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Pre-test results from the NESC spinning cylinder project

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ABSTRACT

The Spinning Cylinder Project is the first joint international collaboration of the Network for Evaluating Steel Components (NESC) and is based around a large scale spinning cylinder test. This paper summarises how the test conditions were defined and analysed, and how a method for detecting the moment of crack growth was developed. The test will create an important international benchmark for the understanding and validation of fracture methodologies used by the nuclear industry to assess reactor pressure vessels against pressurised thermal shock.

INTRODUCTION

On 9-10 September 1993, the global network NESC and the first NESC project were launched at the HSE's Laboratory in Sheffield UK [1]. On 20 March 1997, the project will reach a key milestone with the spinning cylinder test at AEA Technology's facility at Risley [2], Fig 1. A simulated pressurised thermal shock will be applied to a cylinder of reactor pressure vessel material with defects specified by the international community. At least 50 organisations world-wide have participated in this benchmark project. Defect growth is predicted in the test.

The A508 class 3 steel cylinder was manufactured by Sheffield Forgemasters, welded from two halves by MAN Germany, clad internally with stainless steel by Framatome, and implanted with both through- and sub-clad defects by Framatome, MPA (Germany) and JRC / AEAT [3]. The cylinder has been circulated to key centres in Europe where it has been subjected to a rigorous inspection [4]. Teams from 7 countries as far afield as Russia and the USA have reported their findings to the Reference Laboratory at JRC Petten. The inspection phases will effectively validate current non-destructive testing practice world-wide. Stress and fracture teams from Europe and the USA predict ductile and cleavage growth in at least one of the defects during the test.

The reactor pressure vessel (RPV) of a PWR reactor is a component critical to the safety of the reactor itself. A PTS transient is the event which, although unlikely, poses the greatest challenge to the integrity of the RPV, particularly when the vessel has been aged by irradiation [5]. Validation of the methodologies used for demonstrating safety in this event is the principal objective of this NESC project. The entire process of structural integrity is addressed through a holistic approach where the individual capabilities and interactions of materials, non-destructive examination (NDE) and fracture analysis are assessed with their proper context.

This paper describes how the test conditions have been set, the predictions of defect behaviour by structural analyses, and the development of a method for detecting crack growth.

DEFINITION OF THE TEST CONDITIONS

The loading conditions for the test were dictated by the need to generate a high enough thermal shock to produce crack growth and the capacity of the spinning cylinder rig. The conditions for crack growth required a high crack driving force to be generated at the same time as the crack front was cooled to a temperature sufficiently low for cleavage fracture to be a strong possibility. A high crack driving force could be generated using a high rotational speed and a severe thermal shock.

The severity of the thermal shock required the maximum difference between the initial temperature of the cylinder and the temperature of the water quench and a high heat transfer coefficient (HTC). However, as it was also necessary to reduce the temperature of the crack front to a low value at the maximum crack driving force, the initial cylinder temperature had not to be too high. The lowest temperature of the quench water was influenced by practical considerations. Although the NESC Task Groups considered using an antifreeze solution cooled to below 0° C, it was agreed that the new features this would introduce would require a further development programme of rig engineering and heat transfer trials and would in any case not be representative of a realistic PTS transient. Hence, it was decided to use the lowest practical quench water temperature of 5° C, generated by cooling the water in the quench tank using a standard industrial cooler.

The initial cylinder temperature was determined as a result of a series of sensitivity analyses carried out by NESC Task Group 3 [6]. A range of temperatures between 265° C and 300° C was considered as being representative. The analyses showed that the temperature of peak crack driving force could be lowered to 80° C by using T_0 of 265° C but as this also reduced the crack driving force compared with using a high T_0, there was no clear advantage in using a lower T_0. Eventually it was decided to use an initial cylinder temperature of 290° C on the grounds that a slightly higher crack driving force would promote more ductile crack growth before cleavage and was more consistent with the values used in previous spinning cylinder and thermal shock tests.

