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NESC I PROJECT - STATUS REPORT AFTER THE SPINNING OF THE NESC CYLINDER

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ABSTRACT

The International Network for Evaluating Steel Components (NESC) addresses issues relating to the validation of the entire process of structural integrity assessment. The first NESC Project is providing a unique insight into the relative roles which NDT, material properties, instrumentation measurements, and stress and fracture analyses can make in providing a robust safety case for pressurised thermal shock of a thick reactor pressure vessel of aged material containing defects. NESC I is unique insofar as the NDT and the analyses of stress and fracture have been carried out without exact knowledge of the defects as is the case in the real world. The project reached a major milestone on 20 March 1997 with the completion of the thermal shock test using the AEA Technology Spinning Cylinder facility at at Risley. Early indications suggest that crack propagation has occurred in both the sub clad and through clad defects.

INTRODUCTION

On 20 March 1997, when the spinning cylinder test took place, the first NESC project reached a key milestone: a simulated pressurised thermal shock was applied to a cylinder of reactor pressure vessel material containing a range of defects specified by the international community [1]. Since the launch of the Network for Evaluating Steel Components (NESC) on 9 September 1993 [2], at least 50 organisations worldwide have contributed to this first benchmark project. Over 40 participants representing six European Union countries and the United States as well as the CEC Joint Research Centre were present at the test which was conducted by AEA Technology at their facility at Risley in the UK [3]. A pre-test seminar hosted by the Project's lead sponsor, the UK Health and Safety Executive, highlighted the achievements of the project up to the test.

An A508 Class 3 steel cylinder was manufactured from material supplied and forged by Sheffield Forgemasters, welded from two halves by MAN GHH at Oberhausen, Germany, clad internally with stainless steel by Framatome, and implanted with a range of surface breaking and sub surface defects of different types and sizes by MPA Stuttgart, Framatome and JRC/AEA Technology [4]. The cylinder was then circulated to key centres in Europe where it has been subject to rigorous inspection under realistic conditions. Teams from Russia, USA, Finland, Sweden, France, Germany and the UK have reported their findings of the defects to the Reference laboratory at the Joint Research Centre, Petten. The inspection of the cylinder provides a means to validate and compare current and proposed non destructive examination procedures from different countries in a manner similar to the PISC trials [5].

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The properties of the cylinder were determined in a comprehensive materials characterisation programme undertaken by eight European Laboratories. This has resulted in a materials data handbook for what is now probably the best characterised material of its type in the world [6].

Using the data generated from the inspection and materials characterisation, around 15 stress and fracture teams have made predictions as to how the defects would behave during the spinning cylinder test in terms of crack growth by ductile and cleavage fracture mechanisms [7].

This paper describes the instrumentation of the cylinder for the detection of crack growth and the NESC spinning cylinder test itself. Observations from examination of the cylinder made after the test by the Reference Laboratory are reported together with the initial interpretation from the test instrumentation. Post-test activities of the NESC Inspection and Analysis Task Groups are now in progress, and the future programme of evaluation and reporting is outlined.

INSTRUMENTATION FOR THE DETECTION OF CRACK GROWTH

Strain Gauges

One of the key tasks of the instrumentation was to detect the moment of cracking during the test and hence the time of initiation after commencement of the quench.

In previous spinning cylinder tests [8,9], alternating current potential difference (ACPD) methods had been used to detect crack growth. However, these had not proved very satisfactory in that the change in output due to crack growth was small when the crack tunnelled beneath the surface and could not be easily distinguished from thermal effects. For these reasons, the NESC Instrumentation Task Group concluded that the application of ACPD to a cylinder where tunnelling was expected beneath 4mm thick stainless steel cladding would not be successful.

The initial plan was to detect crack growth by measuring the change in crack mouth opening using strain gauges *spanning the mouth* of the surface breaking machined defect. This technique had been successfully applied by the Finnish utility IVO to measure crack growth in the Promotey PTS tests [10]. A laboratory trial by IVO had shown that an Ailtech Type SG 325 high temperature strain gauge could give a continuously increasing output up to a strain of over 10% although they were guaranteed to a value to 2 %. These gauges had flanged lengths of 28mm for spot welding, but were welded for only 8mm at each end.

Since Ailtech gauges were no longer available, the only other comparable high strain gauges were ordered from the manufacturer HEAT. Tests on these gauges showed that the strain to failure was much less than the 10% predicted across the defect mouth during the NESC test and therefore spanning gauges were likely to fail before any growth occurred. Investigations of other gauges available worldwide indicated that their performance could not be guaranteed to be better than HEAT.

