Explosive Welded Plug Design for Permanent Obturation of Defectives Steam Generators Tubes in PWR Nuclear Power Plants

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Abstract. In nuclear plant steam generators, when the wall of an Inconel (nickel-chromium alloy) hairpin tube becomes perforated, this requires repairing by entering the generator water box. For contamination related and positioning reasons (the vertical hairpin tube can only be plugged at a depth of 60mm), the only presently usable technique consists in fitting metal plugs, also made of Inconel and achieving a very reliable seal, in the hairpin tube concerned.

For this purpose, we developped a plug which can be set in place directly, without requiring any modification of tube and geometry, and which will meet requirements.

First, this process totally avoiding the migrating combustion residues in the steam generator, and second, the quality of the explosive welded bond and the constitutive materials fully comply with the security specification issued by nuclear powerplant authorities.

Development was conducted through a three phases'program involving :

- Design and full scale evaluation of differents parts,
- Numerical simulation,
- Full scale experimentation.

1. Introduction

French nuclear plant steam generators are equipped with nickel-chromium alloy (Inconel) vertical hairpin tubes. When a series of hairpins become punctured, their ends must be closed and the prevailing irradiation requires a fast and highly reliable sealing system. Various patents have been registered for explosion welding seal plugs [1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10] and several publications have been issued on this topic [11 - 12 - 13]. For this application, SNPE and E DF developped a new explosion weldable seal plug specially designed for specific nuclear plant requirements [14 - 15], in compliance with ASME code requirements [16] .

2. Spécification

Inconel hairpins are expanded vertically over the full length of the holes in the plate. Hairpin ends are welded on the Inconel cladding of the steel plate lower face, in a square pattern (fig.1).

After explosion welding, the pyrotechnical plug Inconel envelope should show the following properties :

- be free of chlorine, sulphur, lead and mercury,
- be welded and expanded over a minimum 45mm length, in which 6.35mm is continuous,
- withstand a 226 bar differential pressure between primary and secondary systems, at +20°C, and 100 bar at + 320°C,
- allow other plugs to be fitted into adjacent hairpins,
- not give rise to redhibitory stresses within 40mm from plate end,
- leave a 60mm minimum free height from plate end.

3. Experimental research and development

The pyrotechnical seal plug consists of four main parts (fig.2) :

- Inconel envelope : glove finger shaped, machined from bar. The inside profile is a truncated cone in the expanding section, in order to withstand explosion forces, while allowing gradual expansion.
- welding explosive charge, consisting of :
  . welding explosive, essentially composed of penthrite and polybutadiene, moulded with a center hole allowing the detonator to be inserted into seal plug just before firing, for safety reasons. Detonation velocity : is approx. 3700m/s.
  . explosive relay : penthrite and natural bis-polyisoprene base, circular shaped. Détonation velocity : approx. 7000m/s.
  . electric detonator : 5mm dia., with high electrical energy firing head (20mJ in .05 Ω) for high safety in use. For easier coaxial installation of various seal plug parts w/o impairing explosive charge dimensions the enamelled silver electric leads are very small in dia. (.32mm with insulation).
- Machined polyamide 6-6 transmitting medium has been chosen for its chemical (compatibility and bonding), mechanical and physical (s.g., yield strengh) properties. This transmitting medium achieves detonator centering and transmits detonation gas pressure to the truncated cone shaped section of the metal envelope, to expand the envelope against hairpin before welding completion.
- pin -shaped locator holding the envelope in centered position at 60mm height in the hairpin to be sealed. It is cast from semi-rigid polyurethane foam, in truncated cone shape, to apply a slight lateral pressure against tube walls, thus preventing plug from slipping down.

This pyrotechnical seal plug displays the following properties after firing (fig. 3) :

- undamaged envelope inner wall,
- 18mm average welded length extending to open envelope end,
- extremely reduced number of melted areas, thus indicating excellent weld quality,
- 65mm average expanded and welded length,
- perfect resistance to pressure and temperature conditions imposed,

- very small effect of firing on adjacent hairpin diameters, maintaining way for easy fitting of another pyrotechnical plug.