The capacity of the spinning cylinder rig was determined in a series of rig trials [7]. It was necessary to accelerate the cylinder from an initial speed at the start of the quench so as to reach the maximum speed at the time of the peak crack driving force due to the thermal shock. In order to achieve a high heat transfer coefficient, a high flow rate quench was required. The trials established that the capacity of the rig to meet these requirements was ultimately limited by the power of the 400 kV electric motor and that the drag forces created by the quench water hitting the moving cylinder surface imposed a limit to the maximum speed obtainable.

A balance therefore needed to be struck between the flow rate necessary to produce a high heat transfer coefficient and the maximum speed and acceleration. After a series of trials at different flows, it was found that a flow of 727.5 l/min would produce a heat transfer coefficient of 10,000 W/m^2 °C. This was determined by measuring the temperature profile through the cylinder wall as a function of time and equating the integrated heat loss through the wall to that transmitted to the quench across the inside surface of the cylinder. A series of analyses by NESC Task Group 3 showed that the thermal shock conditions were relatively independent of HTC for values of HTC above 10,000 W/m^2 °C but below this value both the severity and the cooling of the shocks would be significantly reduced [7].

The maximum acceleration and rotational speed obtainable at a quench water flow rate of 727.5 l/min were determined by running the motor at maximum rated electrical power Attempts to exceed the rated power resulted in the control system being unable to function properly and motor overheating. Controlling the motor power to just within the rated value was achieved by progressively lowering the acceleration demand as the speed increased. The limiting speed-time profile for a quench rate of 727.5 l/min was determined, Fig 2. The maximum speed obtainable was 2300 rpm when the power needed to overcome the drag forces of the quench equalled that of the motor and no further acceleration was possible.

The initial cylinder rotational speed at the start of the quench was determined by considering the calculated time of the peak thermal crack driving force from the analysis and the limiting speed time profile. From this, it was agreed that an initial cylinder speed of 2100 rpm at the start of the quench would enable the rig to approach its maximum speed while still slightly accelerating at the time of peak thermal crack driving force. The requirement for an increasing rotational load generating the primary stress was based on warm prestressing considerations. From this work all the necessary test conditions were defined.

PRE-TEST STRUCTURAL ANALYSIS

One of the key objectives of the project is to compare structural analyses of the behaviour and growth of the defects during the spinning cylinder test from the use of different analysis methods and as-measured materials properties [8] and defect dimensions [9]. This is being accomplished by NESC Task Group 3 where analyses by over 25 different organisations are being undertaken. The approaches differ widely ranging from comprehensive three dimensional elastic plastic finite element calculations to simplified elastic approaches where approximations are made to estimate the stress distribution and crack driving force. The Rousselier and Beremin local approaches to ductile and cleavage fracture are also being applied [10].

The teams are being asked to make their best prediction of the amount of ductile tearing prior to cleavage, the time and location of cleavage initiation, and the extent of cleavage propagation prior to crack arrest. Results to date indicate that most teams are predicting both ductile and cleavage growth of the major defects but by differing amounts. The results support the conclusions of the comprehensive test design analyses carried out by Oak Ridge National Laboratory and others [11], Fig 3.

The analysis data will be collected before the test by the Reference Laboratory (JRC Petten) for post test evaluation by the Network. Issues for evaluation will include the effect of constraint and scale on ductile growth and cleavage initiation compared with small scale deep and shallow crack data, the effect of the cladding on the mode of growth, the margins in terms of temperature and toughness between the observed initiation and that assessed using code or regulatory methods, and the validity of simplified methods and 2-D analyses. The evaluation will be aimed at identifying the methods which perform best drawing generic conclusions form the test data.

DETECTION OF CRACK GROWTH

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 AC potential difference methods had been used to detect crack growth [12]. 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 signal noise. NESC Task Group 4 concluded that the application of ACPD to a cylinder with stainless steel cladding would not be successful because of the problems of signal noise and tunnelling under the 4 mm cladding thickness.