A second approach for the detection of crack growth was based on detecting the change in strain in initially uncracked material *beyond* the ends of the defect as a result of the crack tunnelling or sideways crack extension beneath the gauges. Finite element calculations showed that the maximum mean hoop strain in uncracked material would be about 0.4% over a 12 mm gauge length, but that this would increase by nearly an order of magnitude to 3-4 % due to crack tunnelling, Fig 1 [11]. There was therefore confidence that the HEAT strain gauges mounted over uncracked material would survive the test and that the moment of crack growth would be detected by a discontinuous change in strain or by gauge failure. Reliance for the detection of crack growth was therefore placed on four additional gauges placed beyond the ends of the defects. These additional gauges were Ailtech type SG 355. The HEAT gauges were selected with a thermal compensation to suit the mean expansion coefficient of the cladding material between 10°C and 300°C.

Gauges were symmetrically mounted beyond the ends of the through and sub clad defects at distances of 5, 15 and 40mm from the defect tips along the line of the defects, Fig 2. A further single gauge was placed 40 mm beyond the upper end of the complex defect. These gauges were end welded in order to avoid changes in the gauge profile produced by the slip planes and averages peak strains over the gauge length. However, the manufacturer's individual gauge calibrations for continuous welding installation were used and therefore the gauge outputs had only limited numerical significance. Trials showed that 8 mm of spot welding at each end of the gauge avoided flange failure leaving a 10 - 12 mm free gauge length in the centre.

Since the opening of the through-clad defects and the change in strain over the major sub clad defect were of interest to validate finite element models and for comparison purposes, a total of four gauges were also placed across the centre of these defects, although it was recognised that these gauges would probably fail before growth occurred. Two further gauges were continuously welded to the cylinder at the centre line remote from any defects to measure the hoop and axial strains on the cladding surface. This completed the total complement of 19 gauges, Fig 2.

The strain gauge connecting wires were routed up the inside surface of the cylinder, across the support disc and through the drive shaft to the 100-ring slip ring unit above the gear box. The outputs from the slip ring were connected to a multi-channel data logger and graphical screen displays for on-line monitoring of strain during the test. Calculations predicted that the surface hoop strain would increase rapidly from the value of the start of the quench rising to reach a plateaux. If no defect growth occurred, the strain would gradually reduce as the transient proceeded. The moment of defect growth would be indicated by a step change in the strain gauge output which would be clearly visible and detectable.

Thermocouples

The NESC cylinder was instrumented with 21 thermocouples. The purposes of these thermocouples were:

1. to measure the through wall temperature distribution through the test,
2. to determine differences between the temperatures of the upper and lower cylinder halves
3. to measure the temperatures inside the machined surface breaking defect
4. to measure the inside surface temperature close to the strain gauges near the defects
5. to measure the water outflow temperature at the top and bottom of the cylinder
6. to create a breaking wire system for the detection of excessive crack growth

The provision of the thermocouples on the cylinder is shown in Fig 3. All thermocouples used were of the Chromel-Alumel K type enclosed in 1 mm diameter stainless steel sheaths. The thermocouples were individually calibrated at 100°C, 200°C and 300°C, traceable to the UK National Physical Laboratory.

Measurement of the through wall temperature distribution through the test was by an array of nine thermocouples arranged horizontally in the upper half of the cylinder above the level of the machined surface breaking defect. As well as thermocouples on the inner and outer surfaces, seven thermocouples were located within the material at depths graduated to correspond with the expected non linear temperature profile. The thermocouples within the material were located into blind socket holes drilled from the outside surface. All the thermocouple wires were well secured against the centrifugal forces using individual shim strips continuously spot welded to the surface. A corresponding array of 4 thermocouples was located beneath the upper array in the lower half of the cylinder and by comparison these were used to determine any temperature differences between the upper and lower halves. The two thermocouples on the inside surface were positioned 80 mm above and below the tips of the "complex" defect and flange welded horizontally for 130mm to act additionally as breaking wire gauges for the detection of excessive crack growth.

Three thermocouples were located within the machined surface breaking defect, one near the deepest point (approximately 72mm from the surface) and the others close (15mm) to the surface at each end of the defect in the region where cleavage initiation was expected. The wires from these thermocouples were routed around the ends of the plugging blade.

On the bore of the cylinder, one thermocouple was located above the major sub clad defect at mid height. The water outflow temperatures from the top and bottom of the cylinder were measured by one thermocouple at each end. Thermocouples were also positioned 80mm above and below the tips of the machined surface breaking defect and flange welded horizontally for 130mm to act additionally as breaking wire gauges for the detection of excessive crack growth.

