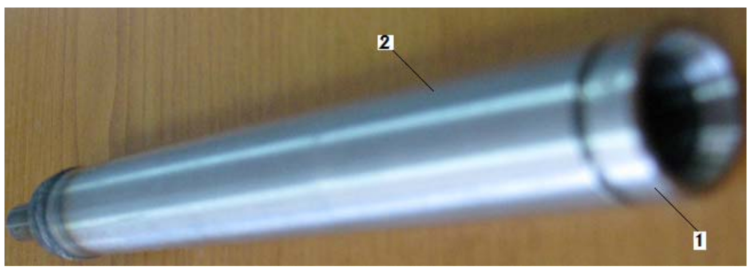

Fig. 3. Plug experimental model after installation

The tests performed in laboratory conditions proved that the plastic deformation technique by electro-hydraulic shock can be controlled by choosing the discharge electric power value, the electric tension level at the impulse generator jacks, the fusible material and sizes used and the initial water volume [5-7].

3. The mathematical model

The mathematical model has been built based on the experimental results and it is continuously improved by deeper understanding of the process itself in order to increase the performances of the experimental plug models and to extend the application of the high speed plastic deformation technique (by electro-hydraulic shock).

The mathematical model employs the data resulted from the experimental tests and physical characteristics of the materials. The model is presented below:

- The resistance of the whole electric circuit is calculated with relation:

$$R_t = \frac{\Delta t U_{med}^2}{\Delta L} \tag{1}$$

where: U_{med} is the average discharge voltage; Δt represents the vaporization time of the fusible; ΔL is the charging voltage of the impulse generator.

- The electric resistance of the fusible is calculated:

$$R_f = \rho_f \frac{l}{s} \tag{2}$$

where: ρ_f is the specific resistance of the fusible; l is the active length of the fusible; d is the fusible diameter.

- The average discharge current is calculated:

$$I_{med} = \frac{U_{med}}{R_f} \tag{3}$$

- The water amount reaching instantaneous the vaporisation temperature of the process is calculated:

$$m = \frac{\Delta L^*}{c_p t_v} \tag{4}$$

where: ΔL^* is the electric voltage discharged on the fusible; c_p represents the specific heat of water at constant pressure and t_v is the vaporisation temperature;

- The water volume converted at constant pressure in overheated steams is calculated by:

$$V = \frac{M}{\rho} \tag{5}$$

- The theoretical diameter for pressure wave propagation speed is calculated considering the water volume converted in overheated steams at constant pressure:

$$D = \sqrt{\frac{4V}{\pi d}} \tag{6}$$

- The water amount vaporised at constant volume is calculated:

$$m' = \frac{\Delta L^*}{c_v t_v} \tag{7}$$

where: c_v is the specific heat of water at constant volume;

- The steam volume overheated into the constant volume enclosure of the plug socket is given by:

$$V' = \frac{m'}{\rho} \tag{8}$$

- The theoretical pressure peak generated at constant volume is calculated:

$$p = \frac{V'}{V^*} \tag{9}$$

where: V^* represents the water volume from the swelling socket of the plug;

- The theoretical propagation diameter of the pressure wave peak is calculated considering the value obtained for the water volume converted into overheated steam at constant volume:

$$D' = \sqrt{\frac{4V'}{\pi \cdot l}} \tag{10}$$

- The theoretical propagation speed of the pressure wave is calculated:

$$w = \frac{\frac{D'}{2}}{\Delta t} \tag{11}$$

4. Development of the numerical model

To study the plastic deformation under high speed wave propagation inside a solid specimen considering the elasto-plastic behavior of the material the AutoDyn code [8] was employed. The code permits the automatic calculation of the plastic work performed in the material if a proper viscoplastic strength model is used.

Viscoplasticity [9] is a theory in continuum mechanics that describes the rate-dependent inelastic behavior of solids. Rate-dependence in this context means that the deformation of the material depends on the rate at which loads are applied. The inelastic behavior that is the subject of viscoplasticity is the plastic deformation which means that the material undergoes unrecoverable deformations when a load level is reached. Rate-dependent plasticity is important for transient plasticity calculations.