Instead, it was initially decided to try to measure crack growth by detecting the change in crack opening using strain gauges placed across the mouth of the open crack. This technique had been previously successfully applied by IVO to measure crack growth in the Prometey PTS tests [13]. A laboratory trial by IVO had shown that an Ailtech Type SG 325 high temperature demountable strain gauge welded over a length of 8 mm at the ends could give a continuously increasing output up to a strain of over 10%. However, when this approach was evaluated for the NESC cylinder, it was found that the crack opening predicted during the test exceeded the working range of the HEAT gauges supplied which were likely to fail before any growth occurred.

Therefore, a different approach was adapted based on detecting the change in strain in initially uncracked material beyond the ends of the defect as a result of the crack tunnelling beneath them. Finite element calculations showed that the peak 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. There was good confidence that the gauges supplied would survive the test over uncracked material and that the moment of crack growth would be detected by a rapid discontinuous change in strain or by gauge failure.

Gauges were symmetrically mounted beyond the ends of the principal through- and sub-clad defects at distances of 5, 15 and 40 mm from the defect tips along the line of the defects. These gauges were also end weld in order to accommodate the changes in strain between the 45° slip planes through the cladding. Trials had shown that 8 mm of spot welding at each end was sufficient to avoid 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 sub clad defect were of interest to validate finite element models and for comparison purposes, gauges were also placed across the centre of these defects, although it was recognised that these gauges would probably fail before growth occurred. A further single gauge 40 mm beyond one end of the second through-clad defect completed the total complement of 19 gauges, Fig 4.

The gauge connecting wires were routed up the inside surface of the cylinder, across the support plate and through the drive shaft to a slip ring unit above the gear base. The outputs from the slip ring were connected to a multi-channel data logger and graphical screen displays for on-line monitoring during the test. Calculations predicted that the surface hoop strain would increase rapidly from its value at the start of the quench rising to reach a plateau. If no defect growth occurred, the strain would gradually reduce as the transient proceeded. Defect growth would be indicated by a step change in the strain gauge output which would be clearly detectable. From the time of initiation of rapid growth, the loading and temperature conditions can be determined by calculation. These are the conditions against which the various predictive methodologies will be validated.

CONCLUDING REMARKS

On 20 March 1997 the steel cylinder prepared by the Network for Evaluating Steel Components will be tested in the AEA Technology Spinning Cylinder Facility. The test will follow three years preparation during which the cylinder has been manufactured with defects, inspected by seven national teams in a blind trial, characterised by materials testing, and whose behaviour during the test has been assessed by over 25 organisations. After the test, a programme of evaluation will begin during which the cylinder will be re-inspected to determine the capability to detect changes in the defects and fracture mechanics predictions will be evaluated against the test results. The project represents a milestone of international collaboration in the field of nuclear safety research in structural integrity and through the large scale spinning cylinder test will raise the understanding of the complex issues to improve standards of structural integrity assessment.

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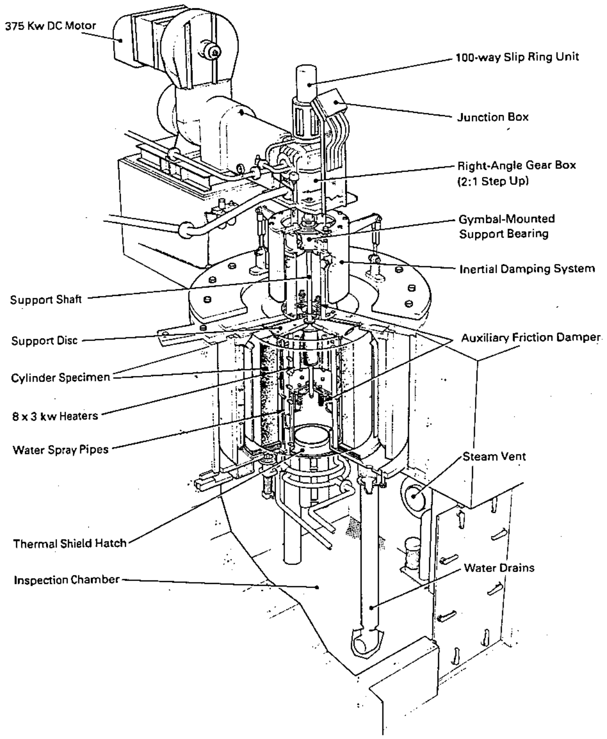