NESC SPINNING CYLINDER TEST

The NESC spinning cylinder test was carried out at 14.15hr on 20 March 1997 at Risley. Over 50 people were present including key representatives from the HSE, the Network management at JRC Petten, and all the Task Groups. Attendees came from UK, France, Germany, the Netherlands, Sweden, Finland and the United States. The test was preceded by a short series of presentations in which the background, contributions and achievements of the project as a whole were highlighted.

The test was carried out according to the prepared procedure, Fig 4. The cylinder temperature prior to the quench was 293°C and the temperature of the quench water was 2.0°C. The cylinder was raised from rest to a hold speed at 1200rpm at a rate of 100rpm/min. A series of checks were carried out, and the cylinder speed was increased to 1,800 rpm for final checks. The acceleration demand was then raised to 170rpm/min and a target speed of 2600rpm set. The rig had reached full power (1,200 amps armature current) and maximum acceleration when the quench was fired at 2,100rpm.

The acceleration demand was progressively backed off so that the armature current did not exceed 1,200 amps. The quench continued for 12 minutes during which time the speed increased to reach a maximum of 2,400rpm. The speed profile attained was close to that specified. After 12 minutes the quench was switched off and by this time the level in the quench tank had dropped 498mm corresponding to flow rate of 44m^3/hr (162gal/min). The cylinder responded to the reduced drag by accelerating to 2,430 rpm. The cylinder was then brought to rest at 150 rpm/min. Data logging was terminated and the test data copied. This concluded the test.

After the test, the cylinder was allowed to cool slowly in the pit. It was then carefully unloaded from the rig, packed, and transported to JRC Petten for the Reference Inspection, Fig 5.

REFERENCE INSPECTION BY JRC PETTEN

The first detailed inspection of the cylinder after the spinning cylinder test was carried out by staff of the Reference Laboratory at JRC Petten. On arrival, all the internal surfaces over and adjacent to the major defects were cleaned, dried and protected with a polyethylene film. The support disc, shaft and external blanket were removed, together with the connecting leads and packing weights, after examination of the transducer connections and photographing the instrumented defects. A detailed visual examination of the cylinder surface together with the condition of each defect and transducer was made.

The examination revealed the following features:

- There were marks of surface straining above some of the sub clad defects
- All functioning transducers remained firmly secured to the cladding by the spot attachment welds
- The strain gauges spanning the surface breaking cracks had buckled during cooldown after yielding in tension during the test
- The shim bellows sealing the major surface breaking defect
- The cladding above the major sub clad defect had split and blistered at one point towards the lower end of the defect, tearing a non active strain gauge away from the cladding surface
- Discolouration along the line of the sub clad defects indicated possible further failure of the cladding
- The packing blade in the EDM slot was found to be loose and was easily removed

The final crack opening of the EDM slot was measured at several positions together with the buckling of the strain gauges. This will enable the maximum opening during the test to be determined and will serve as a useful benchmark for the finite element analyses. The defects were again photographed after the shims and transducers had been removed. The visual examination and a dye penetrant test did not reveal any conclusive signs of new cracking on the surface but this should not be discounted as the test has generated high compressive residual stresses in the surface regions. Further inspection using high power X ray equipment is planned by the Reference Laboratory at a later stage.

The defects and their surroundings were cleaned again using ethyl alcohol and the surface breaking defect was sealed with acid free silicon sealant. The cylinder was then ready for the post test inspection trials.

POST-TEST INSPECTION TRIALS

After examination by the Reference Laboratory, the NESC cylinder was released for the post-test inspections. The model of the round robin trials conducted within the framework of third phase of PISC is being used to organise the inspections. The same seven teams as took part in the pre-test inspection were invited to inspect the cylinder again, and two additional teams have also agreed to participate. Teams from Finland, Sweden, Russia, USA, France, Germany and UK are taking part.

The objectives of the post-test inspection were to detect and measure changes in the cylinder surfaces and in the size of the original defects following the pressurised thermal shock test. Some defects may have grown during the test whilst others might appear smaller due to the effects of residual stress induced by the test.

The inspection teams are expected to use the same procedures as used for the pre-test inspection which were representative of their national practice. Invigilation is being carried out by staff from JRC Petten. The inspections started in May 1997, and the cylinder will be transported between inspection centres around Europe before it returns to JRC Petten at the end of December 1997.

The results from the inspection will be analysed by to determine the relative performance of the different methods used to detect and size underclad defects and crack growth before and after the pressurised thermal shock test. Confidentiality of the teams' identity will be strictly preserved. Evidence of crack closure due to residual stress would be a key finding. The results from the evaluation of inspection are expected to be available to the Network from 1998 onwards.