One consequence of yielding is that as plastic deformation proceeds, an increase in stress is required to produce additional strain. This phenomenon is known as Strain/Work hardening. For a viscoplastic material the hardening curves are not significantly different from those of rate-independent plastic material (see Fig. 4).

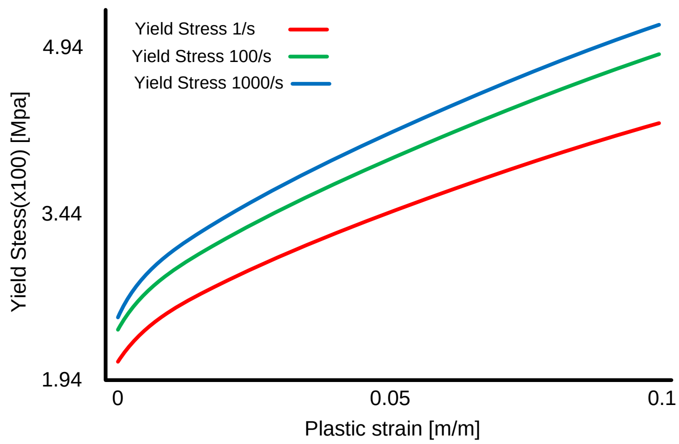

Fig. 4. Stress-strain response of SS321 at different strain rates

An elastic-viscoplastic material with strain hardening is described by equations similar to those for a elastic-viscoplastic material with perfect plasticity. However, in this case the stress depends both on the plastic strain rate and on the plastic strain itself. For an elasto-viscoplastic material the stress, after exceeding the yield stress, continues to increase beyond the initial yielding point. This implies that the yield stress in the sliding element increases with strain and the model may be expressed in generic terms as:

$$\varepsilon = \varepsilon_e = E^{-1}\sigma \quad for \quad |\sigma| < \sigma_y \tag{12}$$

$$\varepsilon = \varepsilon_e + \varepsilon_{vp} = E^{-1}\sigma + f(\sigma, \sigma_y, \varepsilon_{vp})\sigma \quad for \quad |\sigma| > \sigma_y \tag{13}$$

where f(σ, σ_y, ε_{vp}) is a yield function, σ is the Cauchy stress, ε_{vp} is the plastic strain.

In this paper the yield function is given by an empirical model, Johnson-Cook relation:

$$\sigma_y = [7.92e5 + 5.1e5\varepsilon_p^{0.26}][1 + 0.014\ln(\varepsilon_p^*)] \tag{14}$$

where ε_p is the equivalent plastic strain, ε^*_p is the plastic strain-rate.

AudoDyn code has an explicit solver; the transient simulation time step is automatically controlled to meet the criterion of stability of solutions. The mesh grid created in our case (see Fig. 5) contains two sub layers for both plug and pipe walls.

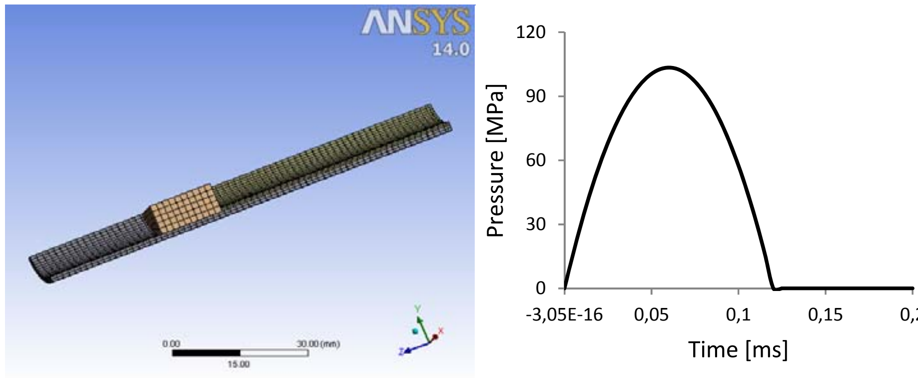

Fig. 5. Finite element model (right) and applied pressure time variation (left)