Figure 1 The AEA Technology Spinning Cylinder Test Rig

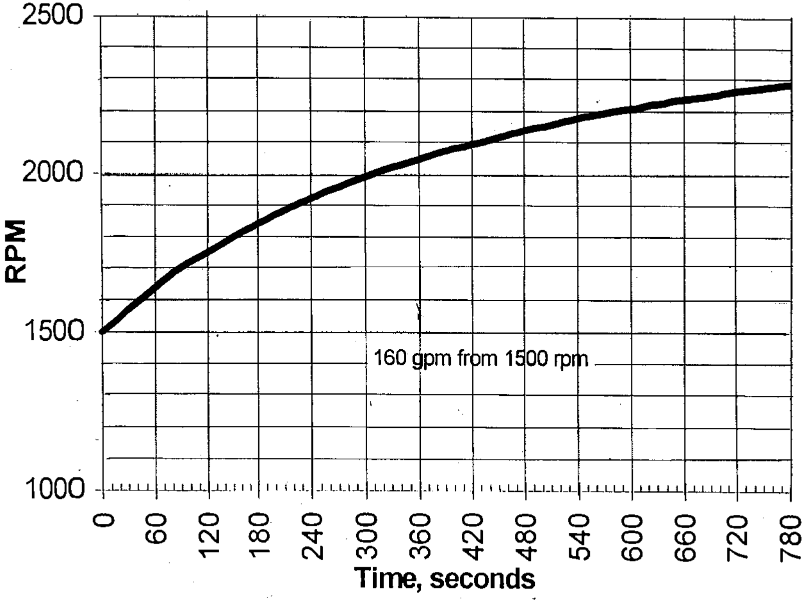

Figure 2 Acceleration Profile of the NESC Test