TEST INSTRUMENTATION EVALUATION

Evaluation by the NESC Instrumentation Task Group of the AEA technology test report [12] of the strain gauge and thermocouple outputs found that all the strain gauges and thermocouples survived the test except those spanning the major defects which failed early into the quench as a result of the strains exceeding their working range. These failures were expected from the pre-test calculations. The gauges beyond the ends of the major defects showed signs of buckling during cooldown after yielding in tension during the test.

The thermocouple data confirmed the transient delivered and shod the cooldown rates in the cylinder. There was evidence of water ingress early during the quench from the thermocouples located inside the surface breaking defect, but the outputs showed that the temperatures had normalised well before the time at which the cleavage event was expected.

Between 213 and 217 seconds (the time step of the data logger), the strain gauges beyond one end of the major surface breaking defect showed a distinct step change in output indicative of a cleavage event and this is the best sign that crack growth has occurred, Fig 6. Confirmation of cleavage crack growth will be made by destructive examination of the cylinder planned for 1998.

The outputs from several of the strain gauges after the application of the quench were erratic and will require detailed interpretation. Although the gauges appeared to have succeeded in their primary task of detecting cleavage initiation, their performance under the severe conditions of the thermal shock test is an area for further investigation and trials. Increasing the working range of the strain gauges spanning the defects is another area where further development would been beneficial.

POST TEST ANALYSIS

Before the spinning cylinder test, 16 organisations from 10 countries submitted technical analyses assessing and predicting the behaviour of one or more of the defects in the cylinder. The methods used ranged from simple analytical calculations following codified rules to complex three dimensional elastic plastic finite element analyses [13]. The results from these analyses were collected by the Reference Laboratory. The task of evaluating so many different analyses is a complex one and Task Group 3 have decided to form a Sub Group to undertake this work and prepare a pre-test analysis summary report.

Prediction of the Cleavage Event

The organisations were asked to make their prediction of the time of cleavage initiation of the major defect during the test. A preliminary examination of the results show the predictions ranging from 150 to 300 seconds after the start of the quench. The closest prediction to the actual time (213 to 217 seconds) was the 226 s predicted by Oak Ridge National Laboratory (Bass/Kenney) using a complex 3D finite element model; the next closest was TWI (Phaal) using the PD 6493 defect assessment code backed by engineering judgement. An approach based on the local approach to fracture using the Beremin model by AEA Technology (Sherry et al [14]) gave a time of 190 s.

Comparison of Test Design and Real Conditions

Although they were a good approximation, the actual conditions achieved in the test for practical reasons did not match exactly the design transient. In particular, the actual speed attained tended to run ahead of the intended speed throughout the test and the rig had to be backed off at stages so as to avoid reaching the maximum speed too early. The temperature of the quench water at 3°C was slightly lower than the 5°C planned. A constant heat transfer coefficient of 10,000 W/m^2 °C was assumed in the pre-test analyses, but the actual variation of the HTC during the NESC test itself is being directly determined from the temperature measurements made during the test.

These minor differences should not make any difference to the validity of the analyses and the conclusions. However, in order to confirm this, some simple re-analysis of the defects using the actual test conditions is being carried out. These differences would have tended to have increased the likelihood of cleavage fracture and therefore of meeting the project's objective.

Comparison with spinning cylinder tests 4 and 6

It will be recalled that the NESC test cylinder was manufactured from the halves of the cylinders used for spinning cylinder tests 4 and 6 with the yielded material on the inside surface machined away. Test cylinders 4 and 6 both contained surface breaking semi-elliptical defects, but unlike the NESC cylinder, were not clad. Spinning cylinder tests 4 and 6 were both thermal shock tests: test 4 was undertaken at a lower speed of 500rpm using a high flow quench whereas test 6 reached a speed of over 2000rpm with a low flow rate quench. The existence of *three* tests *using the same material* (test cylinders 4 and 6 came from the same initial forging) presents a unique opportunity to assess the affect of the cladding in inhibiting cleavage fracture.

Probabilistic analysis of the NESC test

The extensive materials characterisation studies and the round robin inspections have produced a significant amount of data amenable to statistical analysis. Distributions generated from this data will be used for a probabilistic fracture mechanics assessment of the NESC test to predict the probability of cleavage fracture with time as the test proceeded. This will provide a benchmark for comparison with deterministic analyses and test data.

Further analyses

Further post-test analysis will be undertaken when the post test inspection and destructive examination of the cylinder are complete. In the meantime. it is expected that Task Group 3 will play an important part in the identification of the key issues for structural integrity assessment and the evaluation of the results.