4. Digital simulation

The pyrotechnical plug operation generates unstationary stresses in hairpin tube and tube plate. It is necessary to ensure that these stresses are not beyond the stress levels allowed for the materials. A digital process simulation has been perfomed, in order to obtain an order of magnitude for these stresses, using HEMP code [17 - 18] . This is a 2-dimensional Lagrangian code, with finished differences, intended for the study of continuous media dynamic behaviour. The modelization simplifies [19] the configuration (fig.2) as follows :

- the transmission medium is not compressible and medium influence is limited to the volume occupied after being projected to the bottom of this envelope.
- the electric detonator is assimilated to a pure penthrite volume distributed to give a truncated cone shape to the relay, the relay itself being assimilated to pure penthrite.
- the locator is regarded, due to its constitution, as having no influence on a process and is therefore neglected.
- the detonation wave is supposed to be plane with a direction of propagation parallel to the Center Line.
- the hairpin tube and tube plate are regarded as one continuous medium. The stressed volume radius I is the distance from the concerned hairpin tube center to the next hairpin wall. Materials characteristics and behaviour are as follows :

- welding explosive :

  specific gravity $\rho = 3.66$; detonation velocity $\Delta = 3700\text{m/s}$

  equation of state $P = (\Gamma - 1)\,\frac{E}{V}$ (1)

  with pressure P; measured polytropic factor [17] $\Gamma = 384$; specific energy $E = 1823\text{J/cm}^3$ and relative volume V.

- explosive relay

  specific gravity $\rho = 1.35$; detonation velocity $\Delta = 7000\text{m/s}$

  equation of state (JWL) $P = A\,(1 - \frac{\omega}{R_1 V})e^{-R_1 V} + B\,(1 - \frac{\omega}{R_2 V})e^{-R_2 V} + \frac{\omega}{R\,V}$ (2)

  with $A = 7.056$; $B = 0.26$; $R_1 = 6$; $R_2 = 1.8$; ω [18] $= 0.28$; and specific energy $E = 7700\text{J/cm}^3$.

- Inconel envelope has an elastic-yielding behaviour, with work hardening and with the following quasi-static mechanical characteristics :

  specific gravity $\rho_0 = 8.51$; shear modulus $\mu = 8406\text{hbar}$; bulk modulus $K = 18211\text{hbar}$; yield strength $Y_o = 27.4$ hbar; rupture strength $Y_R = 59\text{hbar}$; rupture elongation $\varepsilon_R = 51\%$; equation of state, obtained by smoothing the Inconel Hugoniot curve in a way to maintain elastic behaviour at low compression levels

  $P\ (\text{Mbar}) = 1.821\,(\frac{\rho}{\rho_o} - 1) + 4.2\,(\frac{\rho}{\rho_o} - 1)^{\ominus} + 3.8\,(\frac{\rho}{\rho_o} - 1)^3$ (3)

- carbon steel (plate and hairpin tube) : has a perfect elastic-yielding behaviour. specific gravity $\rho_0 = 7.85$; shear modulus $\mu = 8160$hbar; bulk modulus $K = 16500$hbar; yield strength $Y_0 = 45$hbar; equation of state $P = 1.65 \left(\frac{\rho}{\rho_0} -1\right) + 1.87 \left(\frac{\rho}{\rho_0} -1\right)^2$ (4)

The simulation has been performed for the first 30 µs following seal plug firing and required many remeshings because of high distortions in gaseous areas (production of a jet), (fig. 4). More precisely, calculations show that the impact starts at approx. 3.5µs and ends at approx. 10µs. During projection, the envelope wall is raised by an angle β of approx. 10° and is propelled at an average plating speed V_P = 600m/s. These 2 values are in agreement with experimental knowledge. Some other experimental facts are qualitatively confirmed, particularly the maximum welded envelope wall driving into hairpin and plate wall is of the same order as its thickness.

As regards stresses, the area which was specially examined covers the first 40mm of hairpin and plate, as this area is more sensitive to circumferential stress σ_θ . The general pattern of σ_θ (t) evolution oscillates very much in time (fig.8), which can be explained by multiple wave reflections on the various system interfaces and free surfaces. The order of magnitude of σ_θ in the studied area is 4 kbar maximum in compression and 3kbar maximum in tension. Yielding distortions in this area can be evaluated (fig.5). These small distortions can be further reduced by driving the pyrotechnical plug further into the hairpin tube.

Besides giving the order of magnitude of phenomena taking place in this welding process, digital simulation allowed a better understanding of the transient phase in seal plug operation.