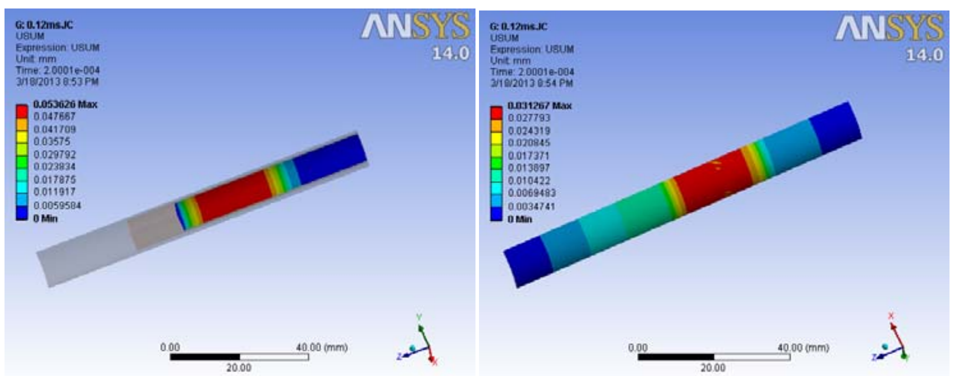

Fig. 6. Plastic deformations: plug inner wall – right, SG tube outer wall - left

The geometrical characteristics of the numerical model are:

- SG tube inner diameter: D_{it} = 13.610 mm
- SG tube outer diameter: D_t = 16.132 mm
- Expanded water volume: 3.768 cm^3
- Peak vale of the pressure wave (evaluated according to the above mathematical model and presented in Fig. 5): p_{max} = 103.4 MPa

The permanent deformation of the plug and tube walls obtained from the numerical simulation were compared against experimental results (see Table 1).

Table 1

Numerical vs. experimental results

Data	Plug inner wall deformation [µm]	SG Tube outer wall deformation [µm]
Experimental	69.4	25
Numerical	53.6	31.2

5. Conclusions

The mechanical deformation technique by electro-hydraulic shock is briefly approached in literature, information stopping at general matters regarding the synthetic description of the technique insisting on the advantages and disadvantages relative to the typical mechanical deformation technology. Thus, we showed that the mechanical deformation technique by electro-hydraulic shock is an unconventional technique based on the effect produced by the pressure wave peak generated instantaneous by an explosive vaporisation of the:

- Water volume nearby an electric arc primed between two electrodes;
- Fusible settled between two electrodes and of the water volume surrounding it.

To isolate the defective steam generator tube ends, we have chosen the plastic deformation technique by electro-hydraulic shock based on the pressure wave generated instantaneous by a plasma track obtained by vaporisation of a fusible settled between two electrodes and of a water volume surrounding it. Selection of the design version, in this case, has been imposed by the short distance between the electrodes and respectively, between the fusible and the swelling socket wall.

The applied technique is characterized by the generation of a high speed deformation (about thousand of m/s). Hence the great advantage of the application is the lack of residual mechanical stresses into the deformed material. For such kind of applications, the swelling socket wall material of the plug subjected to inertial forces actions „is flowing" to the opposite area without heat development and implicitly without cold-hardening. The experimental results have shown that the values of residual mechanical stresses are insignificant.

The similar mechanical deformation technique by explosion leads to same results and has the same no residual stresses advantage, but is more difficult to control it. By contrast, the control of the deformation technique by electro-hydraulic shock can be performed by adjusting some parameters of influence such as: the potential difference between electrodes, the discharge voltage, the discharge energy, the fusible geometry (length and diameter), and the fusible material and last but not least, the liquid volume.

Hence the need for mathematical and numerical models is required for improvement of both experimental model plug design and performance during the installing process.

The mathematical model has been built based on the tests performed in laboratory condition into a high capacity free surface water vessel for visualization of the generated electric arc. The initial model has been continuously improved using the tests results performed on t experimental plug models.

The mathematical and numerical models have been used both for design of experimental plug models versions and for interpretation of the obtained results. The unconventional plugging technique of a defective steam generator tube (without residual mechanical stresses) and the development of the mathematical and numerical modelling models could be considered as original approaches.

The validity of the pressure wave peak evaluation model generated by an electro-hydraulic shock has been ratified by the results obtained both during the development of this technique and in other various applications. Also, the metal radiography results made on samples from the joints used for application of this technique have demonstrated the lack of cold hardening at jointing components materials and the fact that the grains maintain the sizes in their micro-structure, deformation taking place by their sliding.

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