EVALUATION AND REPORTING OF THE RESULTS FOR TECHNOLOGY TRANSFER

Responsibility for the evaluation and reporting of the results of the NESC project lies with the NESC I Evaluation Task Group. This comprises the Chairman of the inspection, materials, analysis and instrumentation Task Groups together with the project and network managements. It will be aiming to identify the how the interactions between the different disciplines have influenced the whole entire structural integrity process and the sensitivity of the results to variations in the data. Their first task will be to identify the issues to be addressed from the data that has been obtained. These issues are likely to include: the effects of cladding and its associated heat affected zone, constraint and scale, inspection method and sizing accuracy, scatter in materials data, margins of codified assessment methods, and the probability of cleavage and crack arrest. It is likely that a series of new Task Forces drawn from members of NESC will be set up to focus effort in these areas. Task Group 5 will also be responsible for reporting the conclusions of the project and agreeing publications in due course.

A number of projects have been set up within the framework of the CEC DGXI Working Groups on Codes and Standards aimed at harmonisation within the European Community. These projects include the transferability of data from specimens to large scale structures and the treatment of cladding within codes covering cladded vessels. It is expected that the data from the NESC project will also find application within these other projects and formal lines of communication have been established..

Evaluation and reporting of the results from the first NESC project is expected to be complete by the end of 1998 when the CEC Fifth Framework begins. The results themselves will continue to be used as a benchmark for many years.

CONCLUDING REMARKS

With the successful completion of the spinning cylinder test, the project has entered a new phase. The focus now is on the post test inspection and analysis followed by destructive examination of at least part of the cylinder. Evaluation of the results is underway and it is through this process that the project's objectives of examining the individual interactions of materials, non destructive testing and fracture analysis through a holistic approach will be realised. Reporting and publications will continue for many years long after work on the NESC 1 project is complete.

The major achievement of the NESC 1 project will be to establish NESC as a global network for co-operation in major structural integrity projects which will continue into the future.

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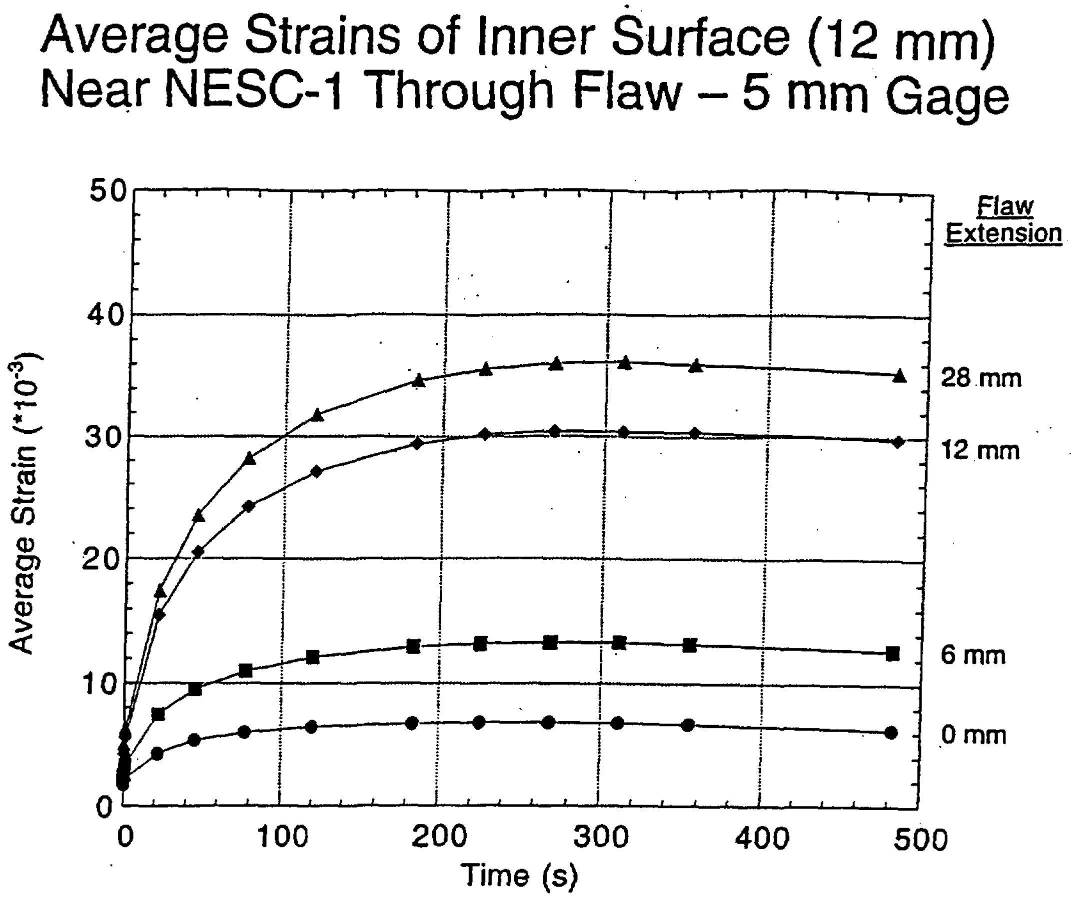