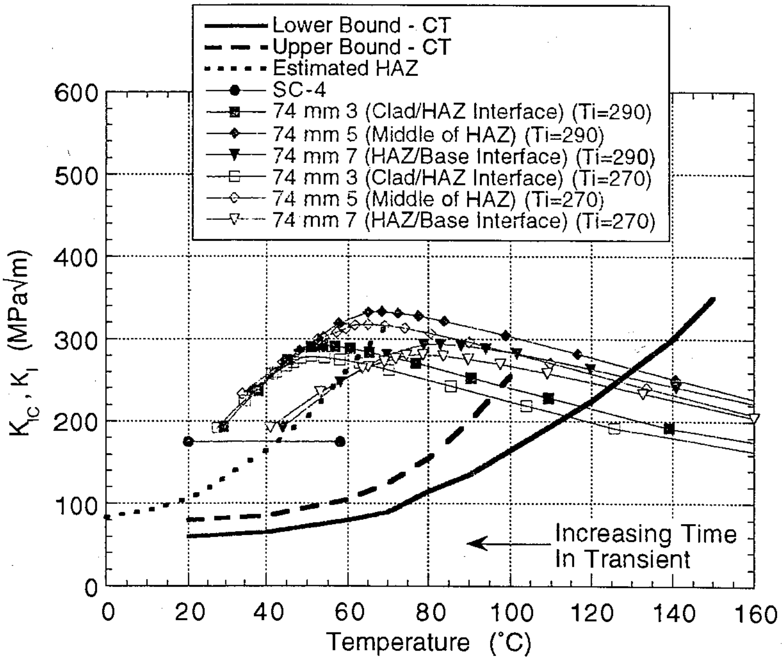

Figure 3 ORNL Test Design Analysis

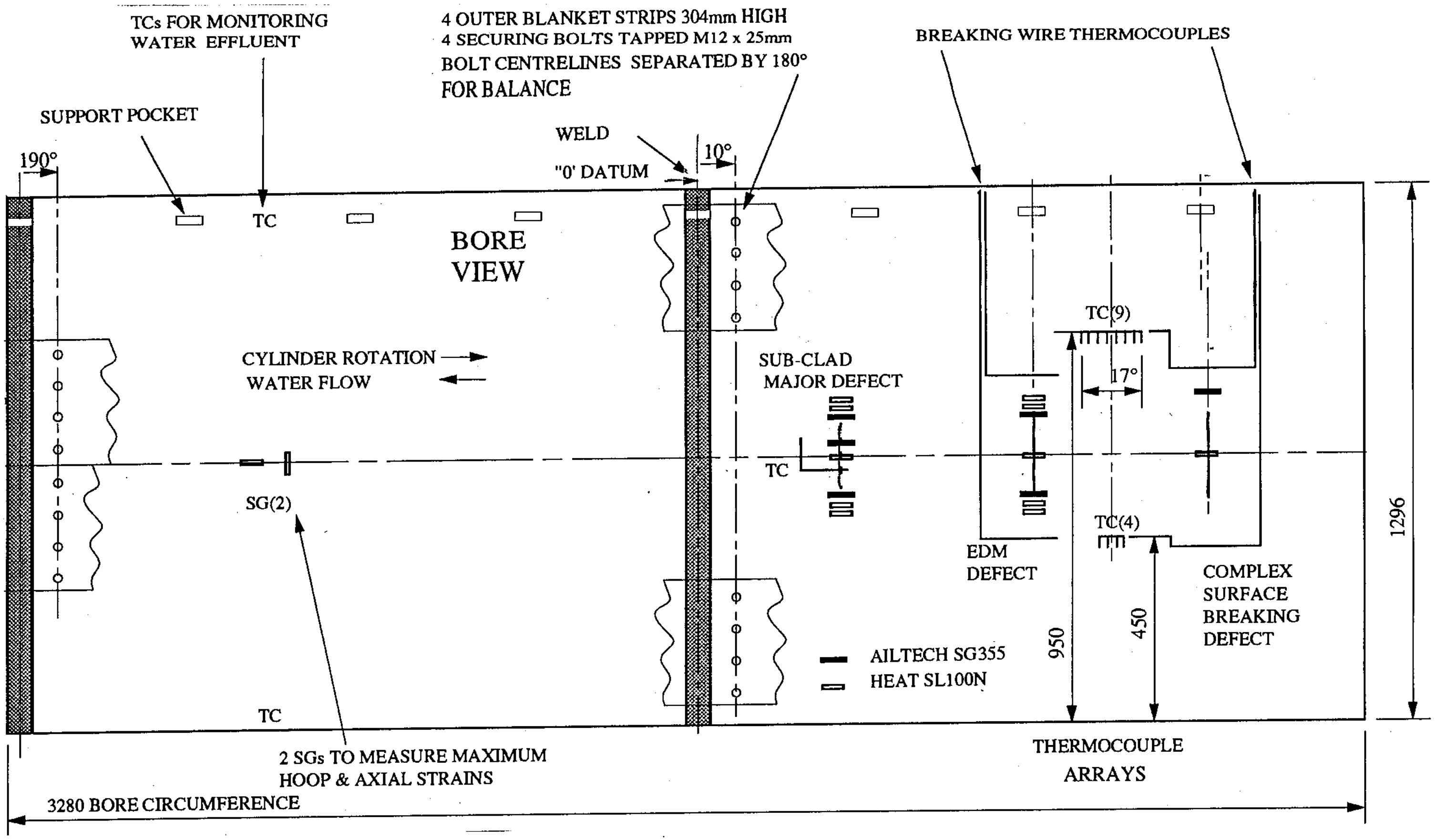

Figure 4 Strain Gauge Locations