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Experimental and numerical testing of an innovative steam generator tube plugging procedure

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ABSTRACT

This paper presents the development of a finite element model used to numerically investigate the behaviour of an innovative defective tube isolation device. The high-speed plastic deformation by electro-hydraulic shock was proposed for plug installing in a steam generator tube simulator. The objective of the study was to evaluate the influence of the geometrical, material and hydraulic shock parameters upon the performance of the plugging procedure using an advanced 3-dimensional simulation model created in LS-DYNA general code. The computational model employs the Johnson–Cook plasticity model for SS321 to study the high strain rate, elastic–plastic dynamics of the process. The results of the simulations compared against experimental data have shown the great influence of the model parameters uncertainties on the success of the plug installation.

1. Introduction

Surface defects identified at steam generators (SGs) tubing are generally secondary-side specific and are mostly a result of aging phenomena during power-plant operation. Aging effects of the steam generators are a cause of (1) corrosion mechanisms more or less aggressive depending on the chemical nature of the secondary cooling fluid, (2) erosion degradation due to flow regimes, (3) wear generated by impact, fretting, cavitation or even (4) materials metallographic structure changes (IAEA et al., 1997). 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 sides) and flow parameters.

The steam generators in conventional nuclear power plants (NPPs) with pressurized light or heavy water reactors are in most cases of the shell-and-tube type. The reactor coolant passes through the tubes at the primary side and boils water on the outside of the tubes (secondary shell side) to produce steam. Consequently, one can highlight the important safety functions of the SGs tubes among which we can mention: integral component of the reactor coolant pressure boundary, heat transfer surface between the primary and secondary systems such that reactor nominal power and residual heat can be removed from the primary (nuclear) side; isolate the radioactive fission products inside the primary coolant (IAEA et al., 2008).

Several approaches have been exploited over time in order to minimize the degradation issues and increase steam generators operation life. Fluid chemistry control and chemical cleaning have been employed to diminish the number of failures and limit the plugging or sleeving procedures. However, the installation of plugs inside the failed tube remains the most common corrective actions taken by NPPs operators. Usually, the plugging of the steam generator tube is performed 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. A large number of primary steam generators installed decades ago are still in operation and some of them may operate without replacement until the final shutdown of the plants. Consequently, the degradation mechanisms of the steam generator tubes and remedial corrective actions are still the target of current research and maintenance operations (Lee et al., 2010; Revankar et al., 2009; Hur et al., 2010; Pagan et al., 2009).

Because in the scientific literature the electro-hydraulic installation technique is summary approached (Pow, 1997) the need for improved understanding of the phenomena and technological

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Nomenclature

ε_p (m/m)	equivalent plastic strain
$\dot{\varepsilon}_p$ (1/s)	plastic strain rate
$\dot{\varepsilon}_{p0}$ (1/s)	effective plastic strain-rate
ρ (kg/m^3)	density
σ_{ij} (Pa)	stress tensor components
Γ_0 (–)	Gruneisen coefficient
b_i (N/m^3)	body force
c_0 (m/s)	parameter in Mie–Gruneisen equation
$\dot{e}$ (J/kg s)	specific energy time derivative
$i, j = x, y, z$	coordinates
m_0 (kg)	mass inside an grid element
m (–)	thermal softening exponent
n (–)	hardening exponent
s (–)	parameter in Mie–Gruneisen equation
s_i (Pa)	stress deviatoric tensor
$\ddot{x}_i$ (m/s^2)	acceleration components
A (MPa)	material constant
B (MPa)	material constant
C (1/s)	strain rate constant
P (Pa)	hydrostatic pressure
T_0 (°C)	reference temperature
T_m (^{0}C)	reference melting temperature
V (m^3)	volume of an grid element
Y (Pa)	yield stress
INR	institute for nuclear research
NPP	nuclear power plant
SG	steam generator

limitations have represented the driving motivation of our work. The performed numerical analyses were correlated with laboratory results in order to validate the results and gain new insights. The general-purpose finite element (FEM) code – Ansys LS-Dyna (ANSYS, 2012) was used to simulate the plastic deformation of the plug and SG tube walls subjected to a transient electro-hydraulic shock load. Some modelling issues related to the model development based on the experimental results and material properties were investigated. The paper is structured as described further. The "Experimental setup and results" section contains a description of the unconventional plugging technique and experimental bench and testing results; some modelling aspects of the high strain rate plastic deformation phenomena are presented in "Numerical modelling approach" section. Further, in "Parametric studies" the results of the numerical simulations are given along with some commentaries. The last section summarizes the conclusions of the paper.

2. Experimental setup and results

The INR Pitesti have initiated and developed a plugging procedure of defective tube ends in a CANDU steam generator applying an unconventional plastic deformation technique. The key element of the procedure is the installation of the plug by an electro-hydraulic shock. The method is based on ultra-high-speed deformation of metal using shockwaves in water. Via the discharge of current from a low voltage system an electric arc is generated in a water volume between two electrodes. This electric arc vaporizes the surrounding water, converting the electrical energy into an intense shockwave of mechanical energy. The connection takes place by swelling of the plug wall with high speed on the SG tube wall due to the pressure peak resulted almost instantaneously. The explosion of the plasma passage is created after the melting and vaporization of the fuse into a constant volume of water (see Fig. 1) (Gyongyosi et al., 2008).

A similar technique is the plastic deformation obtained 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 deformation speed, i.e. $w \gg 100$ m/s. For such deformation speed values, the elastic theory of materials (Hooke's law) does not 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 dilatations (Lubliner, 1990).

The plugging procedure itself consists of several stages (1) preparation (fitting-out) of the experimental model plug; (2) arrangement of the plug equipped for installation in the steam generator tube simulator; (3) execution of the electric connection; (4) installing process itself by discharging the high power impulse generator; (5) dismantling and removing the additional components of the plug followed by cleaning the inner socket of the plug (Gyongyosi and T., 2011).

One of the standard plugs tested in IRN laboratory is shown Fig. 2. The tests performed in laboratory conditions proved that the plastic deformation technique by electro-hydraulic shock can be controlled by choosing a series of variables such as the discharge electric power value, the electric tension level at the

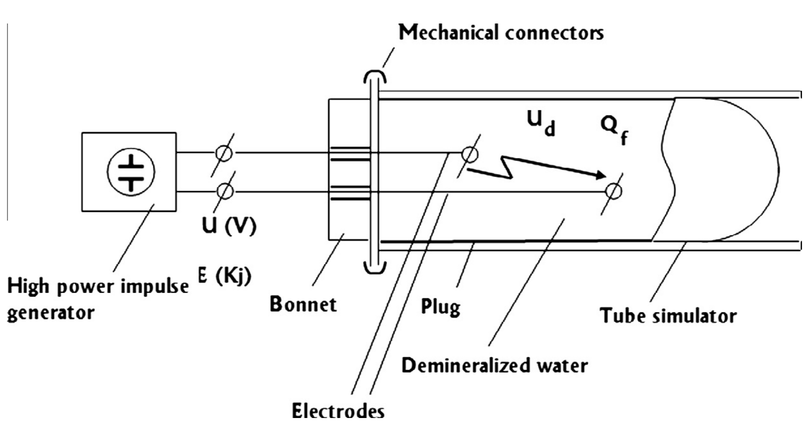

Fig. 1. Basic diagram of the plugging setup.