Fig 1 Strains beyond ends of crack

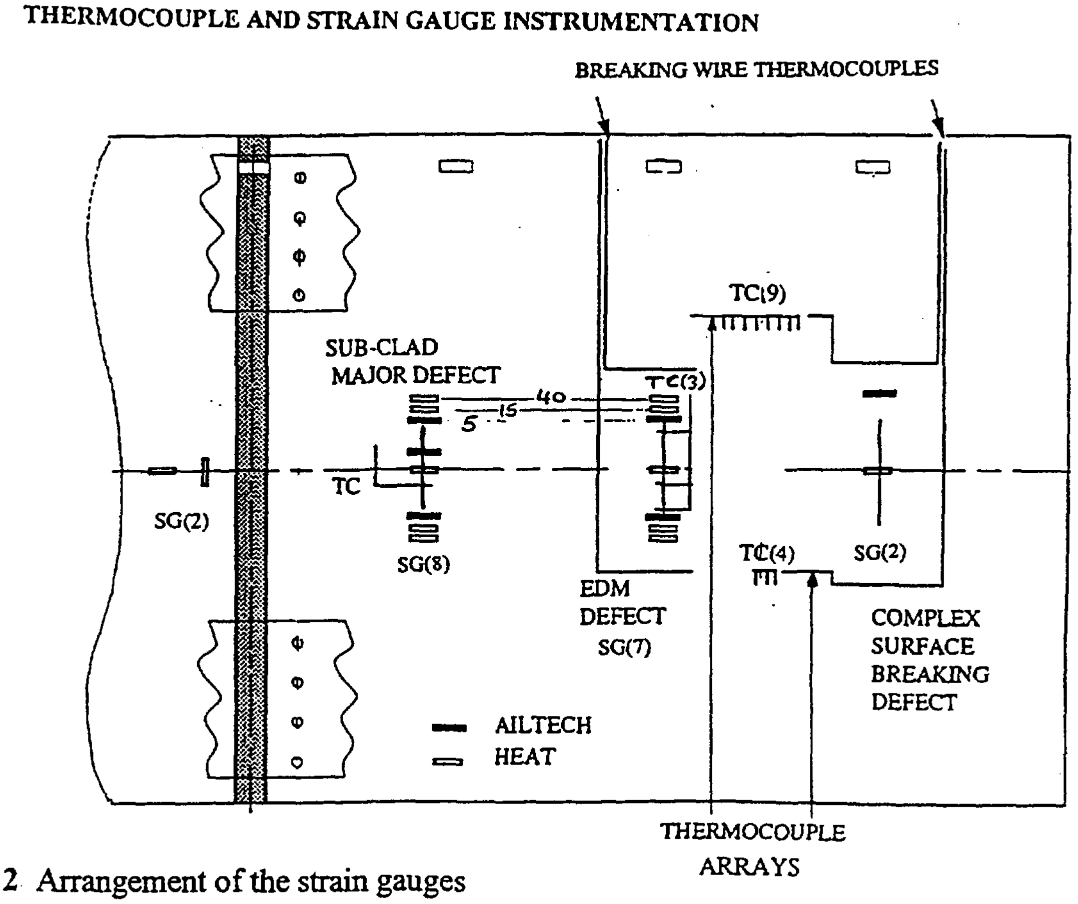

Fig 2 Arrangement of the strain gauges

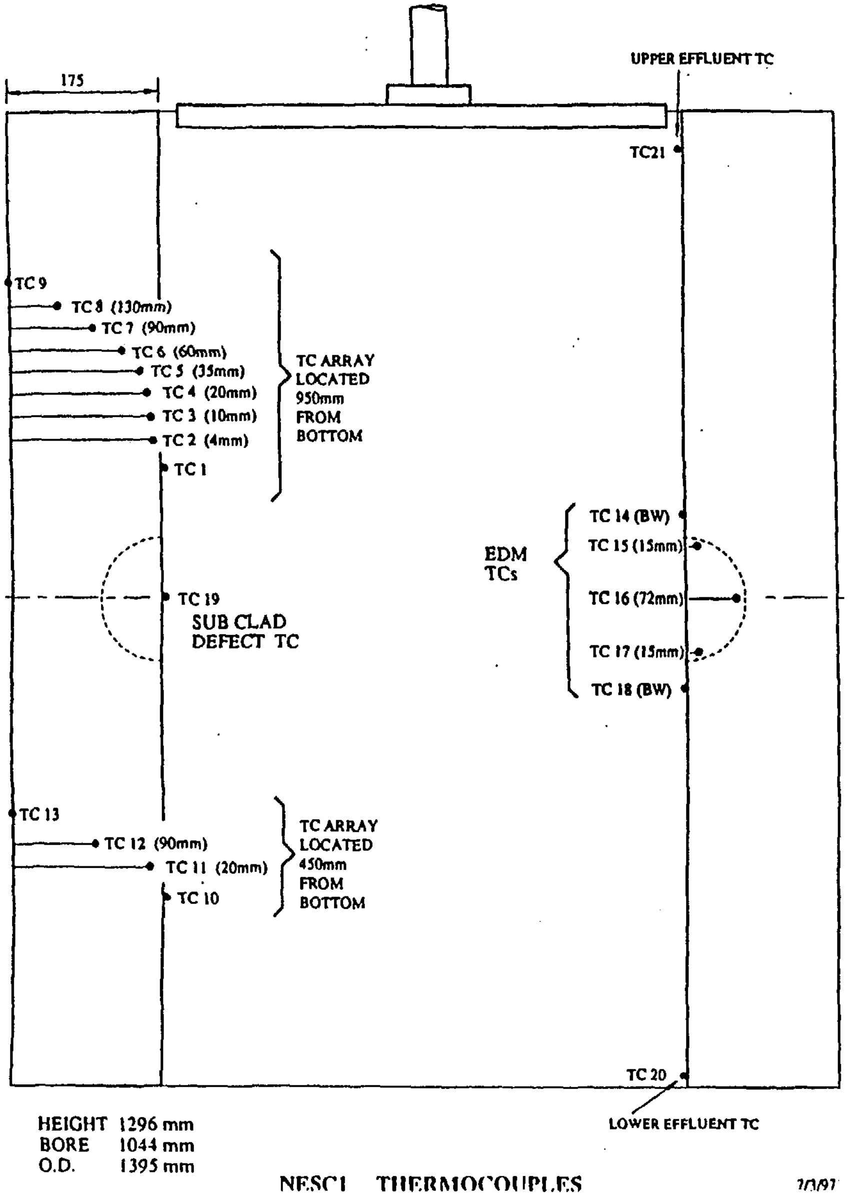