5. Stress measurements

In conjunction with digital simulation, mechanical stress measurements have been performed for comparison, during pyrotechnical plug operation [20]. For this test, a sample section of tube plate with 3mm thick Inconel cladding, equipped with hairpin ends, was fitted with 4 strain-gauges (fig.6). Strain-gauge positioning was designed to measure the circumferential distortion to which hairpin and binding are subjected during firing. Three gauges are bonded at 30mm from the plate block face, 2 of them being diametrically opposed in the hairpin in which the plug is being fitted. Considering the high process speed, strain-gauges were chosen with particular care and the adhesive frequency response was thoroughly investigated. During firing, the signal as detected by the gauges is amplified and recorded on a magnetic tape. It is then filtered and sampled by a transient recorder, then plotted on a plotting board (fig.7). After this distortion detection stage, the plate and hairpin tube are regarded, as previously (§ 4), as one carbon steel piece. Using the distortion behaviour law, the distortion is translated into tress values. An homothetic value transformation allows the experimental graph to be superimposed on the design graph (fig.2). The differences in profile found arise from the simplified modelization of the pyrotechnical system as compared with the real plug (specially regarding priming) and the receptacle, as regards simulation : in fact, the problem has been limited to a cylindrical cross-section tangent

to adjacent holes, moreover the hairpin tube as well as the Inconel cladding, both of thin cross-section, have been assimilated to the steel of the plate. Therefore, the mechanical reinforcement provided by adjacent bindings and the complex oscillation pattern arising from multiple wave reflections due to adjacent holes, have not been taken into account.
As regards measurement itself, distortion value translation into stress values is performed using the steel plate behaviour law. Here again, considering its small impact, the Inconel in hairpin tube and cladding has been disregarded. However, it can be seen that stress rise rate and stress level remain of the same order (3kbar on fig.8). Frequency variations between the 2 curves arise from the above-stated simplifications and from the phenomenon discretizing. Calculations show mesh related average values while strain-gauges measure surface values. Within 30 microseconds from system priming, the magnitude of strength values is such that the material maintains an elastic behaviour throughout. Considering the process progression pattern, maximum stress amplitude should not change significantly over further periods.

6. Conclusion

Through the joint action of several disciplines such as :

- calculation, formulation and trial of special explosives (slow detonation velocity, small critical dia., quick achievement of steady operation, high safety of use),
- system material selection (metallurgical, rheological, mechanical and machining properties),
- digital simulation of operation,
- stress measurements confirming the simulation,

it was possible to develop a seal plug using the explosion welding method and producing an excellent weld quality and repeatability, with predictable and checkable effect on the remaining structure.

With these advantages, plus fast implementation and operation, this pyrotechnical seal plug is of particular value to close punctured hairpin tubes, specially in nuclear plant steam generators.

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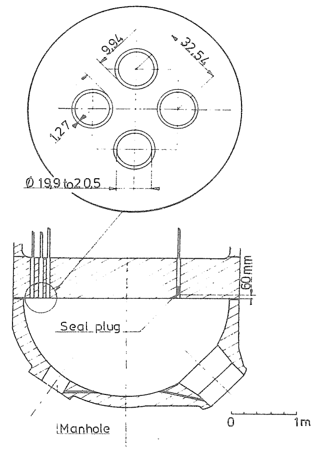
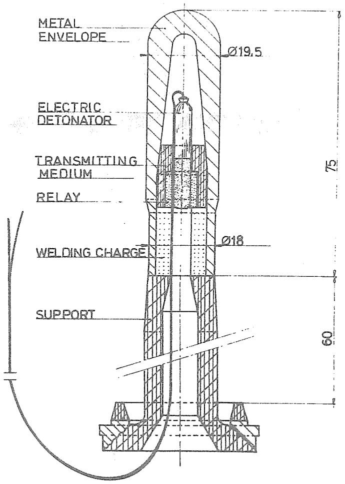
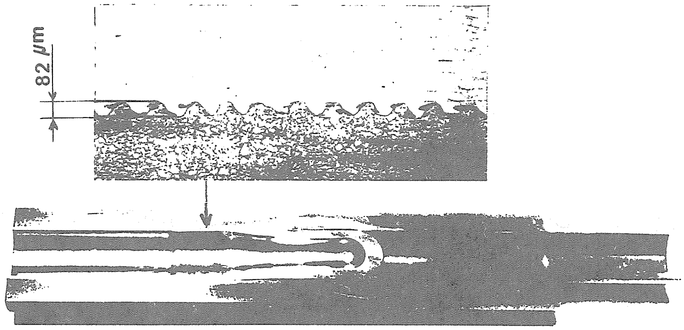