Fig 3 Arrangement of thermocouples

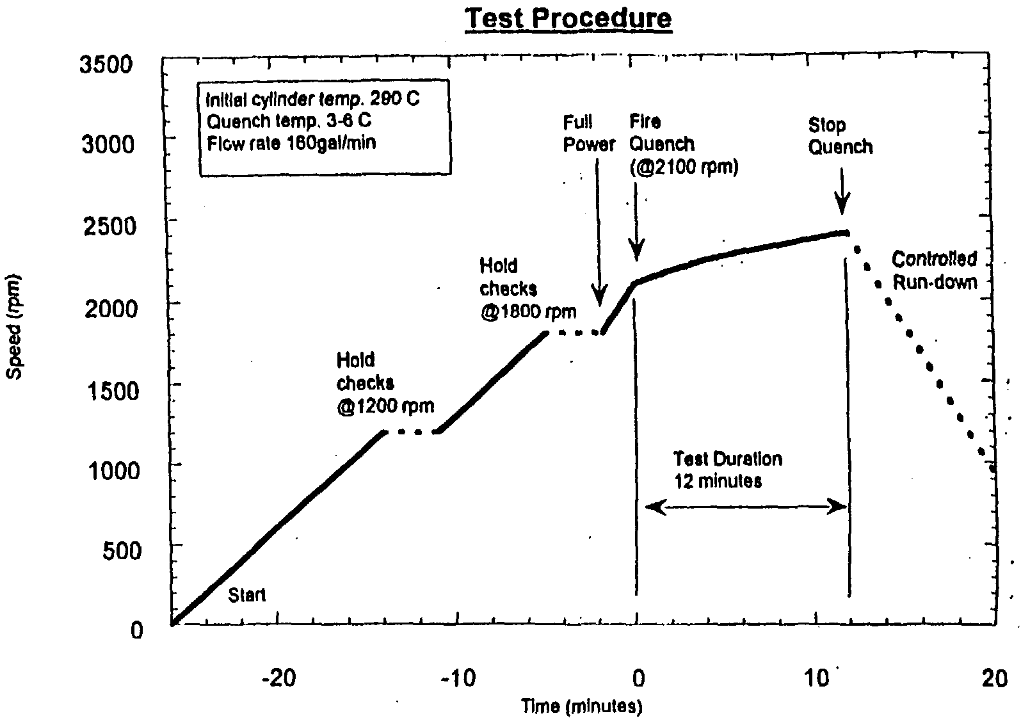

Fig 4 Design test transient

Fig 5 Cylinder after removal from pit

EDM defect SGs

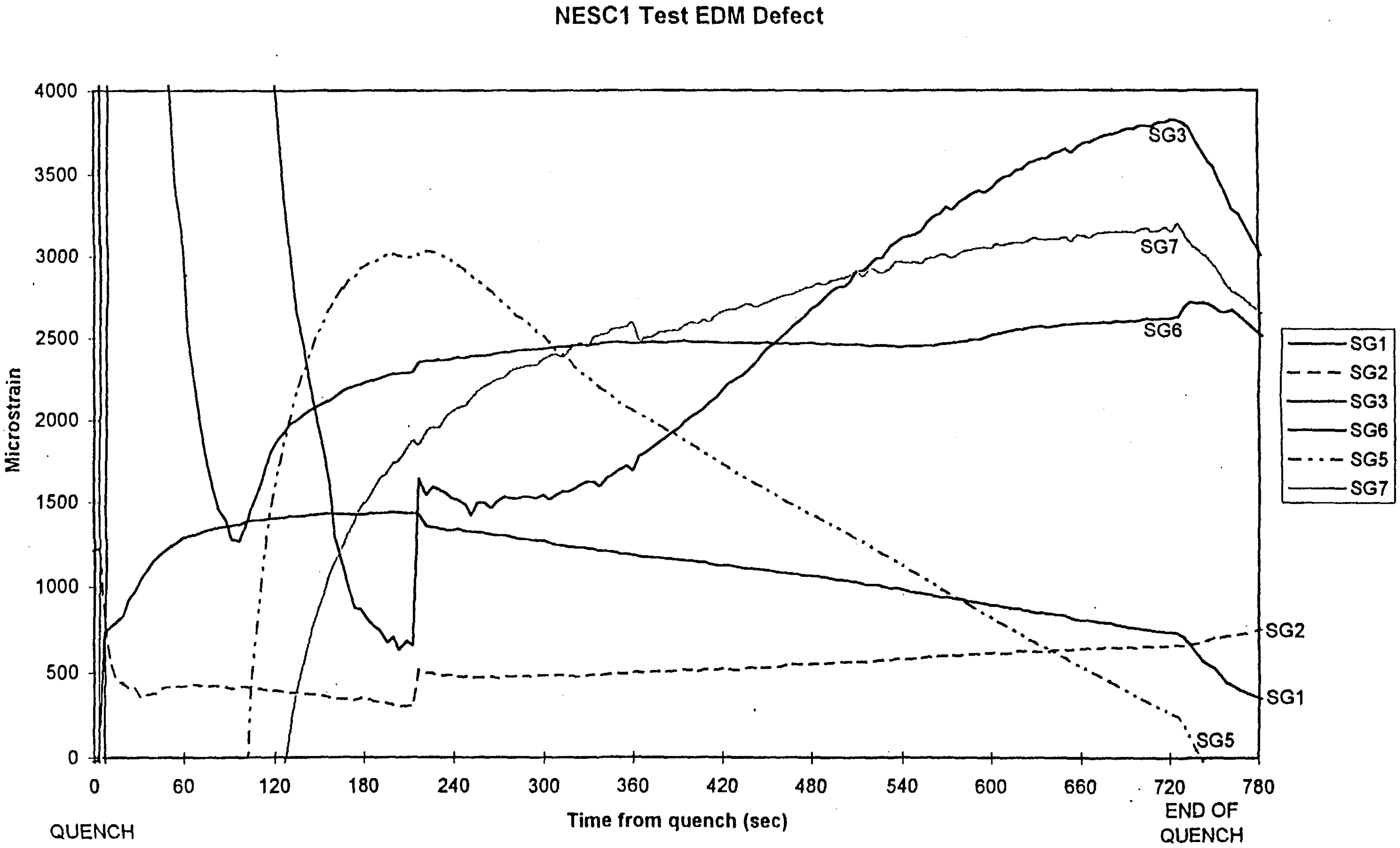

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Fig 6 Strain gauge output