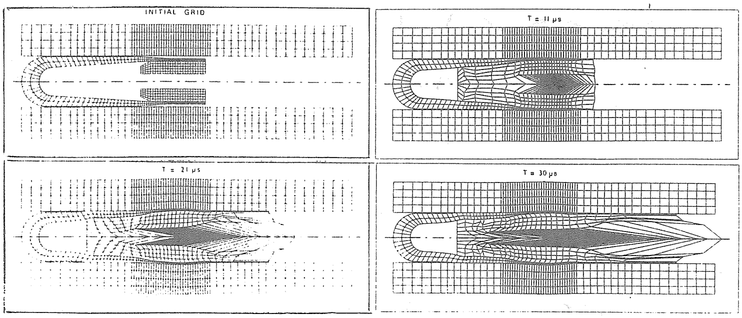
1-STEAM GENERATOR WATER BOX CROSS-SECTION



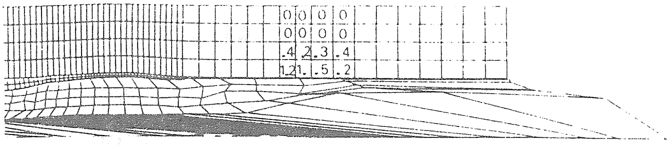
2-PLUG CROSS SECTION



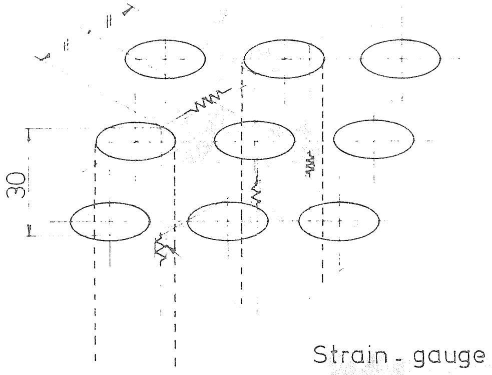
3-CROSS SECTION THROUGH WELDED PLUG IN A TEST SAMPLE AND WELD MICROGRAPH

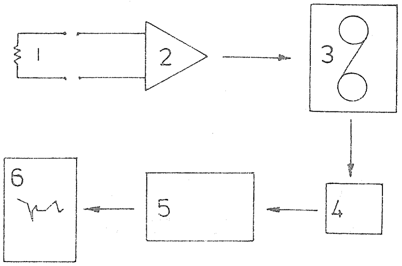


4-MESHING EVOLUTION AT VARIOUS INSTANTS



5 - EXAMPLE OF PLASTIC STRAINS (°/00) IN THE WEAK AREA

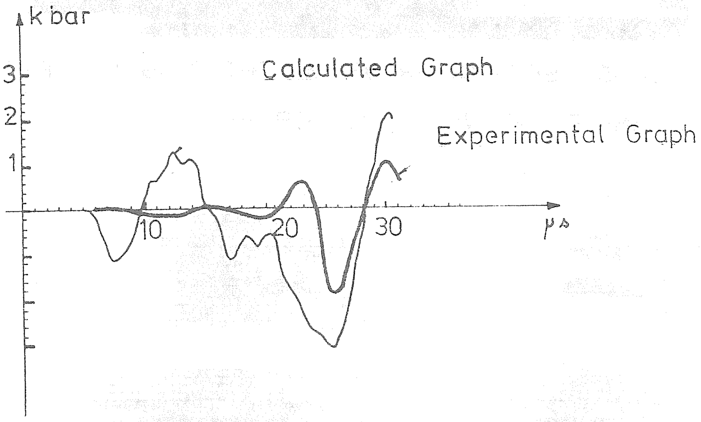




1 Strain - gauge
2 Conditioning amplifier
3 Magnetic recorder
4 Filter
5 Transient recorder
6 Plotting board

6 - GAUGE POSITIONING

7 - MEASURING SYSTEM DIAGRAM



8 - EXPERIMENTAL GRAPH: COMPARISON WITH A GRAPH DERIVED FROM DIGITAL SIMULATION (SEALED HAIRPIN TUBE AREA)